Third (unedited) draft, for consideration by the Ad Hoc Working Group of the Whole
(English only)

Regular Process for Global Reporting and Assessment of the State of the Marine Environment, including Socioeconomic Aspects (Regular Process)

Second World Ocean Assessment

Output of the second cycle of the Regular Process

Summary

In its resolutions 57/141 and 58/240, the General Assembly decided to establish a regular process under the United Nations for global reporting and assessment of the state of the marine environment, including socioeconomic aspects, both current and foreseeable, building on existing regional assessments. In resolution 71/257, the General Assembly recalled that the scope of the first cycle of the Regular Process focused on establishing a baseline, and decided that the scope of the second cycle would extend to evaluating trends and identifying gaps. The Programme of work for the period 2017-2020 of the second cycle of the Regular Process includes the second world ocean assessment(s) to be prepared by the Group of Experts, building on the baselines established by the first global integrated marine assessment. In its resolution 72/73, the General Assembly further decided that the Group of Experts should proceed on the basis of a single comprehensive assessment. The present document was prepared by the Group of Experts in accordance with these decisions.

PREFACE

The goal of the United Nations General Assembly in creating the Regular Process for the Global Reporting and Assessment of the State of the Marine Environment, including Socioeconomic aspects was to ensure that there is a comprehensive overview of the ocean and the relationships between the ocean and humans, covering all environmental, social and economic aspects. Such an overview would serve as a background to the many decisions that must be taken in this field at international, national and local levels in the pursuit of sustainable development. The First Global Integrated Marine Assessment (World Ocean Assessment I) was completed in 2015, and represents a major step towards that goal.

Inevitably, with such an ambitious goal, not only were some aspects not fully covered in that first output of the Regular Process, but also, as time passes, the assessment that was made up to 2015 needs to be up-dated. The General Assembly therefore provided for further global integrated marine assessments to record developments from the baseline provided by World Ocean Assessment I and, where possible, to show trends. In 2016, it decided that a second comprehensive assessment should be prepared by the end of 2020.

This volume presents that Second World Ocean Assessment – World Ocean Assessment II. It provides more information on aspects of the ocean and its relationships with humans – for example, it now has separate assessments of the abyssal plains and marine hydrates – and brings together in specific chapters matters that were addressed in various different sections of World Ocean Assessment I – for example, the state of fish species and marine infrastructure.

As with World Ocean Assessment I, producing this second Assessment has been a major task, relying essentially on voluntary efforts of hundreds of experts in many fields, although supported this time by the United Nations' Regular Budget. As before, the Group of Experts of the Regular Process has been privileged to organize, to contribute to, and to finalize this Assessment. Crucial support has again been provided by the United Nations Secretariat, the Division for Ocean Affairs and the Law of the Sea, by several international organizations and by a number of United Nations Member States, as detailed in Chapter 2 (Approach to the Assessment). The Group of Experts is grateful to all these people and institutions but, under the terms of reference and working methods endorsed by the General Assembly, is ultimately responsible for the final text.

The bulk of the text of World Ocean Assessment II was written before the outbreak of the Covid-19 pandemic. Some mention of the effects of that pandemic has been included (for example, in the sections in Chapter 8C (Maritime industries) dealing with fisheries, shipping and tourism). But the full implications of the pandemic on human interactions with the ocean are still being worked out, and will need to be explored fully in the third cycle of the Regular Process. Nevertheless, the ocean and the services that it provides will have an important role in the recovery from COVID-19. We hope that the information in this Assessment will help that process.

As with World Ocean Assessment I, this Assessment contains no policy analysis or recommendations, in line with the guidance endorsed by the General Assembly. It is therefore for national governments and competent international authorities to decide what action to take in the light of the assessments under the Regular Process.

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Summary

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Keynote points

- Understanding of the ocean continues to improve. Innovations in sensors and autonomous observation platforms have substantially increased observations of the ocean. Regional observation programmes have expanded with better coordination and integration.
- Some responses to mitigating or reducing pressures and their associated impacts on the ocean have improved since the First World Ocean Assessment (WOA I).[1] These include expansion and implementation of management frameworks for conserving the marine environment, including the establishment of marine protected areas and, in some regions, improved management of pollution and fisheries. However, many pressures from human activities continue to degrade the ocean, including important habitats, such as mangroves and coral reefs. Pressures include those associated with climate change; unsustainable fisheries, including illegal, unreported and unregulated (IUU) fishing; introduction of invasive species; atmospheric pollution causing acidification and eutrophication; excessive inputs of nutrients and hazardous substances, including plastics, microplastics and nanoplastics; increasing amounts of anthropogenic noise; and ill-managed coastal development and extraction of natural resources.
- Quantification of the impacts of pressures and their cumulative effects continues to be lacking. A general failure to achieve integrated management of human uses of coasts and the ocean is increasing risks to the benefits humans receive from the ocean, including food safety and security, material provision, human health and wellbeing, coastal safety and maintenance of key ecosystem services.
- Improving management of human use of the ocean to ensure sustainability will require improved coordination and cooperation to ensure capability development in regions where it is lacking, innovations in marine technology, integration of multidisciplinary observation systems, implementation of integrated management and planning and improved access to, and exchange of, ocean knowledge and technologies.
- The COVID-19 pandemic is having major effects on many aspects of the ocean. The full implications of the pandemic on human interactions with the ocean are still to be fully assessed.

1. Introduction

The ocean covers more than 70 per cent of the surface of our planet and forms 95 per cent of the biosphere. Changes in the ocean drive weather systems that influence both land and

[1] United Nations (2017). *The First Global Integrated Marine Assessment: World Ocean Assessment I.* Cambridge: Cambridge University Press.

marine ecosystems. The ocean also provides significant benefits to the global community, including climate regulation, coastal protection, food, employment, recreation and cultural well-being. These benefits depend, to a great extent, on maintaining ocean processes, marine biological diversity and related ecosystem services.

Concerned by the declining state of the ocean, States Members of the United Nations, through the United Nations General Assembly, established the Regular Process for Global Reporting and Assessment of the State of the Marine Environment, including Socioeconomic Aspects. The aim of the Regular Process is to provide an evaluation of the state of the global ocean, the services it provides and the human activities influencing its state. The First World Ocean Assessment (WOA I)[Error! Bookmark not defined.] was completed in 2015. It concluded that many parts of the ocean had been seriously degraded, and that, if the problems it described were not addressed, they would produce a destructive cycle of degradation in which the ocean could no longer provide many of the benefits on which humans rely. As part of work identified for the second cycle of the Regular Process, three process-specific technical abstracts were produced and summarized the content of WOA I in relation to climate change, biodiversity in areas beyond national jurisdiction and Sustainable Development Goal 14 (Life Below Water).[2]

This Second World Ocean Assessment (WOA II) updates WOA I to take account of developments and changes known to have occurred since 2015 and complements this by describing further human interactions with the ocean. Most of the text of the assessment was written before the outbreak of the COVID-19 pandemic, and its full implications will take time to become apparent. Where appropriate, WOA II provides an evaluation of how the developments and changes since WOA I contribute to the achievement of relevant Sustainable Development Goals (SDGs).[Error! Bookmark not defined.] Developments and changes are indicated relevant to the societal goals of the United Nations Decade of Ocean Science for Sustainable Development 2021–2030.[3]

2. Drivers

In WOA II, drivers are characterized as social, demographic and economic developments in societies, including changes in lifestyles and associated consumption and production patterns applying pressures to the ocean (Chapter 4). Relationships between drivers and pressures (and their impacts) are complex and dynamic, with interlinkages leading to cumulative interactions. Drivers identified in Chapter 4 of the present Assessment are:

(a) **Population growth and demographic changes**: The world's population continues to grow, though at a slower rate, and population movements are increasing, especially in coastal areas. The extent to which an increasing global population places pressures on the marine environment varies, depending on a range of factors, including where and how people live, their consumption patterns, and technologies used to produce energy, food and materials, provide transport and manage waste;

(b) **Economic activity**: Economies continue to grow globally, although at slower pace. As the global population has grown, demand for goods and services has increased, with associated increases in energy consumption and resource use. Many countries have developed, or are developing, strategies for growing ocean-based economies ("the blue economy"). However, an important constraint on the growth of ocean economies is the current declining health of the ocean and the pressures being placed on it;

[2] See United Nations General Assembly resolution 70/1.
[3] See United Nations General Assembly resolution 72/73.

(c) **Technological advances**: Advances in technology continue to increase efficiencies, expand markets and enhance economic growth. These innovations have enabled outcomes for the marine environment both positive (e.g. modernization of energy generation) and negative (e.g. overcapacity in fisheries);

(d) **Changing governance structures and geopolitical instability**: At both international and national levels, improved methods across some regions of cooperation and implementation of effective policies have resulted in reducing some pressures on the ocean. However, in regions where there is conflict over access to resources and maritime boundaries, policies and agreements focused on sustainability can be undermined;

(e) **Climate change**: Anthropogenic greenhouse gas emissions have continued to rise, with widespread effects throughout the ocean persisting for centuries and causing further long-term climate changes, affecting the ocean. The impacts of climate change have been further recognized through the adoption of the Paris Agreement[4] which aims to strengthen the global response to threats from climate change.

The global influence of these five drivers is not uniformly distributed. Human populations are not evenly dispersed and population growth varies between countries and regions. Geographic disparities in economic growth have been increasing since the 1980s. Associated differences in technological advances mean that some countries can extract resources from previously inaccessible areas, with likely increased pressures in these regions. Many regions, particularly with countries considered as least developed, still lack access to technologies that can assist in the sustainable[5] use of marine resources. Regional disputes and geopolitical instabilities may affect the implementation of global and regional treaties and agreements, thereby affecting economic growth, transfer of technologies and implementation of frameworks for managing ocean use. Climate change effects are also not uniform, with some regions warming at higher rates than the global average, including the Arctic Ocean (Chapter 5).

3. Cleaning up the ocean

Lack of appropriate wastewater treatment and release of pollutants from manufacturing industry, agriculture, tourism, fisheries and shipping continue pressurize the ocean, impacting food security, food safety and marine biodiversity. Marine litter, ranging from nano to macro, is a further problem since, apart from damage caused by its presence, it can also carry pollutants and non-indigenous species over long distances (Chapters 10, 11 and 12).

3.1. Linkages with the Sustainable Development Goals and the United Nations Decade of Ocean Science

SDG Target 14.1: By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution;

Decade of Ocean Science societal outcome: A clean ocean where sources of pollution are identified and reduced or removed.

Concentrations of some pollutants (e.g. persistent organic pollutants and metals) in some

[4] Adopted under the United Nations Framework Convention on Climate Change in FCCC/CP/2015/10/Add.1, decision 1/CP.21, annex.

[5] Unless otherwise indicated, "sustainable" and "sustainability" are used with reference to all aspects – environmental, social and economic.

regions are declining, however information on concentrations is not spatially uniform. Knowledge gaps remain, not only on recognised pollutants, but also on emerging pollutants. In several regions, capacity gaps remain in applying consistent, coherent policies and related enforcement to prevent and control inputs into the ocean of pollutants (Chapters 10, 11, 12, 21). The particular ways in which progress towards other SDGs will assist achievement of SDG Target 14.1 are set out in Table 1. The particular ways in which achievement of SDG Target 14.1 will assist progress to other SDGs are set out in Table 2.

3.2. Nutrient pollution

Anthropogenic inputs of nitrogen and phosphorus to coastal ecosystems from direct discharges, land run-off, rivers and the atmosphere have generally continued to rise, though better control of releases are reducing inputs into some waters. Due to excessive inputs of these nutrients, eutrophication is an increasing problem and numbers of hypoxic zones (sometimes called “dead zones”) have increased from over 400 globally in 2008 to around 700 in 2019. Ecosystems most impacted include the northern Gulf of Mexico, the Baltic and North Seas, the Bay of Bengal, and the South and East China Seas. It is estimated that coastal anthropogenic nitrogen inputs will double during the first half of the twenty-first century. Additionally, deoxygenation is projected to worsen through climate-change-driven increases in ocean temperatures and changes in stratification and ocean currents (Chapter 5), particularly in coastal regions of Africa, South America, South and South-East Asia and Oceania (Chapter 10).

3.3. Hazardous substances

Industrial development and the intensity of agriculture have continued to increase, resulting in both ongoing and new inputs of hazardous substances to the ocean. New types of input include pharmaceuticals and personal care products (PPCPs) and nanomaterials that cannot be removed by wastewater treatment in major parts of the world. Detection of PPCPs increasing across the ocean, including in the Arctic and Southern Oceans. A number of PPCPS have been observed to cause harm to plants and animals, but the scale of these impacts in marine organisms is unknown, largely because they are not generally monitored (Chapter 11).

Although the Stockholm Convention on Persistent Organic Pollutants[6] is generally having a positive effect on global concentrations, persistent organic pollutants (POPs) continue to be detected in marine areas and in marine species remote from their sources of production and use. Even low concentrations have been shown to reduce reproductive success in marine species, including Arctic seals. In most ocean regions, information on trends is lacking (Chapter 11).

The Minamata Convention on Mercury[7] is generally reducing global mercury concentrations, with evidence, in most regions, that mercury concentrations in the ocean are levelling off. However, a slight increase in concentrations of some metals in higher trophic organisms has been reported. To better assess metal-concentration trends, expanded coastal time-series analyses are needed globally, including of levels of metal nanomaterials in the ocean (Chapter 11).

[6] United Nations, *Treaty Series*, vol. 2256, No. 40214.
[7] Entered into force on 16 August 2017; United Nations Treaty Series registration number 54669; see also UNEP(DTIE)/Hg/CONF/4, annex II.

Concentrations of most radioactive substances continue to decrease through decay of historical inputs. There have been no major nuclear accidents since 2011, and discharges from nuclear reprocessing plants in Europe continue to decrease substantially. Smaller amounts of radionuclides continue to be released by nuclear-power reactors operating across 30 countries (Chapter 11).

Globally, shipping accidents have continued to decrease: an annual average of 88 ships of over 100 gross tonnage were lost between 2014 and 2018, compared with 120 across the preceding five years. Progress is being made in reducing air pollution form ships. Oil spills have remained low: an annual average of six spills of over seven tonnes from oil tankers occurred between 2010 and 2018, compared with an annual average of 18 spills in the previous decade. Offshore oil and gas installations also release hydrocarbons into the marine environment, but the long-term impacts of such releases remain a knowledge gap (Chapters 11 and 20).

3.4. Solid waste

Inputs of solid waste to the ocean (including marine litter) from unintentional releases and intentional dumping of wastes are largely globally unquantified. Plastics represent up to 80 per cent of marine litter, with annual inputs to the ocean from rivers estimated at 1.15–2.41 million tonnes. Plastics have been recorded in over 1,400 marine species. Less is known about the effects of microplastics (pieces less than 5 mm in size) and nanoplastics (smaller than 100 nm), although nanoplastics have been observed to enter the cells of organisms. These two groups of plastics are derived from both the breakdown of macroplastics and deliberate manufacture (for example, as ingredients in personal care products). Dumping of sewage sludge and organic and inorganic waste remains low, with dumping of sewage sludge continuing to decline as a result of the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972 (the London Convention)[8] and the 1996 Protocol thereto[9] and many regional conventions. However, shortcomings in reporting under these agreements remain, resulting in uncertainties in the extent of dumping of waste. Munitions dumped at sea continue to present low risks to the marine ecosystem and (when caught in nets) to fishers. Recent research, however, suggests that the release of compounds from the munitions might cause sub-lethal genetic and metabolic effects in marine organisms (Chapter 12).

3.5. Noise

Anthropogenic inputs of noise into the ocean are derived from many sources (vessels, oil and gas exploration, industrial activities and sonar), with inputs varying across space and time. Regions with the highest inputs of anthropogenic noise are those with heavy industrial use, such as the Gulf of Mexico, the North Sea and the Atlantic Ocean. Unlike many other sources of marine pollution, noise does not persist once the sound source has been removed from the environment. Understanding of the impacts of anthropogenic noise on marine biodiversity has increased over the last two decades, with a range of direct and indirect impacts observed across a number of taxa, from zooplankton to marine mammals. Associated with better understanding of those impacts, there is increasing recognition of the need to monitor noise entering the marine environment and identify and reduce any impacts. While some efforts are

[8] United Nations, *Treaty Series*, vol. 1046, No.15749.
[9] The 1996 Protocol entered into force on 24 March 2006.

being made to reduce noise created by a variety of sources, increasing use of the ocean is likley to offset such efforts (Chapter 21).

3.6. Key knowledge and capacity-building gaps

Methods for standardizing observations of pollutants including noise and data sets are needed urgently, so that both spatial and temporal differences in pollutants can be evaluated and priorities established. Capacity-building is needed to reduce the input of pollutants into the ocean, particularly through the introduction of cleaner production and quieter technologies and cheaper and readily deployable wastewater-processing technologies. To reduce duplication of effort, a general database on hazardous substances and a baseline of ambient noise would be desirable to support risk assessment and modelling. The extent of transboundary marine pollution is poorly understood in many parts of the world, particularly in respect of airborne pollutants; more accurate data on their emissions and transport is needed. Finally, much better understanding is needed of the effects on the marine environment of pollutants, including anthropogenic noise (Chapters 10, 11, 12, and 21).

4. Protecting marine ecosystems

The main threats to marine ecosystems come from human activities such as fishing, aquaculture, shipping, sand and mineral extraction, oil and gas exploitation, building of renewable energy infrastructure, coastal infrastructure development, and pollution, including the release of greenhouse gases.

4.1. Linkages with the Sustainable Development Goals and the United Nations Decade of Ocean Science

SDG Target 14.2: By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans;

SDG Target 14.5: By 2020, conserve at least 10 per cent of coastal and marine areas, consistent with national and international law and based on the best available scientific information;

Decade of Ocean Science societal outcome: A healthy and resilient ocean where marine ecosystems are understood, protected, restored and managed.

Many marine species and habitats continue to be adversely impacted by anthropogenic pressures that, in themselves, are increasing. (Chapters 6A–6G/H, 7A–7S, Part 5). Understanding of the distribution and status of species and habitats and how they are being impacted by anthropogenic pressures is improving. As of 2020, marine protected areas cover 18 per cent of the ocean within national jurisdictions, representing approximately 8 per cent of the entire ocean. About 1 per cent of the ocean in areas beyond national jurisdiction (ABNJ) has been made the subject of protective action (Chapter 30).

The particular ways in which progress towards other SDGs will assist achievement of SDG Targets 14.2 and 14.5 are set out in Table 1. The particular ways in which achievement of these targets will assist progress to other SDGs are set out in Table 2.

Protection of marine ecosystems from the many threats that impact them is embedded in many international agreements, for example, the United Nations Convention on the Law of the Sea[10] and the Convention on Biological Diversity,[11] as well as in regional conventions and national legislation. Despite the objectives of such agreements and conventions, the status of many marine species and habitats continues to decline globally, and thus the functioning of ecosystems is at risk. In addition, climate change is resulting in ocean warming, acidification, changes in circulation, dissolved oxygen concentrations and water cycle amplification. Consequently, primary productivity is being altered including declining export of production to the deep sea. Globally, about 2,000 marine non-indigenous species have been introduced to new locations via human-mediated movements (Chapters 5, 6A–6G/H, 7A–7S and 25).

Many management frameworks for protecting marine ecosystems have a sectoral focus and therefore can have differing objectives for protection of the marine environment across sectors. Management tools utilised can be area-based (e.g. marine protected areas, fishery closures) or non-area-based (e.g. global emission controls, catch and effort controls, technology controls). Management approaches are increasingly moving away from focusing on sectoral use toward including diverse links between ecological and societal/economic/cultural aspects. The ecosystem approach, integrates environmental, social and economic aspects globally, regionally, nationally or locally. Cultural information is becoming an integral part of management frameworks, both in the context of community-based management, and for safeguarding the cultural dimension of the marine environment. Such information can be diverse and intangible, e.g. traditional marine resource use, sea routes, ancient navigational skills, maritime identities, legends, rituals, beliefs and practices, aesthetic and inspirational qualities, cultural heritage, and places of spiritual and sacred and/or religious importance (Chapter 30).

In some areas, particularly in South-East Asia, "blue infrastructure development", as well as approaches such as nature-based solutions, are being introduced as attempts to harmonize coastal protection with development and habitat and ecological protection (Chapters 8C, 13 and 14).

4.2. Coastal ecosystems

Despite increases in marine protected areas and the expansion of Ramsar Sites,[12] mangroves (except in the Red Sea) and seagrass meadows (particularly in South-East Asia) continue to decline, with 19 per cent of mangroves and 21 per cent of seagrass species identified as threatened. The combined effects of ocean warming and human activities are increasingly impacting tropical and subtropical coral reefs and kelp forests globally. In recent years, coral reefs have undergone mass bleaching on an annual basis while kelp forests have been impacted by marine heatwaves (Chapter 9), resulting in rapid losses (Chapters 6G/H, 7E and 7J).
Overall, about 6 per cent of known fish species and nearly 30 per cent of elasmobranch species are listed as threatened or vulnerable. Globally, the status of marine mammals varies, with 75 per cent of species in some groups (sirenians, freshwater dolphins, polar bears and otters) threatened or vulnerable. Many large whale species are now recovering from past harvesting as a result of prohibitions and regulation of commercial catches and national recovery plans. The conservation status of marine reptiles has varied greatly: protection in

[10] United Nations, *Treaty Series*, vol. 1833, No. 31363.
[11] Ibid., vol. 1760, No. 30619.
[12] See Convention on Wetlands of International Importance especially as Waterfowl Habitat; United Nations, *Treaty Series*, vol. 996, No. 14583.

some regions has increased some populations; while in other areas, populations are declining because of continuing or increasing threatening processes. The global conservation status of **s**eabirds has worsened, with over 30 per cent of species now listed as threatened (Chapters 6C, 6D, 6E and 6F).

4.3. Open ocean and deep-sea ecosystems[13]

The open ocean continues to be affected by ocean warming, acidification and deoxygenation, and marine pollution. Nutrient inputs derived from the Amazon River and brought up by the coastal upwelling off West Africa appear to have fuelled a massive seaweed bloom of floating *Sargassum*: the 20 million tonne bloom began developing in 2011 in the equatorial Atlantic Ocean and, by 2018, had extended 8,850 km across that area (Chapters 7P, 10 and 12).

Understanding of the distribution of cold-water corals has increased and they are known to occur along continental margins, mid-ocean ridges and seamounts worldwide. They and other deep-sea features (seamounts, pinnacles and ridges, trenches and hydrothermal vents and cold seeps) remain under threat from fishing, offshore oil drilling, deep-sea mining and pollution, including plastic waste, and to a lesser extent from climate change. Some efforts to curb deep-water bottom trawling and establish marine protected areas where cold-water corals occur have partially restored some damaged cold-water coral communities. However, these habitats can take decades to centuries to recover, making identifying trends of improvement difficult (Chapters 7F, 7N, 7Q and 7R).

4.4. Key knowledge and capacity-building gaps

Since 2015, on average, one new species of fish has been described per week, highlighting our lack of understanding. Although knowledge of ecosystem composition and functioning has improved since WOA I, gaps remain, particularly about deep-sea ecosystems and open-ocean planktonic and benthic species. Gaps remain in understanding the biology and ecology of coastal species, particularly in the waters of developing countries. We lack a well-organized structure to study the 2,000 or so non-indigenous species that have spread to new areas as a result of human activities and their impacts on natural ecosystems. Less than 1 per cent of macroalgal species have been assessed for their extinction risk (Chapters 6A, 6B, 6C, 6G/H, 7P and 25).

While the ecosystem approach has been widely acknowledged as an effective framework for managing human impacts, further research and capacity-building is needed to realize its full potential across the whole ocean. Many regions lack good understanding of links between ecological cause and effect and socioeconomic priorities, through modelling and scientific support for decision-making. Enhanced collaboration in monitoring will help share capacity across sectors and institutions and provide more efficient monitoring, data and information. Increased capacity in understanding management approaches and implementing them, will support governments and other stakeholders in understanding options for marine management and governance (Chapter 30).

5. Understanding of the ocean for sustainable management

The sustainable use of the ocean cannot be achieved before having a deep understanding of ocean processes and its functioning as well as on the coherent knowledge of the human

[13] See Chapter 2 of the present Assessment with regard to the terminology of “open ocean” and “deep-sea”.

activities impacts in the ocean (Chapters 8C and 30).

5.1. Linkages with the Sustainable Development Goals and the United Nations Decade of Ocean Science

SDG Target 14.3: Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels;

SDG Target 14.a: Increase scientific knowledge, develop research capacity and transfer marine technology, taking into account the Intergovernmental Oceanographic Commission Criteria and Guidelines on the Transfer of Marine Technology, in order to improve ocean health and to enhance the contribution of marine biodiversity to the development of developing countries, in particular small island developing States and least developed countries;[14]

Decade of Ocean Science societal outcome: A predicted ocean where society understands and can respond to changing ocean conditions;

Decade of Ocean Science societal outcome: An accessible ocean with open and equitable access to data, information and technology and innovation.

Decade of Ocean Science societal outcome: An inspiring and engaging ocean where society understands and values the ocean in relation to human wellbeing and sustainable development.

Input of carbon dioxide to the ocean is continuing, although variably, resulting in acidification and thus a more acid ocean. This, alongside other pressures, impacts negatively on a wide range of organisms, particularly those that form calcium-carbonate shells, with the potential for altering biodiversity and ecosystem structure. Ocean acidification, combined with rising temperatures, sea level rise, deoxygenation and increasing extreme climate events, further threatens the goods and services provided by coastal ecosystems (Chapters 5 and 9).

Scientific understanding of the ocean, its functioning and the impacts on it grows ever faster. However, in many parts of the ocean, knowledge and capacity-building gaps remain, particularly for areas beyond national jurisdiction. Quantification of the cumulative effects of pressures on the ocean is nascent, as is the quantification of comprehensive and standardized indicators of ocean health. Capacity to enable people to access and use scientific understanding remains a need for applying integrated approaches to the management of human impacts on the ocean (Chapters 3, 28 and 30).

The particular ways in which progress towards other SDGs will assist achievement of SDG Targets 14.3 and 14.a are set out in Table 1. The particular ways in which achievement of these targets will assist progress to other SDGs are set out in Table 2.

5.2. Global scientific understanding

Innovations in technology and engineering related to sensors and autonomous observation platforms have allowed for ocean data collection at finer temporal and spatial resolutions and expanded those observations into remote areas. Cost-effective and user-friendly sensors,

[14] See United Nations General Assembly resolution 71/313, annex.

along with smartphone applications, the enhanced participation of citizens and the deployment of sensors on non-scientific ships are also facilitating the expanded collection of ocean observations. This has increased our understanding of physical and biogeochemical systems in the ocean, how the ocean is changing in response to climate change and enhanced ocean modelling capabilities at global and regional scales (Chapters 3 and 5).

Promotion of networking and coordination of regional observation programmes have further developed global ocean observations within an integrated system. The standardization and/or harmonization of observation methods is also being developed through international initiatives. Platforms that share best practices in ocean observing, data sharing and community dialogues have also been established with the aim of improving the effective use of ocean data for the benefit of society (Chapter 3).

5.3. Sustainable management

Over the past two decades, many frameworks for assessing interactions between human activities and natural events ("cumulative effects"), have been developed using different approaches and terminologies and applied at differing scales. These, along with other assessments of the environment, including environmental impact assessments and strategic environmental assessments, form useful tools for informing marine spatial planning and resource management (Chapters 28, 29 and 30).

Both marine spatial planning and management frameworks comprise a spectrum of processes, but have a unified objective of identifying users of the marine environment, planning the activities of those users and effecting some form of regulation of that use to ensure sustainability. In general, marine spatial planning has been most effectively developed with the involvement of all relevant authorities and stakeholders and included economic, environmental and social perspectives. Management frameworks increasingly recognize social perspectives and social and cultural values, but reconciling a multiplicity of heterogenous values is a challenge. Addressing multiple values is best done by engaging affected communities. Hence there is a need to recognise community-based management sensitive to the cultural dimensions of the sea within ecosystem approaches to management. Increased understanding of the rights, tenures and traditional and indigenous customary uses of inshore marine environments have catalysed recognition of the strengths of community-based management. Culture is potentially powerful, , both as a factor to be managed and monitored, and as the foundation upon which management incorporating ecosystem approaches d may be developed in the context of sustainable developmentt (Chapters 29 and 30).

5.4. Key knowledge and capacity-building gaps

Globally disparities remain in knowledge to support ecosystem-based management. Most research and information available (based on numbers of publications) relates to the North Atlantic, North Pacific and Arctic Oceans. Disparities in infrastructure and professional capacities limit ocean research, resulting in regional and national disparities in scientific understanding. To better monitor significant changes in physical and biogeochemical environments and their impacts on ecosystems and society, further integration of multidisciplinary observation systems and better models are needed. Innovation in funding strategies is also required to sustain such systems (Chapter 3).

Most cumulative-effects assessments tend to focus on existing activities and past effects in the marine environment. Similarly, much marine spatial planning has been carried out in areas where activities are ongoing, and many management frameworks are applied to existing resource extraction and use, making them retrospective in nature. Assessments that allow foresighting are needed, to inform planning of future activities and support management that is adaptive to future conditions and sustains ecosystems and human well-being. Developing such approaches is not straightforward and will require substantial effort. Increased capacity in transboundary cooperation, strengthening of science-policy capacity, and greater coordination between social and natural sciences, and between science and civil society, including industry and recognition of traditional knowledge, culture and social history, are needed to support holistic management (Chapters 28, 29 and 30).

6. Promoting safety from the ocean

A wide range of events in and on the ocean threaten those who live near or work on the ocean or rely on it for food. Examples of such events are tsunamis, storm surges, rogue waves, cyclones, hurricanes and typhoons, coastal flooding, erosion, marine heatwaves and harmful algal blooms. Oceans play an important role in driving hydrological variability, such as droughts and pluvials over land, on intraseasonal to interannual (and longer) timescales (chapter 9). Such events, together with various effects of hazardous substances and excessive nutrients, have the potential to threaten food security and hamper sustainable economic development.

6.1. Linkages with the Sustainable Development Goals and the United Nations Decade of Ocean Science

SDG Target 14.1: By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution;

SDG Target 14.3: Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels;

Decade of Ocean Science societal outcome: A safe ocean where life and livelihoods are protected from ocean-related hazards.

Marine heatwaves and tropical cyclones, hurricanes and typhoons are increasing in frequency and severity as a result of climate change. These are projected to become more frequent in the future with the severity of impacts increasing, but such increases can be reduced by climate change mitigation efforts. As mentioned above, the ocean also drives hydrological variability over land. Construction of dams and reservoirs is, in some areas, reducing sediment supply to the coast by more than 50 per cent, thus leading to erosion of deltas and adjacent coasts. As a result of nutrient pollution, harmful algal blooms are becoming more frequent. The number of pollutants in the ocean continues to increase and thus the mixtures to which biota are exposed to and that are integrated into food systems are becoming more complex (Chapters 9, 10, 11 and 13).

The particular ways in which progress towards other SDGs will assist achievement of SDG Targets 14.1 and 14.3 are set out in Table 1. The particular ways in which achievement of these targets will assist progress to other SDGs are set out in Table 2.

6.2. Hazards from the ocean

In addition to continuing threats such as tsunamis, climate change is increasingly affecting areas and their associated communities not previously exposed to rising sea levels. Such rises can also exacerbate coastal erosion. Precipitation, winds and extreme sea level events associated with tropical cyclones have increased as has the annual global proportion of Category 4 or 5 tropical cyclones in recent decades. There are increasing risks to locations that have historically not been exposed to storms by unprecedented storm trajectories. Management of risk from such changing storm trajectories and intensity proves challenging because of the difficulties of early warning and the reluctance affected populations to respond (Chapters 9 and 13).

Over the last two decades, marine heatwaves have negatively impacted marine organisms and ecosystems in all ocean basins. These events are projected to increase in frequency, duration, spatial extent and intensity under future global warming, thus pushing some marine organisms, fisheries and ecosystems beyond the limits of their resilience, with cascading impacts on economies and societies. Coastal erosion, driven by, for example, decreased fluvial sediment supply to the coast due to changed river management, coastal sand mining and longshore impoundment by coastal structures is increasingly causing problems. Changes in the coastal profile following destruction of mangroves, salt marshes and barrier islands add to these problems. Inputs of nitrogen and phosphorous to coastal ecosystems via river run-off and atmospheric deposition have increased due to the use of synthetic fertilizer, combustion of fossil fuels and direct input of municipal wastes. This is leading to an increase in harmful algal blooms, including toxic algal events, which, inter alia, can lead to shellfish and fish becoming poisonous, thus causing paralysis and other illnesses in humans (Chapters 9, 10 and 13).

6.3. Key knowledge and capacity-building gaps

Improved understanding of the ocean and its interrelation with the atmosphere is essential for improving human safety from extreme weather events. Similarly, better understanding of the scale, progress and distribution of pollution and of coastal dynamics is needed. The Sendai Framework for Disaster Risk Reduction 2015–2030[15] identifies the need to strengthen and harmonize warning systems for reducing the risks associated with ocean hazards. To do this, forecasting systems for hazards need to be progressed, emergency planning and warnings expanded and preparation frameworks implemented for rapid response for affected communities. Integrated systems which allow for forecasting, detection and response to multiple hazards are required (Chapters 9, 10, 11, 12, 13 and 14).

7. Sustainable food from the ocean

Animal protein from the seas provides about 17 per cent of all animal protein consumed by humans and supports about 12 per cent of human livelihoods. This protein is largely derived from wild fisheries. However, the contribution of aquaculture to food security is growing rapidly and has greater potential for growth than capture fisheries. Fishing practices place multiple stressors on the marine environment in many regions and the expansion of aquaculture brings new or increased pressures on marine ecosystems, particularly in coastal areas (Chapters 15, 16 and 17).

7.1. Linkages with the Sustainable Development Goals and the United

[15] See United Nations General Assembly resolution 69/283, annex II.

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SDG Target 14.4: by 2020, effectively regulate harvesting and end overfishing, illegal, unreported and unregulated fishing and destructive fishing practices and implement science-based management plans, in order to restore fish stocks in the shortest time feasible, at least to levels that can produce maximum sustainable yield as determined by their biological characteristics;

SDG Target 14.6: By 2020, prohibit certain forms of fisheries subsidies which contribute to overcapacity and overfishing, eliminate subsidies that contribute to illegal, unreported and unregulated fishing and refrain from introducing new such subsidies, recognizing that appropriate and effective special and differential treatment for developing and least developed countries should be an integral part of the World Trade Organization fisheries subsidies negotiation;

SDG Target 14.7: By 2030, increase the economic benefits to small island developing States and least developed countries from the sustainable use of marine resources, including through sustainable management of fisheries, aquaculture and tourism;

SDG Target 14.b: Provide access for small-scale artisanal fishers to marine resources and markets;[**Error! Bookmark not defined.**]

Decade of Ocean Science societal outcome: A productive ocean supporting sustainable food supply and a sustainable ocean economy

The particular ways in which progress towards other SDGs will assist achievement of SDG Target 14.2, 14.7 and 14.c are set out in Table 1. The particular ways in which achievement of these targets will assist progress to other SDGs are set out in Table 2.

7.2. Marine capture fisheries

Estimated global landings of marine capture fisheries increased by 3 per cent to 80.6 million tonnes, valued at 127 billion United States dollars (in 2017 prices) between 2012 and 2017. About 33 per cent of world fisheries, especially at higher trophic levels, are classified as being fished at biologically unsustainable levels, with close to 60 per cent maximally sustainably[16] fished. The sustainability of many of the world's capture fisheries continues to be hampered by over-exploitation, overcapacity, ineffective management, harmful subsidies, by-catch, in particular of threatened endangered and protected species, and illegal, unreported and unregulated (IUU) fishing, with ongoing habitat degradation and loss of gear creating further pressures on the marine environment. Overfishing, is estimated to have led to an annual loss of 88.9 billion United States dollars in net benefits. Fish markets continue to exhibit fast-paced globalization, thus increasing the vulnerability of small-scale fisheries to the depletion of locally important stocks. Negotiations under the auspices of the World Trade Organization on reducing harmful fishery subsidies have continued, although no firm agreement has yet been reached. Less than 40 per cent of the world's States have signed the 2016 Agreement on Port State Measures to Prevent, Deter and Eliminate Illegal, Unreported and Unregulated Fishing. The application of information technologies to help to expand the opportunities of small-scale fisheries in areas such as safety, sharing of local knowledge, capacity-building, and governance have been outlined by the Food and Agriculture Organization of the United Nations (FAO) in its Small-Scale Fisheries Guidelines, and a growing use of human rights approaches are providing opportunities for the empowerment of such fisheries (Chapter 15).

Promisingly, scientific stock assessments and management have been shown to lead to more sustainable outcomes across a number of regions. New approaches to identifying illegal, unreported and unregulated (IUU) fishing are now being applied in some regions. Recent research has shown that, with appropriate governance, the median time required to rebuild overfished stocks could be less than 10 years, and, if reforms were to be implemented, 98 per cent of overfished stocks could be considered healthy by the middle of the twenty-first century.

The impacts of climate change are expected to include increases in the intensities of natural hazards and in their frequencies, thus affecting local distributions and abundances of fish populations. Fishery-dependent developing States may be impacted most severely and, due to expected changes in species distributions and consequent expected increases in transboundary migrations of stocks, future international governance may need to account for such redistributions (Chapter 15).

7.3. Aquaculture

Aquaculture continues to grow faster than other major food production sectors, although this growth has slowed over the last decade. The sector was valued at 249.6 billion United States dollars in 2017. It supports the livelihoods of 540 million people, of which 19 per cent were women in 2014. The importance of this form of food production lies in its high protein content and high essential micronutrients and fatty acids content. Aquaculture's reliance on fishmeal reduced from 4.20 million metric tons in 2005 to 3.35 million metric tons in 2015. Aquaculture sustainability is more likely to be closely linked with the sustained supply of terrestrial animal and plant proteins, oils and carbohydrate sources for aquafeeds. Diseases

[16] "Maximally sustainably fished" is here used in the sense explained in Chapter 15 (Changes in capture fisheries and harvesting of wild marine invertebrates).

continue to challenge global aquaculture and are one of the primary deterrents to aquaculture development of many species. In general, the environmental performance of aquaculture has improved significantly over the past decade. Challenges to be met in expanding aquaculture production include the impacts on valuable coastal ecosystems such as mangroves, the provision of external feed, the management of fish diseases and the effects of escaped fish on native species (Chapter 16).

7.4. Seaweed production

Seaweeds for direct human consumption amount to 80 per cent of total seaweed harvesting. Since 2012, global harvesting of seaweeds has risen at a rate of about 2.6 per cent a year, mostly from aquaculture, to 32 million tonnes in 2017, with an estimated value of 12 billion United States dollars. Apart from food, seaweeds are increasingly used in industrial applications, such as cosmetics, pharmaceuticals and nutraceuticals, and as feeds for livestock. Macroalgae cultivation amounts to 96 per cent of total aquaculture production. Benefits from production include provision of high-quality food, and the creation of new jobs and increased incomes to coastal residents. In addition, such production supports carbon sequestration and oxygen production and reduces eutrophication (Chapter 17).

7.5. Key knowledge and capacity-building gaps

Understanding is limited of the extent to which changing conditions could contribute to shifts in marine ecosystem structure and functioning and the flow-on impacts on marine productivity. Improved approaches for assessing fisheries and accounting for fisheries' contributions in data-poor environments have progressed, but further work is needed to fill capacity-building gaps for coastal fisheries in developing regions. The science of fish stock propagation is still in its infancy, but shows some potential for increasing fishery yield beyond that achievable by the exploitation of wild stocks alone. However, understanding of ecological consequences is lacking. Capacity-building gaps in the management of fisheries include those associated with identifying impacts on target species and incorporating the effects on other species as part of management frameworks. Capacity-building gaps remain for developing countries in terms of their ability to take part in regional and international negotiations for reaching consensus on management practices for sustaining healthy fish stocks.

To boost sustainable aquaculture development, improved extension services are needed. Training of extension workers needs to incorporate information delivery methods, as well as practical farming techniques, to help them better assist farmers to improve their production practices. Information technology and media, farmer associations, development agencies, private sector suppliers and others will all need to come together to enhance sectoral training. Establishment of offshore aquaculture and mariculture will need to be supported by sufficient marine services to ensure sustainability and safety of operations. Many knowledge gaps remain with regard to the large-scale production of seaweeds and likely impacts of climate change. Some efforts to address these knowledge and capacity-building gaps are underway. The biology of many seaweed species is still unknown and, even for those already harvested or farmed, some aspects of their biology are still not well understood (Chapters 15, 16 and 17).

8. Sustainable economic use of the ocean

The ocean supports a wide range of economic activities, including maritime transport as part of world trade, tourism and recreation, extraction of natural resources such as hydrocarbons and other minerals, provision of renewable energy, and the use of marine genetic resources.

8.1. Linkages with the Sustainable Development Goals and the United Nations Decade of Ocean Science

SDG Target 14.2: By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans;

SDG Target 14.7: By 2030, increase the economic benefits to small island developing States and least developed countries from the sustainable use of marine resources, including through sustainable management of fisheries, aquaculture and tourism;

Target 14.c: Enhance the conservation and sustainable use of oceans and their resources by implementing international law as reflected in the United Nations Convention on the Law of the Sea, which provides the legal framework for the conservation and sustainable use of oceans and their resources, as recalled in paragraph 158 of "The future we want".[**Error! Bookmark not defined.**]

Very widely, economic use of the ocean has increased. Many countries either are developing or have developed strategies for growth of maritime activities such as ocean energy, aquaculture, marine biotechnology, coastal tourism and seabed mining (growth sectors of the "blue economy" - a term which can also include sustainable shipping and fisheries). The distribution around the world of the economic benefits drawn from the ocean, however, is still very uneven. (Chapters 4, 8C, 19 and 31).

The particular ways in which progress towards other SDGs will assist achievement of SDG Target 14.2, 14.7 and 14.c are set out in Table 1. The particular ways in which achievement of these targets will assist progress to other SDGs are set out in Table 2.

8.2. Seabed mining

Seabed mining within national jurisdiction continues to produce growing amounts of sand and gravel to supplement diminished land-based sources. The scale of extraction can have significant effects on the local marine environment and cause coastal erosion. The scale of other major mining activities (such as for diamonds, phosphate, iron ore and tin) continues to be more or less stable. Deep sea-bed mining in areas beyond national jurisdiction is closer to becoming a commercial reality, however exploiting many mineral resources requires advanced technology and so is largely limited to those able to access such technologies (Chapter 19).

8.3. Extraction of offshore hydrocarbons

The offshore oil and gas sector is expanding globally into deep and ultra-deep waters. Over the next decade, growth is likely to be focused in such areas as the eastern Mediterranean Sea, and areas off the coast of Guyana and the west coast of Africa. Mature areas such as the North Sea and the Gulf of Mexico are seeing the exhaustion of some resources and the resulting increased decommissioning of offshore installations, although some may be used for renewable marine energy. Extraction techniques continue to evolve to protect the marine environment (Chapter 20).

8.4. Maritime transport

The tonnage of cargo carried by international shipping has reflected growth in world trade following the recovery of the world's economy post 2012. Such growth, however, has occurred against a weak competitive background. A large proportion of the world's tonnage continues to be registered in a relatively small number of registries and ownership/control of shipping continues to be concentrated in the hands of firms in a relatively small number of countries. This concentration has significant implications for future port development, possibly resulting in fewer and larger main ports serving as distribution hubs for intercontinental trades. There was a slight decline in the total number of attempted and actual cases of piracy and armed robbery on ships between 2015 and 2019 (Chapter 8C).

8.5. Tourism and recreation

International travel and associated tourism are economically important in many parts of the world, particularly in the "sun, sea and sand" type of tourism concentrated in coastal marine regions. Throughout all tourist areas, the major impact on the marine environment comes from coastal development, including the proportion of land covered by buildings, such as hotels, restaurants, retail shops, and transport infrastructure, including airports and train terminals, and the need for "armoured" coastal defences, street lighting and sewerage. Snorkelling, diving and wildlife viewing continue to be significant elements in coastal tourism (Chapter 8C).

8.6. Marine genetic resources

Marine genetic resources continue to be the focus of an expanding range of commercial and non-commercial applications. Rapidly shrinking costs of gene sequencing and synthesis, and swift advances in metabolic engineering and synthetic biology, have reduced dependency on obtaining physical samples from the ocean. Sponges and algae continue to attract substantial interest for the bioactive properties of their natural compounds (Chapter 26).

8.7. Marine renewable energy (MRE)

The MRE sector (offshore wind energy, tidal/ocean current energy, wave energy, ocean thermal energy, osmotic power and marine biomass energy) is evolving and developing at different speeds. Of these power sources, offshore wind technology is mature and technically advanced. Although in 2018 it represented only 1 per cent of total renewable energy sources, it is growing rapidly: between 2017 and 2018, it accounted for 4 per cent of all growth in renewable energy. From 2017 to 2018, it grew in Asia by 59 per cent and in Europe by 17 per cent. In the next decade, Asia and the United States of America could be major growth drivers for offshore wind power development and installation. Tidal energy converters have reached the pre-commercial stage, while other MRE technologies are currently at the developmental stage. Of emerging MRE sources, offshore solar energy is the most promising because components of the relevant technology are well developed (Chapter 22).

8.8. Key knowledge and capacity-building gaps

All maritime industries need high levels of technology to operate safely and without damaging the marine environment. For marine genetic resources, capacity-building remains an issue since most work in this field occurs in a small number of countries. There is a need to build skills in many countries to sustainably plan and develop "blue economies" and to manage the human activities involved (Chapters 8C, 14, 19, 20, 22, 26, 28 and 30).

9. Effective implementation of international law as reflected in the United Nations Convention on the Law of the Sea

Effective implementation of international law as reflected in the United Nations Convention on the Law of the Sea**Error! Bookmark not defined.** (which sets out the legal framework within which all activities in the oceans and seas must be carried out), is essential for the conservation and sustainable use of the ocean and its resources, and for safeguarding the many ecosystem services that the ocean provides both for current and future generations.

9.1. Linkages with the Sustainable Development Goals and the United Nations Decade of Ocean Science

Target 14.c: Enhance the conservation and sustainable use of oceans and their resources by implementing international law as reflected in the United Nations Convention on the Law of the Sea, which provides the legal framework for the conservation and sustainable use of oceans and their resources, as recalled in paragraph 158 of "The future we want".

Steps have already been taken at all levels to strengthen the implementation of international law as reflected in the United Nations Convention on the Law of the Sea, including the level of participation of States in the numerous global and regional treaties that supplement its provisions. Examples at the global level include international conventions such as the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972 (the London Convention)**Error! Bookmark not defined.** and the 1996 Protocol thereto,**Error! Bookmark not defined.** the International Convention for the Prevention of Pollution from Ships (1973), as modified by the Protocol of 1978 and the Protocol of 1997 (MARPOL)[17] (including Annex VI on the reduction of sulphur emissions from ships that entered into force in 2020), and the FAO Agreement on Port State Measures to Prevent, Deter and Eliminate Illegal, Unreported and Unregulated Fishing which entered into force in 2016 (Chapters 8C, 11, 12, 15 and 31).

Key challenges still remain in ensuring participation in international instruments, resource and capacity constraints, strengthening intersectoral cooperation, coordination and information-sharing at all levels, and developing new instruments to address emerging challenges in a timely fashion (Chapter 31).

The particular ways in which progress towards other SDGs will assist achievement of SDG Target 14.c are set out in Table 1. The particular ways in which achievement of this target will assist progress to other SDGs are set out in Table 2.

9.2. Implementation of international law as reflected in the United

[17] See http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx.

Nations Convention on the Law of the Sea

Integration of environmental, social and economic dimensions is at the core of the United Nations Convention on the Law of the Sea. The Convention establishes a delicate balance between the need for economic and social development through the use of the oceans and their resources and the need to conserve and manage those resources in a sustainable manner and to protect and preserve the marine environment. The integrated approach to ocean management as reflected in the Convention is essential for promoting sustainable development, as sectoral and fragmented approaches lack coherence and may lead to solutions that have a limited impact on the conservation and sustainable use of the oceans and their resources.

The Convention is, in many fields, supplemented by more specific, sectoral instruments. In addition to its two implementing agreements, there are numerous international legal instruments both at the global and the regional levels covering many aspects of ocean use. Effective conservation and sustainable use of the ocean and its resources will be achieved only with the full and effective implementation of the whole of this body of international law. Actions and efforts should focus primarily on implementation gaps or any regulatory gaps, especially in areas beyond national jurisdiction.

9.3. Implementation and regulatory gaps

Resource capacity, including financial capacity, remains a significant constraint for the protection and preservation of the marine environment and marine scientific research, whilst technology constraints are often an impediment to effective implementation of a State’s obligations. Gaps also exist with regard to the material (e.g. plastics and microplastics) or the geographical scope of relevant instruments (e.g. geographical coverage by the regional fisheries management organizations and arrangements) (Chapters 30 and 31). Many small island developing States and least developed countries lack access to detailed knowledge and skilled human resources needed for ocean management and resources for managing the large ocean areas under their jurisdiction are often limited. Filling these gaps will ensure that economic benefits can be maximized in an environmentally sustainable manner. Special challenges exist in the enforcement of management measures in areas beyond national jurisdiction due to regulatory gaps and a lack of cross-sectoral coordination. These issues are currently being discussed at the United Nations in the context of the intergovernmental negotiations on the elaboration of a legally binding instrument under the United Nations Convention on the Law of the Sea on the conservation and sustainable use of marine biodiversity in areas beyond national jurisdiction (Chapters 30 and 31).

Table 1: Contribution made by other SDGs to progressing SDG14

SDG14 Target	**Contribution by other SDGs**	**Mechanism**
Cleaning up the ocean		
14.1: Reduce marine pollution.	SDG 6 Clean water and sanitation	Improved wastewater management
	SDG 7 Affordable and clean energy	Improved sources and efficiencies in energy and associated reductions in

		emissions
	SDG 11 Sustainable cities and communities	Sustainable urbanisation and reductions in the environmental impact of cities
	SDG 12 Responsible consumption and production	Environmentally sound management of chemicals and all wastes including reducing waste generation
	SDG 17 Partnerships for the goals	Improved access to science, technology and innovation, enhanced knowledge sharing and transfer of technology and capacity building
Protecting marine ecosystems		
14.2: Manage and protect marine and coastal ecosystems. **14.5**: Conserve 10% of coastal and marine areas.	SDG 6 Clean water and sanitation	Improved wastewater management and protection and restoration of wetlands
	SDG 7 Affordable and clean energy	Improved sources and efficiencies in energy and associated reductions in emissions
	SDG 9 Industry, innovation and infrastructure	Use of clean technologies and associated reductions in emissions
	SDG 11 Sustainable cities and communities	Sustainable urbanisation and reductions in the environmental impact of cities
	SDG 12 Responsible consumption and production	Sustainable management and use of natural resources and reduction in waste along supply chains
	SDG 13 Climate action	Implementation of climate change mitigation, adaptation and impact reduction measures
	SDG 15 Life on land	Reduction in the degradation of natural habitats, loss of biodiversity and prevention of the extinction of species
	SDG 17 Partnerships for the goals	Improved access to science, technology and innovation, enhanced knowledge sharing and transfer of technology

		and capacity building
Understanding of the ocean for sustainable management		
14.3: Address ocean acidification impacts. **14.a**: Increase scientific knowledge, develop research capacity and transfer marine technology.	SDG 9 Industry, innovation and infrastructure	Enhance scientific research, upgrade the technological capabilities of industrial sectors in all countries, in particular developing countries, and encouraging innovation
	SDG 13 Climate action	Implementation of climate change mitigation, adaptation and impact reduction measures
	SDG 17 Partnerships for the goals	Improved access to science, technology and innovation, enhanced knowledge sharing and transfer of technology and capacity building
Promoting safety from the ocean		
14.1: Reduce marine pollution.	SDG 1 No poverty	Reducing exposure and vulnerability to climate-induced extreme events and building resilience to environmental shocks and disasters
	SDG 2 Zero hunger	Strengthening capacity for adaptation to climate change, extreme weather and other disasters
	SDG 6 Clean water and sanitation	Reducing pollution, improved wastewater management and protecting and restoring water related ecosystems
	SDG 11 Sustainable cities and communities	Reducing the number of people affected by disasters, strengthening national and regional development planning and implementing integrated policies and plans for mitigation and adaptation to climate change, resilience to disasters and develop and implement holistic disaster risk management
	SDG 12 Responsible	Environmentally sound

	consumption and production	management of chemicals and all waste
	SDG 13 Climate action	Strengthening resilience and adaptive capacity to climate related and other natural disasters and supporting impact reduction and early warning
	SDG 15 Life on land	Conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and reduction of degradation of habitats
Sustainable food from the ocean		
14.4: Effectively regulate fisheries. **14.6**: Prohibit certain forms of fisheries subsidies. **14.7**: Increase the economic benefits to small island developing States and least developed countries. **14.b**: Provide access for small-scale artisanal fishers to marine resources and markets.	SDG 2 Zero hunger	Increasing agricultural productivity (including aquaculture and mariculture), ensuring sustainable food production, maintaining ecosystems, maintaining the genetic diversity of wild species
	SDG 8 Decent work and economic growth	Improved resource efficiency in consumption and production
	SDG 9 Industry, innovation and infrastructure	Enhancing scientific research and technology development, research and innovation in developing countries
	SDG 12 Responsible consumption and production	Sustainable management and efficient use of natural resources, reducing food losses along production and supply chains, including post-harvest losses, strengthening scientific and technological capacity to move towards more sustainable patterns of consumption and production, implementing tools to monitor sustainable development impacts for sustainable tourism that creates jobs and promotes local culture and products and phasing out harmful subsidies, where they exist, to reflect their environmental

		impacts
	SDG 13 Climate action	Implementation of climate change mitigation, adaptation and impact reduction measures
	SDG 17 Partnerships for the goals	Improved access to science, technology and innovation, enhanced knowledge sharing and transfer of technology and capacity building
Sustainable economic use of the ocean		
14.2: Manage and protect marine and coastal ecosystems. **14.7**: Increase the economic benefits to small island developing States and least developed countries. **14.c**: Implement international law to enhance conservation and sustainable use.	SDG 6 Clean water and sanitation	Improved wastewater management and protection and restoration of wetlands
	SDG 7 Affordable and clean energy	Improved sources and efficiencies in energy and associated reductions in emissions
	SDG 11 Sustainable cities and communities	Sustainable urbanisation and reductions in the environmental impact of cities
	SDG 12 Responsible consumption and production	Sustainable management and use of natural resources
	SDG 13 Climate action	Implementation of climate change mitigation, adaptation and impact reduction measures
	SDG 15 Life on land	Reduction in the degradation of natural habitats, loss of biodiversity and prevention of the extinction of species
	SDG 16 Peace, justice and strong institutions	Promotion of the rule of law at the national and international levels
	SDG 17 Partnerships for the goals	Improved access to science, technology and innovation, enhanced knowledge sharing and transfer of technology and capacity building
Effective implementation of international law as reflected in the United Nations Convention on the Law of the Sea (UNCLOS)		
14.c: Implement international law to enhance conservation	SDG 2 Zero hunger	Ensuring sustainable food production systems, maintain ecosystems and strengthen

and sustainable use.		capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters
	SDG3 Health and wellbeing	Reduction of hazardous chemicals, pollution and contamination
	SDG 6 Clean water and sanitation	Reducing pollution, improved wastewater management and protecting and restoring water related ecosystems
	SDG 11 Sustainable cities and communities	Protecting and safeguarding cultural and natural heritage
	SDG 12 Responsible consumption and production	Environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks
	SDG 13 Climate action	Integration of climate change measures into national policies, strategies and planning
	SDG 17 Partnerships for the goals	Enhancing policy coherence for sustainable development

Table 2: Contribution made by SDG14 to progressing other SDGs

SDG14 Target	Contribution to other SDGs	Mechanism
14.1: Reduce marine pollution.	SDG3 Health and wellbeing	Reduction of hazardous chemicals, pollution and contamination
	SDG 6 Clean water and sanitation	Reductions in pollution, release of hazardous chemicals and materials and wastewater
	SDG 11 Sustainable cities and communities	Sustainable urbanisation and reductions in the environmental impact of cities
	SDG 12 Responsible consumption and production	Environmentally sound management of chemicals and all wastes including reducing waste generation
	SDG 17 Partnerships for the goals	Improved access to science, technology and innovation, enhanced knowledge sharing and transfer of technology and

		capacity building
14.2: Manage and protect marine and coastal ecosystems.	SDG 1 No poverty	Reducing exposure and vulnerability to climate-induced extreme events and building resilience to environmental shocks and disasters
	SDG 2 Zero hunger	Increasing agricultural productivity (including aquaculture and mariculture), ensuring sustainable food production, maintaining ecosystems, maintaining the genetic diversity of wild species
	SDG 8 Decent work and economic growth	Providing opportunities for sustained economic growth and sustainable tourism
	SDG 11 Sustainable cities and communities	Protecting and supporting those ecosystems that afford protection to coastal communities from disasters
	SDG 13 Climate action	Contributing to resilience to climate-related hazards
14.3: Address ocean acidification impacts.	SDG 1 No poverty	Reducing exposure and building resilience to environmental shocks and disasters
	SDG 2 Zero hunger	Ensuring sustainable food production systems, maintaining ecosystems and strengthening capacity for adaptation to climate change and well as enhancing cooperation in research and technology development
	SDG 12 Responsible consumption and production	Supporting developing countries to strengthen their scientific and technological capacity
	SDG 13 Climate action	Implementation of climate change mitigation, adaptation and impact reduction measures
	SDG 17 Partnerships for the goals	Improved access to science, technology and innovation, enhanced knowledge sharing and transfer of technology and capacity building
14.4: Effectively regulate fisheries.	SDG 2 Zero hunger	Increasing agricultural productivity (including aquaculture and mariculture), ensuring sustainable food production, maintaining ecosystems, maintaining the

		genetic diversity of wild species
	SDG 8 Decent work and economic growth	Supporting productive activities
	SDG 12 Responsible consumption and production	Achieving sustainable management and efficient use of natural resources, reducing food losses along production and supply chains, including post-harvest losses, strengthening scientific and technological capacity to move towards more sustainable patterns of consumption and production and phasing out harmful subsidies
	SDG 17 Partnerships for the goals	Enhancing partnerships for sustainable development
14.5: Conserve 10% of coastal and marine areas.	SDG 2 Zero hunger	Maintaining ecosystems and strengthening capacity for adaptation to climate change and well as enhancing cooperation in research and technology development
	SDG 11 Sustainable cities and communities	Protecting and supporting those ecosystems that afford protection to coastal communities from disasters
	SDG 15 Life on land	Reduction in the degradation of natural habitats, loss of biodiversity and prevention of the extinction of species
	SDG 17 Partnerships for the goals	Improved access to science, technology and innovation, enhanced knowledge sharing and transfer of technology and capacity building
14.6: Prohibit certain forms of fisheries subsidies.	SDG 8 Decent work and economic growth	Supporting productive activities
	SDG 12 Responsible consumption and production	Achieving sustainable management and efficient use of natural resources, reducing food losses along production and supply chains, including post-harvest losses, strengthening scientific and technological capacity to move towards more sustainable patterns of consumption and production and phasing out harmful subsidies

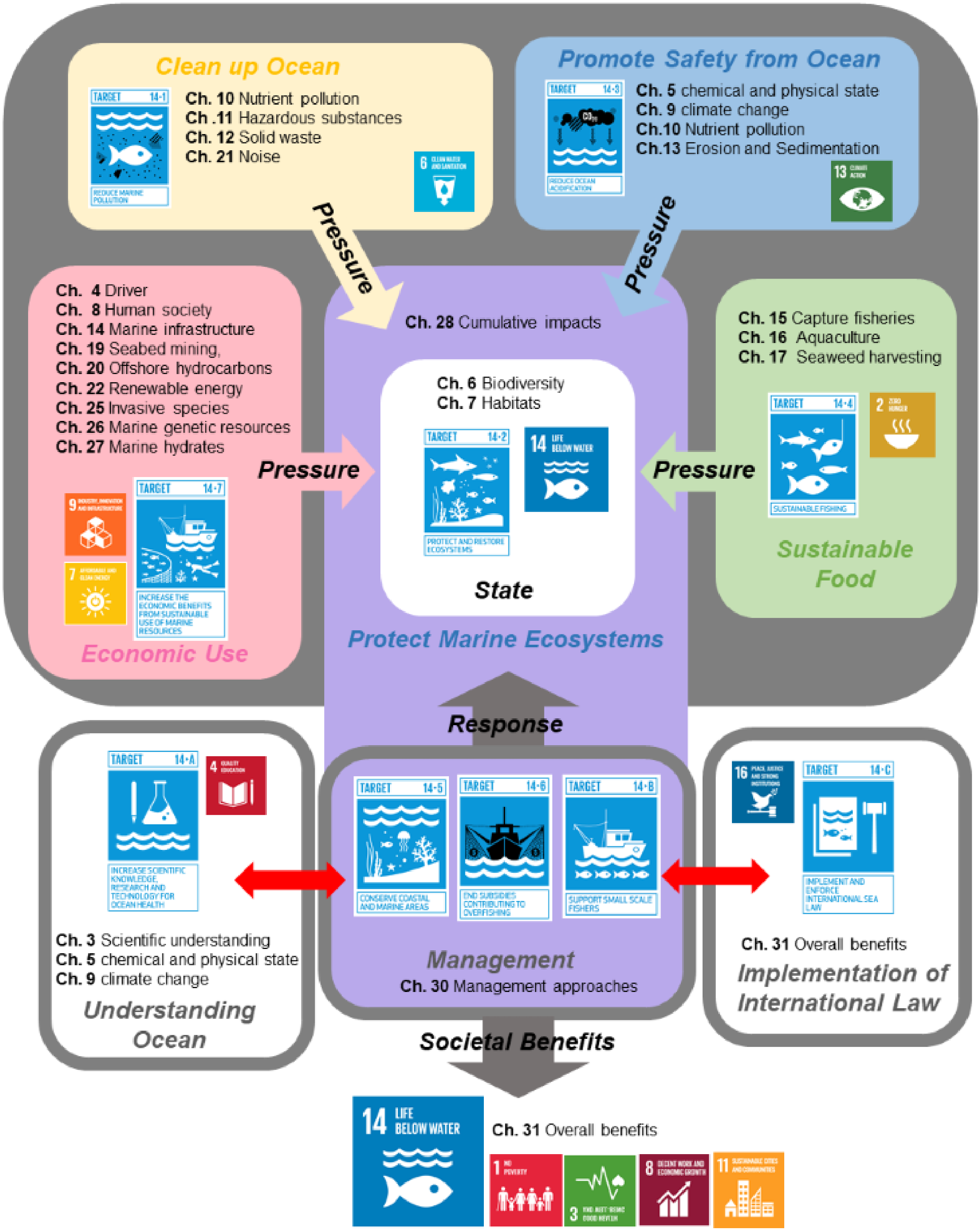
	SDG 17 Partnerships for the goals	Enhancing partnerships for sustainable development
14.7: Increase the economic benefits to small island developing States and least developed countries.	SDG 1 No poverty	Reducing exposure and building resilience to environmental shocks and disasters
	SDG 2 Zero hunger	Increasing agricultural productivity (including aquaculture and mariculture), ensuring sustainable food production, maintaining ecosystems, maintaining the genetic diversity of wild species
	SDG 8 Decent work and economic growth	Providing opportunities for sustained economic growth and sustainable tourism
	SDG 9 Industry, innovation and infrastructure	Enhance scientific research, upgrade the technological capabilities of industrial sectors in all countries, in particular developing countries, and encouraging innovation
	SDG 12 Responsible consumption and production	Achieving sustainable management and efficient use of natural resources, strengthening scientific and technological capacity
	SDG 13 Climate action	Implementation of climate change mitigation, adaptation and impact reduction measures
	SDG 17 Partnerships for the goals	Improved access to science, technology and innovation, enhanced knowledge sharing and transfer of technology and capacity building
14.a: Increase scientific knowledge, develop research capacity and transfer marine technology.	SDG 9 Industry, innovation and infrastructure	Enhance scientific research, upgrade the technological capabilities of industrial sectors in all countries, in particular developing countries, and encouraging innovation
	SDG 12 Responsible consumption and production	Achieving sustainable management and efficient use of natural resources, strengthening scientific and technological capacity
	SDG 17 Partnerships for the goals	Improved access to science, technology and innovation, enhanced knowledge sharing and transfer of technology and capacity building

14.b: Provide access for small-scale artisanal fishers to marine resources and markets.	SDG 2 Zero hunger	Increasing agricultural productivity (including aquaculture and mariculture), ensuring sustainable food production, maintaining ecosystems, maintaining the genetic diversity of wild species
	SDG 8 Decent work and economic growth	Improved resource efficiency in consumption and production
	SDG 9 Industry, innovation and infrastructure	Enhancing scientific research and technology development, research and innovation in developing countries
	SDG 12 Responsible consumption and production	Sustainable management and efficient use of natural resources, implementing tools to monitor sustainable development impacts for sustainable tourism that creates jobs and promotes local culture and products
	SDG 17 Partnerships for the goals	Improved access to science, technology and innovation, enhanced knowledge sharing and transfer of technology and capacity building
14.c: Implement international law to enhance conservation and sustainable use.	SDG 2 Zero hunger	Ensuring sustainable food production systems, maintain ecosystems and strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters
	SDG3 Health and wellbeing	Reduction of hazardous chemicals, pollution and contamination
	SDG 6 Clean water and sanitation	Reducing pollution, improved wastewater management and protecting and restoring water related ecosystems
	SDG 7 Affordable and clean energy	Improved sources and efficiencies in energy and associated reductions in emissions
	SDG 11 Sustainable cities and communities	Sustainable urbanisation and reductions in the environmental impact of cities, protecting and safeguarding cultural and natural heritage
	SDG 12 Responsible	Sustainable management and

	consumption and production	use of natural resources, environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks
	SDG 13 Climate action	Implementation of climate change mitigation, adaptation and impact reduction measures and integration of climate change measures into national policies, strategies and planning
	SDG 15 Life on land	Reduction in the degradation of natural habitats, loss of biodiversity and prevention of the extinction of species
	SDG 16 Peace, justice and strong institutions	Promotion of the rule of law at the national and international levels
	SDG 17 Partnerships for the goals	Enhancing policy coherence for sustainable development

Landscape of SDG 14 sub-goals and relevant WOA II Chapters

Note: the relevance is indicated either in boxes or by arrows. SDGs other than 14 shown are only examples but comprehensive as described in the Chapter 1.



Part 2: Introduction

Chapter 2 Approach to the assessment

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Key points

- The second World Ocean Assessment (WOA II) sets out to update the first World Ocean Assessment (WOA I) by providing an understanding of changes that have occurred in the global ocean since 2010 and associated trends.
- The Assessment also provides an overview of understanding of some aspects not fully covered in WOA I, such as inputs of anthropogenic noise, marine hydrates, cumulative effects, marine spatial planning and management approaches.
- The assessment follows a modified approach to the Drivers-Pressures-State-Impact-Response framework, supported through a series of workshops aimed at identifying region-specific information and input to the assessment, a peer-review process and a process of review by States.

1. Purpose of the assessment

The purpose of the second World Ocean Assessment (WOA II) is derived from the principles guiding the Regular Process, its objective and scope as set out in relevant decisions by the United Nations General Assembly, the Ad Hoc Working Group of the Whole on the Regular Process, and its Bureau. The overall objective is set out in the recommendations of the Working Group on the proposed framework of the Regular Process as, among others:

> The regular process under the United Nations would be recognized as the global mechanism for reviewing the state of the marine environment, including socio- economic aspects, on a continual and systematic basis by providing regular assessments at the global and supraregional levels and an integrated view of environmental, economic and social aspects. Such assessments would support informed decision-making and thus contribute to managing in a sustainable manner human activity that affect the ocean and seas, in accordance with international law, including the United Nations Convention on the Law of the Sea and other applicable international instruments and initiatives (A/64/347).

The recommendations of the Working Group were endorsed by the General Assembly in its resolution 64/71 and the principles guiding the Regular Process and its objective and scope were reaffirmed in resolution 71/257.

The principles guiding the Regular Process include:

> "The regular process would be guided by international law, including the United Nations Convention on the Law of the Sea and other applicable international instruments and initiatives, and would include reference to the following principles:
>
> (a) Viewing the oceans as part of the whole Earth system;
>
> (b) Regular evaluation by Member States of assessment products and the regular process itself to support adaptive management;
>
> (c) Use of sound science and the promotion of scientific excellence;
>
> (d) Regular analysis to ensure that emerging issues, significant changes and gaps in knowledge are detected at an early stage;
>
> (e) Continual improvement in scientific and assessment capacity, including the

promotion and development of capacity-building activities and transfer of technology;

(f) Effective links with policymakers and other users;

(g) Inclusiveness with respect to communication and engagement with all stakeholders through appropriate means for their participation, including appropriate representation and regional balance at all levels;

(h) Recognition and utilization of traditional and indigenous knowledge and principles;

(i) Transparency and accountability for the regular process and its products;

(j) Exchange of information at all levels;

(k) Effective links with, and building on, existing assessment processes, in particular at the regional and national levels;(l) Adherence to equitable geographical representation in all activities of the regular process" (A/64/347).

In the first cycle, the scope of the Regular Process, and the first global integrated marine assessment (first World Ocean Assessment (WOA I)) was to establish a baseline assessment of all aspects of the ocean - environmental, social and economic. In its resolution 72/73, the General Assembly decided that the scope of the second cycle would extend to evaluating trends and identifying gaps.

This assessment, as the first follow-up to WOA I, aims to provide a global overview of trends since 2010 in all aspects of the ocean –. In addition, it reports on some aspects of the ocean which were not fully covered in WOA I. These additional aspects include inputs of anthropogenic noise, marine hydrates, cumulative effects, marine spatial planning and management approaches.

2. Primary audience and framework of the assessment

The Regular Process is primarily accountable to the General Assembly (A/65/358). Given the objective of the Regular Process to "support informed decision-making and thus contribute to managing in a sustainable manner human activity that affect the ocean and seas", this assessment has as its main intended audience people in all sectors who will be taking decisions that will affect the marine environment. They need to be able to gain an overview of the whole of the marine environment as well as to focus on the aspects most relevant to their field.

This assessment has followed the Drivers – Pressures – State – Impacts – Response (DPSIR) framework, as discussed in Chapter 3 of WOA I, with some modifications. This modified approach resulted from the discussions in the first round of regional workshops (described below) on the structure of the assessment. Consequently, this assessment:

(a) Sets out the relevant ***drivers*** of change in the ocean (Part 3);

(b) Describes the trends in the current ***state*** of the main components of the marine environment, including groups of species, types of habitats and human society, including maritime industries (Part 4),

(c) Identifies ***pressures*** and their ***impacts*** on the ocean, including relevant socioeconomic components (Part 5)**,**

(d) Describes developments in the management measures adopted in ***response*** to those pressures and impacts (Part 6).

In the rest of this Part, there is an overview of our current scientific understanding of the ocean, in order to give the background to the assessment.

3. Process of preparation of the assessment

In accordance with the terms of reference and working methods of the Group of Experts for the second cycle of the Regular Process, and the Guidance for Contributors prepared by the Group of Experts, WOA II has been prepared by the Group of Experts and writing teams drawn from the Pool of Experts.

The Group of Experts of the Regular Process was constituted to oversee the work required to undertake this assessment. The Group of Experts comprises experts nominated by each of the United Nations regional groups of Member States. Those writing the individual chapters of the assessment and reviewing drafts of those chapters were drawn from both the Group of Experts and a Pool of Experts. This Pool comprises experts who served in the Pool of Experts during the first cycle of the Regular Process and additional experts nominated by States specifically for the second cycle.

The process of preparing this assessment began with the Group of Experts setting out the structure for the assessment. An initial structuring, based on the structure of WOA I, consisted of a summary followed by four parts focused on components of the ocean; the ocean and its circulation; the food web; coastal and shelf seas and the open ocean. This proposed structure was discussed in a first round of five regional workshops held in 2017, at which the outcomes of WOA I were outlined, recent regional assessments reviewed and regional priorities identified for incorporation into this assessment. Based on inputs from those attending the workshops, the proposed structure of the assessment was revised by the Group of Experts so that it addressed two main issues raised: that it more explicitly follow the internationally recognized DPSIR framework (Smeets and Weterings, 1999) and include specific coverage of management issues. This revised structure was embodied in the outline for the WOA II, which was considered, amended and approved by the Ad Hoc Working Group of the Whole at its Tenth Meeting,

In support of the development of the chapters, a second round of regional workshops was held in 2018, attended by members of the Group of Experts and experts (including members of the Pool of Experts and proposed members of writing teams) nominated by States, especially those in the regions. The workshops focused on developing specific chapters of the assessment with regional inputs, regional capacity-building needs and other issues highlighted by participants.

The Group of Experts ensured appropriate lists of members of the writing teams, and submitted these to the Bureau of the Ad Hoc Working Group of the Whole for approval. A range of methods was adopted to identify possible members of the writing teams: Several experts with relevant expertise were already in the Pool of Experts and agreed to participate in drafting when approached by the Group of Experts; some members took part in a regional workshop, and were later nominated to the Pool of Experts, and some were added following a request for specific expertise from the Group of Experts or a self-nomination. The writing teams primarily conducted their work through teleconferences and correspondence.

The Guidance for Contributors, was developed by the Group of Experts and noted, *inter alia*, the need to strive for a global overview, how to describe risks, how to handle uncertainty, and on ethics in authoring and evaluating material for the Regular Process (UNGA, 2017b; UNGA, 2018a). Lead and Co-Lead Members from the Group of Experts for each chapter gave guidance on acceptable types of information and balance within the chapter. Members of the writing team for each chapter were expected to consider the overall balance of the draft chapter and to ensure that, as far as they were able, each chapter should be based on the best available data and information and that conclusions made were sound and well supported.

The draft of each chapter, once completed and considered as fit for peer review, were sent for peer review by at least two peer reviewers drawn from the Pool of Experts. Peer reviewers acted in a totally independent capacity and were not involved in drafting the chapter they reviewed. They were requested to evaluate each chapter from the point of view of overall balance and to consider whether the best available data and information has been used, and whether the conclusions are sound and well supported.

Following peer review and subsequent revision of each chapter by the writing team, chapters were compiled and edited to produce an integrated assessment for submission for review by States. [Following review by States, chapters were further revised by writing teams and a final draft assessment compiled. This was submitted by the Group of Experts to the Ad Hoc Working Group of the Whole for its authorization of submission to the General Assembly.]

4. Use of terminology

There is an important distinction to be made between the terminology used in the scientific description of the ocean and the legal terminology used to describe States' rights and obligations in the ocean. With the exception of some aspects of the continental shelf beyond 200 nautical miles, the limits of the maritime zones established by the United Nations Convention on the Law of the Sea (UNCLOS) are not based on geomorphic criteria.

In this assessment, unless stated otherwise, the term "continental shelf" refers to the geomorphic continental shelf, and not to the continental shelf as defined in UNCLOS (see in particular chapters 7L, 70 and 7P). The geomorphic continental shelf is usually defined in terms of the submarine extension of a continent or island as far as the point where there is a marked discontinuity in the slope and the continental slope begins its fall down to the continental rise or the abyssal plain (Hobbs 2003).

Similarly, the term "open ocean" refers to the water column of deep-water areas that are beyond (that is, seawards of) the geomorphic continental shelf. It covers the whole of the water column (pelagic zone) in the areas beyond the geomorphic continental shelf.

The term "deep sea" refers to the sea floor of deep-water areas that are beyond (that is, seawards of) the geomorphic continental shelf. It is the benthic zone that lies in deep water (generally >200 m water depth).

On the other hand, the term "areas beyond national jurisdiction (ABNJ)" refers to the high seas and the Area (i.e. the seabed and ocean floor and subsoil thereof, beyond the limits of national jurisdiction) as defined in UNCLOS.

5. Acknowledgements

Very importantly, the regular budget of the United Nations has provided resources for WOA II. This has made a significant difference in carrying out the work.

None of the members of the Group of Experts or the Pool of Experts have received any remuneration for their work.

The Regular Process is grateful to Australia, Brazil, Ecuador, Estonia, Germany, Ghana, Greece, Indonesia, Japan, Malta, New Zealand, Palau, Poland, Portugal, Qatar, the Republic of Korea, Thailand, Ukraine, the United Kingdom of Great Britain and Northern Ireland, the United Republic of Tanzania, and the United States of America for their support to World Ocean Assessment II. Further support has also been provided by the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization, the Permanent Commission of the South Pacific and an anonymous private donor. The Regular Process is also grateful to Estonia, the Republic of Ireland, the Kingdom of the Netherlands, New Zealand, and the Republic of Korea for their voluntary contributions to the Trust Fund for the Regular Process during the second cycle.

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Chapter 3
Scientific Understanding of the Ocean

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Keynote points

- Innovations in technology and engineering in sensors and autonomous observation platforms have substantially increased observations of the ocean and allowed for those observations to be collected at finer temporal and spatial resolutions.
- The networking and coordination of regional observation programmes has been promoted and has enabled better coordination and integration of efforts and standardization and/or harmonization of observation methods.
- Global disparities in understanding and knowledge gaps at continental regional levels remain, particularly across Oceania, Africa and South America.
- Most observation networks do not incorporate the economic, social and cultural aspects of the ocean and, as a consequence, there is a lack of focused publicly accessible observations of these aspects in standardized formats at regional and global scales; work on supplemental National Accounts may provide this..

1. Introduction

This chapter is describing the changes of the scientific basis for the understanding of the marine environment. Evidence-based science is considered to be the basis for our understanding of all aspects of our world. The natural sciences have been particularly important for the discovery and advancement of understanding of the environment, while social sciences and the humanities are important for understanding values placed on the marine environment and human behavior both in using and valuing the ocean. These disciplines, when combined, have been essential for understanding the challenges facing humanity, from individuals to communities to societies, in achieving sustainable use of the marine environment that preserves those values and ensures that the marine environment is conserved. Inter- and trans-disciplinary approaches are increasingly encouraged in marine sciences and new funding schemes supporting such approaches have been implemented by several international funding bodies such as BiodivERsA[18], JPI Oceans[19] and the Belmont Forum[20], as well as national agencies and scientific diplomacy efforts and initiatives [21,22].

The present Chapter provides an overview of the advances in science that underly our understanding of the ocean as well as the changes in scientific capacity since the First World Ocean Assessment (WOA I) (United Nations, 2017c). It summarizes new developments in science and progress made on scientific capacity, and builds upon Chapter 3 of WOA I, on scientific understanding of ecosystem

[18]See https://www.biodiversa.org/.
[19]See http://jpi-oceans.eu/

[20]See https://www.belmontforum.org/.
[21]See https://allatlanticocean.org/main.
[22]See https://meetings.pices.int/

services (United Nations, 2017a), and Chapter 30, on marine scientific research (United Nations, 2017b). However, it does not provide an update on the concept of ecosystem services or detail the new concept of Nature's Contribution to People from the recent report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (Pascual and others, 2017) as this will be included in Chapter 31 of the present Assessment.

The present Chapter will also look at more general developments since WOA I in relation to specific disciplines and how they have changed our understanding of the ocean (section 2). It summarizes key region-specific changes (section 3), looks at what changes can be expected in coming years (section 4) and provides an overview of existing knowledge gaps (section 5) and capacity-building gaps (section 6).

2. Description of the changes in data, technology and models since WOA I and their consequences for overall understanding, including socioeconomic consequences

Following Valdes and others (IOC-UNESCO, 2017a), changes and growth in scientific understanding are identified for eight global categories of marine scientific research disciplines, namely: (1) marine ecosystem functions and processes; (2) ocean and climate; (3) ocean crust and marine geohazards; (4) blue growth; (5) ocean health; (6) human health and well-being; (7) ocean technology and engineering; and (8) ocean observations and marine data. Innovation in technology and engineering related to sensors (e.g. Wang and others, 2019) and autonomous observation platforms (Zolich and others, 2019) have allowed for data collection at finer temporal and spatial resolutions and expanded those observations into remote areas (Camus and others, 2019). Cost-effective and user-friendly sensors, along with smartphone applications, the enhanced participation of citizens (e.g. Simoniello and others, 2019) and the deployment of sensors on non-scientific ships are also facilitating the expanded collection of ocean observations (Jiang and others, 2019). This has increased our understanding of physical and biogeochemical systems in the ocean (e.g. Moore and others, 2019) and benefited the further development of capacity in early warning and prediction of hazards (Luther and others, 2017). Datasets and methods for accurate assessment of anthropogenic carbon dioxide (CO_2) emissions and their redistribution in the atmosphere, oceans and terrestrial biosphere have been developed (Le Quéré and others, 2018).

Advances in computing technology and statistical approaches to analyzing large data sets, for example through machine learning and artificial intelligence, have resulted in advances in remote sensing and the utility of ocean data sets, notably in fisheries monitoring and surveillance (Toonen and Bush, 2020) and bioinvasion management (Koerich and others, 2020). Advances in genomic approaches to ocean observation, such as through eDNA methods (Ruppert and others, 2019), are advancing our understanding of the distribution and composition of species (Canonico and others, 2019) in the ocean and providing greater insights into food webs, trophic linkages and connectivity of species throughout regions. New frameworks and tools that identify and assess the cumulative impact of multiple pressures on marine ecosystems (Stelzenmüller and others, 2018; Chapter 28 of the present Assessment) and allow for the exploration of management options for sustainable development of human society have been developed (Halpern and others, 2017; Audzijonyte and others, 2019). Projects like the Nippon Foundation-GEBCO Seabed 2030 project[23] have been initiated and set out ambitious goals to map 100 per cent of the ocean floor by 2030.

To further develop global ocean observations within an integrated system and ensure that ocean data

[23]See https://seabed2030.gebco.net/.

are comparable, the networking and coordination of regional observation programmes has been promoted (Moltmann and others, 2019). The standardization and/or harmonization of observation methods, is being developed through international initiatives such as the Global Climate Observing System (GCOS)'s essential climate variables (ECV) (Bojinski and others, 2014) and the Global Ocean Observing System (GOOS)'s essential ocean variables (EOV) initiatives (Miloslavich and others, 2018). Ocean FAIR (Findable, Accessible, Interoperable, Reusable) data services and principles have been proposed (Tanhua and others, 2019a) and platforms that share best practices in ocean observing, data sharing and community dialogues have also been established (Pearlman and others, 2019) with the aim of improving the effective use of ocean data for the benefit of society.

3. Key region-specific changes and consequences

3.1. *The Arctic Ocean*

The Arctic Council, including the Arctic Monitoring and Assessment Programme (AMAP) and the Conservation of Arctic Flora and Fauna (CAFF)'s Circumpolar Biodiversity Monitoring Program regularly publishes reports on the state of the terrestrial, freshwater and marine environment of the Arctic. Recent reports on the state of Arctic biodiversity (CAFF 2017), ocean acidification (AMAP, 2018) and climate change effects (AMAP, 2019) provided new information on rapid changes in the Arctic marine environment, including increasing river discharges associated with low ice coverage that have resulted in an increase in carbon and nutrients and, thus, primary production in coastal regions. Such changes in production, as well as in the timing and intensity of marine algae blooms are having profound impacts on the whole food web. Warming of the Arctic has also resulted in an introduction of 20 species, and in changes of distributional range of 59 others have been confirmed in the Chukchi and Beaufort Seas in the past 15 years. According to observations, ocean acidification is severely affecting the Arctic food web, including commercial species such as cod (AMAP 2019). Despite significant changes in the Arctic Ocean, several regions and ecosystem components continue to be understudied and are lacking long-term monitoring (CAFF, 2017).

3.2. *The North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean and North Sea*

The Joint Baltic Sea Research and Development Programme (BONUS)[24]has made significant progress in improving understanding of the Baltic Sea. Some major trend reversals, such as the return of top predators, recovery of certain fish stocks, and reduced input of nutrient and harmful substances in the Baltic have been noted recently (Reusch and others, 2018). A spatially explicit end-to-end Atlantis ecosystem model was recently developed for the Baltic Sea with the aim of evaluating the effects of anthropogenic pressures on the marine ecosystem (Bossier and others, 2018). The Second Holistic Assessment of the Ecosystem Health of the Baltic Sea (Helsinki Commission HOLAS II) show that, although there are some limited signs of improvement in the state of the Baltic Sea, the Baltic Sea Action Plan goals and ecological objectives have not yet been reached. Results from economic and social analyses were also included for themes where information at the respective sub-regional scale is available (HELCOM, 2018).

The OSPAR Commission for the Protection of the Marine Environment of the North-East Atlantic[25] publishes updates from time to time on the status of the marine environment. According to the assessment (OSPAR, 2017), marine protected areas had expanded, and there had been a decrease in

[24]See https://www.bonusportal.org/.
[25]See https://www.ospar.org/.

contaminants and radioactive discharge and in the discharge of oil and gas installations in particular. However, eutrophication was still an issue and an increase in marine litter, especially plastics, was noted. Although the population of some marine mammals is increasing, for example harbour seals (*Phoca vitulina*) and grey seals (*Halichoerus grypus*), for some others it is declining, for example, the harbour porpoise (*Phocoena phocoena*) and bottlenose dolphins (*Tursiops truncatus*). More than a quarter of the marine bird species assessed are declining, and benthic habitats continue to be affected by bottom trawling.

Under the Barcelona Convention [26], several well elaborated Action Plans are being developed targeting priority issues for the Mediterranean. These include pollution, conservation of habitats and species, climate change, Integrated Coastal Zone Management, and sustainable use of resources.

Large numbers of local hypoxic "dead zone" vortices in the eastern part of the tropical North Atlantic have recently been discovered. North of 12°N, these vortices bring low salinity sea water from the upwelling area of the eastern boundary of the North Atlantic to the high seas, while south of 12°N, these eddies appear to be generated in the open ocean (Schütte and others, 2016a) Increased chlorophyll concentrations associated with enhanced oxygen consumption within the eddy cores result in an increase in the total oxygen consumption in the open eastern tropical North Atlantic Ocean. This is thought to contribute to the formation of the shallow oxygen minimum zone in the region (Schütte and others, 2016b).

3.3. The South Atlantic Ocean and Wider Caribbean

Significant progress has been made in the observation, understanding and prediction of multiple coupled climate changes in the tropical Atlantic, such as continental rainfall, hurricane activity, marine biological productivity, heatwaves, atmospheric circulation with the equatorial Pacific, correlation and impact with social phenomena, and freshwater input from the Amazon (Foltz and others, 2019; Rodrigues and others, 2019). Development of the Prediction and Research Moored Array in the Tropical Atlantic (PIRATA)[27] has seen the array transition to the next generation of mooring to expand and enhance its capability for ocean and climate research and forecasting. More *in situ* observations have been obtained through repeated hydrographic and volunteer ship surveys. There has been a long-term relaxation of upwelling in the coastal regions of Senegal, resulting in diatom blooms. This is expected to result in anoxia and nitrogen loss in the region (Machu and others, 2019). A greater understanding of the cause, movement and ecological impacts of Sargassum blooms in the Caribbean Sea is required (Wang and Hu 2017).

Progress has been made on Coral Reef Early Warning Systems, particular through new partnerships, one being the Caribbean Community Climate Change Centre's partnership with NOAA. Under this agreement, Atlantic Ocean and Met Lab (AOML), partially funded by the Coral Reef Conservation Program, provide consultation and information systems support, including: programming of the data gathering buoy and transmission of the data back to AOML.

3.4. The Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

Advances in understanding of the Indian Ocean and its ecosystems since WOA I are largely due to the

[26]See https://www.unep.org/unepmap/.
[27]See http://pirata.ccst.inpe.br/en/home/.

Second International Indian Ocean Expedition (IIOE-2) which has been operational since 2015 and has recently been extended, as of 2020, for another five years (Hood and others, 2015; Hood and others, 2019). This multinational collaborative effort has observed that subsurface depletion of oxygen is expanding in the western boundary of the Arabian Sea and has led to a dramatic shift in ecosystems both in the Arabian Sea and the Bay of Bengal (Gomes and others, 2014; Bristow and others, 2017). The expedition has also discovered new submarine canyons, provided enhanced understanding of the benthic habitats of the abyssal nodule field of the central Indian Ocean basin, the western continental margin of the Arabian Sea and the western regions of the Bay of Bengal (Hood and others, 2019). Massive changes in the biogeochemistry and ecosystems of the Arabian Gulf resulting from human activities, and the first reported measurements of primary production, nitrogen uptake, and phytoplankton diversity across biogeochemical provinces in the central oligotrophic Indian Ocean, have also been noted as part of the expedition (Hood and others, 2015).

A review of the Indian Ocean Observing System (IndOOS) has led to the redesign of the Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA) moorings to include new sites in the Arabian Sea and a planned eight additional sites just outside the Indian exclusive economic zone. These moorings are providing oceanographic and meteorological data in near real time and are directly available to climate and weather prediction centers for climate modeling and weather forecasting (Hermes and others, 2019). Growing numbers of Argo floats with biogeochemical sensors deployed under the system are providing insights into key processes associated with plankton blooms and oxygen minimum zones (Hermes and others, 2019).

The Indonesian Throughflow (ITF), the leakage of western tropical Pacific water into the southeastern tropical Indian Ocean through the Indonesian seas, is an important pathway for the transfer of climate signals and their anomalies around the world's oceans (Fan and others, 2018; Feng and others, 2017; Iwatani and others, 2018; Lee and others, 2019; Maher and others, 2018; Zhou and others, 2016). Large uncertainties still remain in measuring and modeling the physical and biogeochemical variability within the Indonesian seas.

3.5. The North Pacific Ocean

The Pacific components of the US Integrated Ocean Observing System (IOOS) have expanded their capacity in coastal monitoring and started to include social science disciplines. This has led to a better understanding of the mechanism and ecological impacts of the Alaskan heatwave in 2014–2016 (Yang and others, 2019).

Since WOA I, the North Pacific Marine Science Organization[28] has enhanced its role in coordinating regional observation networks in the North Pacific, and serves as the platform for sharing knowledge among scientists and the bridge between science and policymakers. In the period since WOA I, it has released two special issues: one on ocean acidification and deoxygenation in the North Pacific Ocean (Christian and Ono, 2019); and the second on the effects of marine debris caused by the 2011 tsunami in Japan (Clarke Murray and others, 2019). It has also furthered the understanding of climate and ecosystem predictability, drivers of algal and jellyfish blooms, marine ecosystems and the services they provide, human well-being, and top predators (Watanuki and others, 2016; Makino and Perry, 2017; Trainer, 2017; Uye and Brodeur, 2017; Zhang and others, 2015; Jang and Curchitser, 2018). The organization periodically produces a North Pacific ecosystem status report aimed at reviewing and summarizing the status and trends of marine ecosystems in the North Pacific that considers the factors that are causing or are expected to cause change in the near future. The third report, which will detail the trends of physical, chemical and biological properties of the North Pacific Ocean throughout the

[28]See https://meetings.pices.int/.

2010s, is currently being prepared.

Intensive expansion of marine research capability and capacity, including remote sensing and *in situ* platforms and land-based infrastructures, by the People's Republic of China (Chen and Lei, 2019), has enhanced monitoring capacity in marine area under Chinese jurisdiction. China has established a monitoring system to perform routine monitoring of marine environmental quality, and assess ecosystem health status of habitats in the coastal waters along China. This has supported progress in regional cooperation in sustainable development and marine and climate research.

3.6. The South Pacific Ocean

New understanding of the effects of climate change and ocean warming has helped to identify major hotspots within the South Pacific Ocean, including south-east of Australia, west of the Galapagos, eastern Micronesia and Drake Passage, where regions are warming at rates above the global average.[29] At the same time, descriptions and understanding of marine heatwaves and their impacts on marine ecosystems have progressed (Oliver and others, 2018; Fordyce and others, 2019). Assessments of coral atolls across the region have revealed no widespread signs of physical destabilization in the face of sea level rise, with land area remaining stable (Duvat, 2018). Observing systems in the region are now collecting time series of a variety of ocean observations, including the physical and chemical environment, biological productivity and marine animals for which trends and changes are being reported.[30]

New regional partnerships among the South Eastern Pacific Countries (Colombia, Ecuador, Peru and Chile – South Pacific Permanent Commission) have been developed with the aim of monitoring and forecasting oceanographic and climatic variability[31]. The recent Tropical Pacific Observing System report[32] identifies recommendations for a redesigned moored array[33] that could improve observations in the tropical Pacific Ocean.

Every five years, the Government of Australia produces a report on the state of the Australian environment, the most recent of which was issued in 2016 (Clarke and Johnston, 2016; Evans and others, 2016; Evans and others, 2018), The marine and coastal thematic reports concluded that the overall state of the Australian coastal and marine environments could be regarded as good. However, the historical impacts of a number of pressures, such as commercial and recreational fishing, and ongoing pressures caused by activities currently inadequately managed, such as climate change and marine debris, have led to a deterioration in those environments, and are continuing negatively to affect them. As a result, the outlook for the coastal and marine environment was regarded as mixed and largely depended on the escalating trajectory of climate-related pressures and ongoing expansion of coastal and marine development.

New Zealand also produces a regular report on the state of its marine environment, with two released since WOA I, in 2016 and 2019[34]. The most recent report highlighted ongoing issues, including the fact that many species and habitats are under threat, pollution inputs are increasing, as is sediment accumulation of the marine environment, and boat activity and shipping are increasing, resulting in the

[29]See http://www.marinehotspots.org/.
[30]See https://www.imosoceanreport.org.au/.
[31]See http://www.met.igp.gob.pe/elnino/enfen/.
[32]See http://tpos2020.org/.
[33]See https://www.pmel.noaa.gov/gtmba/mission/.
[34]See https://www. mfe.govt.nz/.

spread of non-native species and pollution and increased coastal development, and unprecedented change in the marine environment associated with climate change. Of note, the report highlighted that the cumulative effect of these pressures was the most urgent problem faced by the ocean.

3.7. The Southern Ocean

Within the Southern Ocean, the Southern Ocean Observing System (SOOS), a joint initiative of the Scientific Committee on Antarctic Research and the Scientific Committee on Oceanic Research, established in 2011, facilitates the collection of essential physical, chemical and biological oceanographic observations. Regional networks of observational activities operating under the SOOS framework facilitate information exchange, technology transfer, standardization of measurements and data sharing[35]. Tools developed by the system include an open-access interactive web-based platform (SOOSmap) which allows users to explore circumpolar datasets. facilitate and scientific information exchange. A database of upcoming expeditions to the Southern Ocean (DueSouth) enables users to find out which expeditions, such as voyages, flights or traverses, are planned to help to facilitate coordination of field activities (Newman and others, 2019). The system has supported progress in the number of observations collected since WOA I, particularly with regard to monitoring increasing ocean temperature (Roemmich and others, 2015), increases in westerly winds over the Antarctic Circumpolar Current (Gent, 2016) and freshening of the ocean, most notably close to the continent (Schmidtko and others, 2014). Deployment of biochemical sensors has increased measurements of chlorophyll-a, nitrate, oxygen, light, optical properties and pH throughout the Southern Ocean (Newman and others, 2019). Ice-capable bio-Argo floats are now collecting information on biogeochemical cycles during ice-covered periods (Briggs and others, 2017), and gliders are adding to the collection of ocean observations (Newman and others, 2019). As ecosystems are changing, variable effects on marine predators have been observed; some populations of Adélie penguins (*Pygoscelis adeliae*) and chinstrap penguins (*P. antarcticus*) have declined, while some populations of gentoo penguins (*P. papua*) have increased (Trivelpiece and others, 2011; Hinke and others, 2017; Chapter 7M of the present Assessment). Long-term monitoring of marine species, including penguins and seals, continues to be undertaken through the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) as part of the management of krill fisheries and is increasing understanding of their foraging behaviour and demographics (Newman and others, 2019).

4. Outlook for scientific understanding of the ocean

Further scientific research will help to assess the achievement of targets under SDG 14, especially under the United Nations Decade of Ocean Science for Sustainable Development (2021-2030)[36] . The UN Ocean Decade recognizes innovative approaches to science, involving many disciplines and many societal sectors, are needed to achieve the 2030 Agenda. With respect to ocean and coastal observation at large, the OceanObs'19 Conference[37] has put forward a series of recommendations that focus, inter alia, on sustaining ocean observations; connecting with users and stakeholders; identifying the societal benefits of observations; further developing indicators for the ocean; and fostering trans-disciplinary approaches to research. Work on roadmaps to further the development of a global ocean observing system that includes and integrates abiotic and biotic observations, and goes beyond traditional observation technologies, has begun (Speich and others, 2019). Together with advances in computing technology and analytical methods, the outputs of eDNA studies will help in the analysis of biodiversity observations, with a resulting improvement in input of information into ecosystem models, and their use in ecosystem-based management.

[35]See http://soos.aq/activities/cwg/soflux.
[36]See United Nations General Assembly resolution 72/73; see also https://www.oceandecade.org/.
[37]See http://www.oceanobs19.net/sessions/.

The International Convention for the Control and Management of Ships' Ballast Water and Sediments entered into force in 2017.[38] It aims to prevent the spread of harmful aquatic organisms from one region to another by establishing standards and procedures for the management and control of ships' ballast water and sediments. Further scientific work is needed to generate the required evidence and knowledge, including on the basis of observations and technology development, to assist managers and stakeholders, including governmental authorities, in implementing the Convention.

5. Key remaining knowledge gaps

The near-future scientific challenges are related to topics such as understanding and anticipating ENSO events, understanding and anticipating marine ecosystem tipping points, quantifying the cumulative effects of multiple pressures on marine environments, developing adaptive management approaches and making them more operational, and encouraging broader consideration and integration of local, traditional and indigenous knowledge in marine ecosystem assessment and management.

Global disparities in understanding and knowledge gaps at continental regional levels remain. The bulk of the research and the information readily available (based on numbers of publications) relates to the North Atlantic, North Pacific and Arctic Oceans. For other areas, in particular Oceania, South America and Africa (IOC-UNESCO, 2017b), there is less information available.

Timely dissemination of collected measurements is very important for effective usage of data in today's connected ocean prediction and monitoring systems. This aspect of making data available and also the software for quality control is essential for making best use of the ocean observations.

Currently, most global observation networks do not incorporate economic, social and cultural aspects of the ocean and, as a consequence, focused, sustained and publicly accessible observations of these aspects of marine systems in standardized formats at regional and global scales are lacking (Evans and others, 2019). The compilation of economic, social and cultural information into useable formats for inclusion within an assessment framework for synthesizing at global scales requires considerable effort, often beyond the ability of those individuals or groups of individuals involved in contributing to the WOA. This is an area in which an extension of current observation frameworks to incorporate sustained and standardized monitoring of economic, social and cultural aspects of the ocean would significantly improve assessments undertaken in the WOA framework (Evans and others, 2019). The report of the IPBES (IPBES, 2019) has made clear that we also need to increase our capacity not only to monitor biodiversity but also to understand its functions and the effect human activities, including climate change, have on biodiversity. One of the aims of the variables being developed under GOOS is to expand observations of pressures placed on marine ecosystems by human activities to include ocean noise and marine debris, including plastics. The outputs from the WOA could assist in guiding the process for identifying such variables and, in so doing, could provide a mutual pathway for further improvements to the observations contributing to future Assessments.

6. Key remaining capacity-building gaps

[38] International Maritime Organization, document BWM/CONF/36, annex; see also http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Control-and-Management-of-Ships'-Ballast-Water-and-Sediments-(BWM).aspx.

Advances in global understanding of scientific knowledge depend on uniformity in efforts to engage in research globally across the continental regions. The uniformity of research efforts globally further depends on how advanced infrastructure, specialized scientific human capacity and technology are distributed and shared through partnerships. Many natural science disciplines such as physical, chemical and biological oceanography and marine geology require research vessels or other specialized equipment and upgraded modern technology, and the support of land-based laboratories equipped with modern equipment to support research surveys in the entire depth range of the global ocean. Further support needs to be provided through the use of satellites for remote-sensing studies of the ocean. Innovation for cost-effective *in situ* observation tools and methods is also needed.

Currently, our level of scientific understanding is regionally skewed because of disparities in the capacities of regional infrastructures and in specialized professional human capacity. This, therefore, affects possibilities for engaging in competitive ocean research, and, in turn, leads to the observed disparities in our scientific understanding of oceans at the regional level.

For improving the forecast capacities for ENSO and other ocean-climatic variations, ocean observing systems need to be strengthened and partnerships with regional countries promoted in order to enhance local capacities[18]. In order to monitor the significant changes in physical and biogeochemical environments and their impacts on ecosystems and society, further integration of multidisciplinary observations and a reduction in uncertainty of prediction models are needed. Innovation in funding strategies is also required to sustain integrated observing systems.

The ocean science community has proposed action plans for the next decade (Speich and others, 2019) which include efforts to increase the efficiency of the ocean information value chain (Tanhua and others, 2019b). To maximize the value of ocean data for societal use, the interface of each service, scientific observation, data assembly and management and policy should be smoothly streamlined. For example, integration of observing systems and FAIR data principals must be implemented in a harmonized manner. The aim of WOA is to enable scientific knowledge to be conveyed as information which is usable and understandable for non-academic users, and thus can serve as an important link in the ocean data value chain.

Local, traditional and indigenous knowledge needs to be further integrated, and concepts relating to facilitating collaborations to provide opportunities for recognising synergies and sharing and exchange of information (Wright and others, 2019), need to become best practice.

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Chapter 4
Drivers

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Keynote points

- Drivers that have the greatest influence on the marine environment and its sustainability are: (i) population growth and demographic changes; (ii) economic activity; (iii) technological advances; (iv) changing governance structures and geopolitical instability; and (v) climate change.
- The relationships between drivers and pressures (and their impacts) are complex and dynamic, with interlinkages between drivers leading to cumulative interactions and effects of pressures.
- Drivers vary regionally as a result of global variability in population distribution and demographics, the degree of economic development, technological capacity and the uneven effects of climate change and, as a result, human activities and pressures vary globally; most notable differences are between temperate and tropical regions and developed and least developed regions.
- Integrated modelling frameworks, within which scenarios can be explored that include changes to populations and economies, governance structures and the effects of climate change on maritime industries and the environment that are multisectoral and therefore provide "whole of system" approaches, allow for the identification of sustainable ocean use.

1. Introduction

The drivers-pressures-state-impacts-response (DPSIR) conceptual framework (Smeets and Weterings, 1999) is a widely used approach to assess causes and consequences of ecosystem change and the actions that might be implemented in response to that change. Since its development, it has been further refined and many derivatives have been formulated to address limitations and/or apply the framework to specific environments (e.g. Patricio and others, 2016). Although there are many variants, the underlying framework helps to characterize the effect of human activities on the environment and can be used to inform decision-making and policymaking (Maxim and others, 2009). The DPSIR framework has been used to structure the Second World Ocean Assessment (WOA II) and a detailed description is included in its Chapter 2.

The present Chapter focuses on drivers of change in the marine environment, their development since the First World Ocean Assessment (WOA I) (United Nations, 2017a) and projected changes for the future. Drivers of change in the marine environment were not specifically detailed in WOA I, although they were considered within some individual Chapters.

There is no universally agreed set of drivers that have been defined for the marine environment. Different programmes and assessment processes have defined drivers in varying ways and, in some cases, drivers and pressures, whether they be natural or anthropogenic in nature, are used interchangeably. The Millennium Ecosystem Assessment defined drivers as any natural or human-induced factor that directly or indirectly results in a change in an ecosystem (MEA, 2003). The global assessment of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services takes a similar approach, identifying drivers as direct human influences upon nature and factors behind human choices that affect nature (Balvanera and others, 2019). The European Environment Agency considers only human-induced factors as drivers (EEA, 2005), while the Intergovernmental Panel on Climate Change (IPCC) defines drivers within the context of global emissions as those elements that directly or indirectly contribute to greenhouse gas emissions (Blanco and others, 2014).

In the context of the present Assessment, drivers have been characterized by social, demographic and economic developments in societies, including corresponding changes in lifestyles and associated overall consumption and production patterns (EEA, 2019), that are applying pressures on the marine environment, as detailed in Part 5. Pressures are the immediate factors that lead to changes in the state of the marine environment and are additional to changes resulting from natural processes (UNEP, 2019). The drivers that have the greatest influence on the marine environment and its sustainability are:

1. Population growth and demographic changes;
2. Economic activity;
3. Technological advances;
4. Changing governance structures and geopolitical instability;
5. Climate change.[39]

Increases in the global population, together with global economic growth and technological change, have led to changes in lifestyle and thus an increase in the demand for resources. This includes food, energy and natural resources such as rare earth elements, sand and metals. Increasing populations and their associated demand are causing increases in the emission of greenhouse gases, in the amount of waste produced, including plastic, in the use of chemicals in agricultural production, in energy production and in the extraction of resources.

The relationships between drivers and pressures, and their impacts, are complex and dynamic, with interlinkages between drivers. For example, technological advances can influence economic growth, and changing governance regimes can influence access to and use of technologies. With increasing affluence and access to technologies, efficiencies in resources extraction can occur, leading to greater pressures being placed on the ocean (see also section 2).

The United Nations Sustainable Development Goals (SDGs)[40] were developed to translate human aspirations for a sustainable and equitable future into concrete development goals, while recognizing explicitly adverse ecological threats and the strategies required to mitigate them (United Nations, 2017b). While the marine environment is directly addressed in SDG 14 (Life Below Water), the SDGs are interlinked, with progress made in one thus influencing the others. Accordingly, realization of the sustainable use of the marine environment will depend on successfully addressing the ensemble of the SDGs (ICSU, 2017).

[39] Strictly speaking, the driver is the increase in greenhouse gases that is causing a changed climate. However, the term "climate change" is widely used to describe human activity that directly or indirectly alters the composition of the global atmosphere.
[40] See United Nations General Assembly resolution 70/1.

2. Drivers of change in the marine environment

2.1. Population growth and demographic changes

Although the global human population increased from 7 billion in 2011 to 7.7 billion in 2019,[41] the growth rate has been steadily decreasing from 2.1 per cent in 1968 to 1.08 per cent in 2019. Projections of global population growth suggest an uneven but continuing increase, at a lower rate of change, to a mean population size of 9.7 billion by 2050. This decrease in the growth rate is associated with decreasing births and, combined with lower mortality rates and increasing longevity associated with increasing health standards, means that the average age of the global population is increasing (Baxter and others, 2017).

Migration of people from one country to another has increased from 174 million people in 2010 to 272 million people in 2019 (UNDESA, 2019a). As part of this growth, international migrants have increased from 2.8 per cent in 2000 to 3.5 per cent in 2019. Most migration has occurred between countries within the same region, with the exception of North America and Oceania, where, respectively, 97.5 per cent and 87.9 per cent of international migrants were born in another region, (UNDESA, 2019a).

More than 600 million people live in coastal regions that are less than 10 m above sea level and nearly 2.5 billion people live within 100 km of the coast (UNDESA, 2019b). These regions are experiencing higher rates of population growth and urbanization than inland regions (Neuman and others, 2015). This growth has resulted in many economic benefits to coastal regions, including improved transportation, increased trade, tourism and food production, as well as social, recreational and cultural benefits (Clark and Johnston, 2017). However, as populations in these regions grow, they are placing ever more pressure on coastal ecosystems. The extent to which an increasing global population places pressures on the marine environment varies and depends on a range of factors, including where and how people live, the amount that is consumed and the technologies used to produce energy, food and materials, provide transport and manage the waste produced. The implications of changes to the global population on coastal regions, use of marine resources and generation of wastes are described in detail in Chapter 8 and in Part 5 of the present Assessment.

2.2. Economic activity

Economic growth, as measured in gross domestic product (GDP) per capita, has steadily increased globally,[42] although it has slowed with trade volume. Growth in the first half of 2019 stood at 1 per cent, the weakest level since 2012 (IMF, 2019). Economic growth, when averaged across the global population (noting that there is vast geographical variability in economic growth - see section 3), has resulted in the average annual income of an individual increasing from 3,300 United States dollars in 1950 to 14,574 dollars in 2016. The slowdown in growth is largely associated with weak manufacturing and trade. In contrast, service industries such as tourism have grown (IMF, 2019).

As the global population has grown and the demand for goods and services has increased, there has been an associated increase in energy consumption and resource use. Understanding the relationship between increasing economic activity and the use of natural resources is essential for identifying future sustainability and limiting impacts associated with extraction,

[41] See https://population.un.org/wpp/Graphs/DemographicProfiles/Line/900.
[42] See https://ourworldindata.org/economic-growth.

production, consumption and waste generation (Jackson, 2017).

Total energy demand, as measured in million tonnes of oil equivalent (Mtoe), grew from 13,267 Mtoe in 2014 to 13,978 Mtoe in 2018.[43] At the same time, primary energy intensity, an indicator of how much energy is used by the global economy, has slowed from 1.7 per cent in 2017 to 1.2 per cent in 2019 (IEA, 2019a). This slowing of efficiencies (i.e. the amount of GDP generated for the amount of energy used) is the result of a number of short -term factors, such as growth in fossil fuel-based electricity generation, and longer-term structural changes, such as a slowing transition towards less energy-intensive industries. At the same time, investment targeting energy efficiencies has been stable since 2014. Technical efficiency improvements reduced energy-related carbon emissions by 3.5 gigatonnes of carbon dioxide between 2015 and 2018 (IEA, 2019a). In addition, renewable energy production has grown as many countries shift to energy strategies that rely on this form of energy production as part of efforts to reduce greenhouse gas emissions. Ocean energy production is part of many strategic developments and grew from 1 TWh (Terawatt hour) in 2014 to 1.2 TWh in 2018 (IEA, 2019b). Changes in energy production, including marine renewable energy and the pressures generated on the marine environment, are detailed in Chapters 20 and 22 of the present Assessment.

Economic activity associated with extraction of marine resources also continues to grow as the global population grows. Marine and freshwater food production was a key protein provider and source of income for approximately 59.6 million people globally in 2016, an increase from 56.6 million in 2014. Although marine capture fisheries remain stable at around 80 million tonnes, mariculture is steadily increasing, from 26.8 million tonnes in 2014 to 28.7 million tonnes in 2016 (FAO, 2018). The implications for increasing marine food production demands, including overfishing, bycatch of endangered species and habitat loss/degradation by fishing and aquaculture, are described in detail in Chapters 15, 16 and 17 of the present Assessment.

Many countries are either developing or have developed strategies for the potential growth of maritime activities such as ocean energy, aquaculture, marine biotechnology, coastal tourism, and seabed mining (i.e. growth of "the blue economy"). However, an important constraint on the growth of ocean economies is the current declining health of the ocean and the pressures already being placed on it (OECD, 2016), many of which are detailed in Part 5 of the present Assessment.

2.3. Technological advances

As maritime activities have expanded and demands on resources have increased, technological advances have been key to increasing efficiencies, expanding markets and enhancing economic growth associated with activities. These innovations have led to both positive and negative outcomes for the marine environment. Some advances in fishing technologies have led to an overall increase in capacity and, in many regions in Europe, North America and Asia, to overcapacity (Eigaard and others, 2014). Increased efficiencies generated through the use of technologies (also known as "technological creep"), for example, allowing for more efficient and accurate targeting of catches, have also resulted in effort gains within fisheries, thus contributing to overfishing of stocks (Finkbeiner and others, 2017). Conversely, advances in remote sensing, camera technologies, field deployment of genetic approaches to species identification and use of artificial intelligence and machine learning

[43] See https://yearbook.enerdata.net/total-energy/world-consumption-statistics.html.

approaches are now contributing to better monitoring of illegal, unregulated and unreported (IUU) catches (Detsis and others, 2012), improving reporting of catches (Ruiz and others, 2014), allowing for traceability of products (Lewis and Boyle, 2017) and reducing wastage along supply chains (Hafliðason and others, 2012). These technologies are also assisting in improved monitoring of the movements of fishing fleets, thus ensuring more effective management of protected areas (Rowlands and others, 2019).

Technological advances, including digitalization, are modernizing energy efficiency by reducing energy use, shifting demand from peak to off-peak periods, increasing connectivity and providing flexible loads (that account for increasing shares of intermittent energy generation via the renewable sector), with positive outcomes in terms of greenhouse gas emissions (IEA, 2019a). Improvements in vehicle engines to burn fossil fuels more efficiently and innovations in solar energy and wind energy to produce clean energy are also helping to reduce greenhouse gas emissions.

2.4. Changing governance structures and geopolitical instability

Many international treaties and agreements, including the United Nations Convention on the Law of the Sea,[44] the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972 (the London Convention),[45] the Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks (the Fish Stocks Agreement),[46] the Convention on Biological Diversity[47] and the United Nations 2030 Agenda for Sustainable Development[40] aim to reduce pressures on the marine environment and improve conservation outcomes. Targets set in association with international agreements such as the Aichi Biodiversity Targets[48] and the Sustainable Development Goals[40] have led to an increase in the establishment of Marine Protected Areas and, in association, an increase in the protection of the marine environment. Regional fisheries management organizations provide for the coordination of efforts aimed at managing shared fishery resources (Haas and others, 2020) and in some regions have provided for the implementation of effective stock rebuilding frameworks following overfishing (Hillary and others, 2016).

Supporting policies implemented nationally have also improved the management of marine activities in some areas (Evans and others, 2017). However global inequities, including those associated with wealth, gender, geography, rights and access to resources can have implications for the effectiveness of policies designed to manage the marine environment (Balvanera and others, 2019). Further, consolidation and concentration of company ownership has resulted in a few corporations and/or financiers often controlling large shares of the flows in any market (e.g. Bailey and others, 2018). Corporations have increased potential to negotiate directly with governments, potentially hampering progress towards sustainable outcomes for the marine environment. Where there is conflict over access to resources and property rights, policies and agreements focused on sustainability can be undermined by such conflicts (Suárez-de Vivero and Rodríguez Mateos, 2017). In addition, instability in governments can result in slow or ineffectual development of policies and management frameworks resulting in ongoing or increasing overexploitation of resources.

[44] United Nations, *Treaty Series*, vol. 1833, No. 31363.
[45] Ibid., vol. 1046, No.15749.
[46] Ibid., vol. 2167, No. 37924.
[47] United Nations, *Treaty Series*, vol. 1760, No. 30619.
[48] See United Nations Environment Programme, document UNEP/CBD/COP/10/27, annex, decision X/2.

2.5. Climate change

Climate has always been a major influence on the marine environment, with high natural variability from year to year and longer-term variability associated with climate phenomena at regional and global scales. However, there is strong evidence that our climate is changing at a rate unprecedented in the geological record. The IPCC special report on the ocean and cryosphere in a changing climate (IPCC, 2019) summarizes historic and recent patterns in the global climate and provides projections of changes under different greenhouse gas emission scenarios.

Greenhouse gas emissions have continued to rise over the period since WOA I, with global CO_2 emissions increasing from 30.4 gigatons in 2010 to 33.3 gigatons in 2019.[49] This growth in emissions has resulted in widespread reduction of the cryosphere (frozen water parts of the planet), continued increases in ocean temperature, decreases in ocean pH and oxygen, shifts in currents and increases in extreme events such as heatwaves (IPCC, 2019). These changes are described in detail in Chapter 5 of the present Assessment and the pressures they are generating, including socioeconomic impacts, are described in detail in Chapter 9 of the present Assessment.

Following on from the United Nations Framework Convention on Climate Change (which entered into force in 1994) and the Kyoto Protocol (which entered into force in 2005), the twenty-first meeting of the Conference of the Parties to the United Nations Framework Convention on Climate Change adopted the Paris Agreement in December 2015.[Error! Bookmark not defined.] The Agreement aims to strengthen the global response to the threat of climate change by holding the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels. It recognizes that climate change represents an urgent and potentially irreversible threat to human societies and the planet and thus requires the widest possible cooperation by all countries. It also recognizes that deep reductions in global emissions will be required in order to achieve the ultimate objective of the convention.

The IPCC report on global warming of 1.5˚C (IPCC, 2018) outlined the mitigation pathways compatible with a 1.5˚C warming of the global climate, likely impacts associated with a warming of this nature and what would be needed in responding to such a change. The report highlighted that warming from anthropogenic emissions will persist for centuries to millenniums and will continue to cause further long-term changes in the climate system, including the ocean.

Interactions between climate change and other drivers include influencing the distribution of global populations as people shift from increasingly uninhabitable areas, economic impacts including those associated with food production (including aquaculture and fisheries) and an increasing need for technological innovations and solutions to reducing greenhouse gases, including an increasing reliance on marine renewable energy.

3. Key region-specific issues or aspects associated with drivers

Geographical variability in the distribution of populations, economic development, access to technological advances, capacity in implementing governance and management frameworks

[49] See https://www.iea.org/articles/global-co2-emissions-in-2019.

and effects and responses to climate change result in considerable variability in the influence of each of the drivers described in section 2 across ocean regions.

3.1. Population growth and demographic changes

Fertility rates amongst high income regions are lower than those in middle and low-income regions (Baxter and others, 2017). Varying fertility rates present challenges for those countries where fertility rates are high and population growth is also high (UNDESA 2019c), but also challenges for those countries where fertility is low and the ageing component of the population is growing (see also section 4). Sub-Saharan Africa, Central and Southern Asia and Eastern and South-Eastern Asia are all regions of high population growth. The average rate of population growth in those countries identified as least developed[50] was 2.3 per cent over the period 2015–2020, more than double the global rate. This presents challenges for these countries in achieving sustainable development and conservation of coastal and marine areas, and is further compounded by their vulnerability to climate change, climate variability and sea level rise (UNDESA, 2019c).

3.2. Economic growth

Geographic disparities in economic growth have been increasing since the 1980s, reflecting economic gains in some regions and stagnation in others. While most countries experienced positive growth between 1950 and 2016, others, such as the Central African Republic and the Democratic Republic of the Congo, have experienced negative growth, largely as a result of political instability (Karnane and Quinn, 2019). Notably, disparities within countries in employment and productivity have also been growing, with large differences in the extent of disparities across developed economies (IMF, 2019). Climate change may further exacerbate these disparities, particularly where there is geographical variability in the distribution of susceptible industries such as agriculture (including fisheries and aquaculture). In general, economic activity is affected by increasing temperatures in a non-linear manner. They may bring benefits to economic activities in very cold regions (e.g. opening up of the Arctic Ocean to shipping routes and greater trade potential) but, beyond a certain optimum temperature, there are negative impacts for economic output and labour potential (IMF, 2019).

3.3. Technological advances

Areas beyond national jurisdiction have become increasingly accessible due to technological advancements that facilitate exploration and exploitation of deep sea resources, including biodiversity, minerals, oil and gas. Ensuring the sustainable development of these regions will require international cooperation to manage them effectively. Negotiations on an international legally binding instrument under the United Nations Convention on the Law of the Sea on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction[51] are focused on ensuring such sustainable development and conservation of these areas (see also Chapter 31). The International Seabed Authority is tasked with a dual mandate of promoting the development of deep-sea minerals, whilst ensuring that this development is not harmful to the environment. In areas beyond national jurisdiction appropriate planning will be required to minimize impacts on the marine environment. Uptake of technological

[50] The group of least developed countries includes 47 countries: 32 in Sub-Saharan Africa; 2 in Northern Africa and Western Asia; 4 in Central and Southern Asia; 4 in Eastern and South-Eastern Asia; 1 in Latin America and the Caribbean; 4 in Oceania. Further information is available at http://unohrlls.org/about-ldcs/.

[51] See United Nations General Assembly resolution 72/249.

advances, for accessing and utilizing marine resources, sustainably developing marine industries and effectively managing those uses, are not globally even. Many regions, particularly where there are countries considered as least developed, still lack access to technologies that can assist in the sustainable use of marine resources.

3.4. Changing governance structures and geopolitical instability

There has been an increase in nationalism and protectionism over the last decade, leading to changing trade agreements and, more recently, implementation of tariffs on goods between specific countries. The Democracy Index[52] fell from 5.55 in 2014 to 5.44 in 2019, largely driven by regional deteriorating conditions in Latin America and Sub-Saharan Africa. When indices for individual countries are calculated, stark regional differences are evident. Countries in Scandinavia, far North America and the South-West Pacific had the highest indices, while those in sub-Saharan Africa, the Middle East and parts of Asia had the lowest. These differences affect the implementation of global and regional treaties and agreements, thereby affecting economic growth, the transfer of technologies and implementation of frameworks for managing ocean use, including development of national ocean-related policies. This, therefore, effects the sustainability of human activities and the protection of marine ecosystems in these areas.

3.5. Climate change

Climate change effects are not uniform across the world’s ocean. A number of regions are warming at higher rates than the global average and are identified as marine hotspots (Hobday and Pecl, 2014). A number of these hotspots occur where human dependence on marine resources is greatest, such as South-East Asia and western Africa, with substantive implications for food security compared to other regions. The Arctic is another region where the ocean is warming at 2–3 times above the global average (IPCC, 2018). Similarly, decreases in the pH and carbonate ion concentrations of the ocean, associated with ocean acidification, and other effects of climate change, such as deoxygenation, stratification and sea level rise, are regionally variable, with impacts on the marine environment highly variable. Regional differences in these changes are described in detail in Chapter 5 of the present Assessment and the pressures they are generating, including socioeconomic impacts, are described in detail in Chapter 9 of the present Assessment.

4. Outlook

Within coastal regions, projections under shared socioeconomic pathways estimate a 71 per cent increase in the global human population across the period 2000 to 2050 to over 1 billion, as a result of overall global population growth as well as migration into these areas (Merkens and others, 2016). Under the same scenarios, populations in low- to medium-density areas (<1,000 persons km^2) are projected to decline, while those in higher density areas are projected to increase (Jones and O’Neill, 2016), with an expansion of urban footprints in high-density areas and an increasing strain on associated infrastructure. How and where global populations live and their associated impacts on the environment will be influenced by climate change in many varying ways. As areas become increasingly unlivable as a result of declining precipitation, increasing temperatures, sea level rise and the loss of ecosystems goods and services, people will redistribute themselves to more liveable regions, increasing urban footprints in those regions.

[52] See https://www.eiu.com/topic/democracy-index.

As the global population ages and overall growth slows, the size of the labour force is expected to decline, thus impacting the global economy. The global population considered to be the vast proportion of contributors to global economies, aged 20–64, is estimated to grow less than half as fast over the period 2015–2040 as compared to the prior 25 years, while the population over the age of 65 will grow five times faster than the working-age population (Baxter and others, 2017). How global economies respond to the influence of changing population growth and demographics will depend on public policy, for example, introducing policies that reduce barriers to female employment, and their ability to use advancements in technologies to maintain productivity. These changes in population growth and the distribution and densities of the population, and changing economies, will influence the marine environment in ways yet to be determined.

Economic activity in the ocean is expanding rapidly, with projections suggesting that, by 2030, under a business-as-usual scenario, the ocean economy could more than double, to a value of over 3 trillion United States dollars, with approximately 40 million full-time jobs (OECD, 2016). Technological advances and innovations will be critical for identifying sustainable pathways that allow for development of global economies, including the ocean economy, whilst addressing many of the challenges facing the ocean at present.

In the context of such rapid change, regulation and governance as it currently stands will struggle to keep up. Integration of emerging ocean industries into existing, fragmented regulatory frameworks will restrict the ability to address pressures generated by industries in an effective, timely way. More effective integrated ocean management will be required to ensure a sustainable future for the ocean in light of the drivers of change detailed here (see also Chapter 30 of the present Assessment).

If greenhouse gas emissions continue to be released at the current rate, it is estimated that the surface temperature will warm by 1.5°C sometime between 2030 and 2052 (IPCC, 2018). Many changes to marine ecosystems as a result of climate change have already been observed and future climate-related change and associated risks will depend on whether or not (and when) net zero greenhouse emissions are achieved and the associated rate, peak and duration of surface warming (IPCC, 2018). Even if net zero global anthropogenic CO_2 emissions are achieved, sustained warming will persist for centuries to millenniums and will continue to cause further long-term changes in the climate system and, by association, in the ocean, including sea level rise and ocean acidification (IPCC, 2018). Upscaling and acceleration of mitigative and adaptive approaches will be required to reduce future climate-related risks to food security, maritime industries and coastal communities associated with changes to the marine environment.

As the present Chapter is being written, a global coronavirus pandemic has swept the world, causing major disruption to national economies and populations. In many regions, because of mitigative efforts in reducing the spread of the virus, pressures immediately impacting the ocean, such as fishing effort, tourism activities, pollution and emissions of greenhouse gases, have been temporarily reduced.[53] With restrictions being placed on the movement of populations and on business operations, along with the closing of borders, disruption to supply chains and declining markets have impacted a number of marine industries, notably fisheries.[54] The likely impacts that reduced pressures might have on longer term change by

[53] https://www.carbonbrief.org/analysis-coronavirus-has-temporarily-reduced-chinas-co2-emissions-by-a-quarter.
[54] https://www.ices.dk/news-and-events/news-archive/news/Pages/wgsocialCOVID.aspx.

drivers such as climate change, however, are expected to be minimal and it is currently unclear what benefits might be afforded to marine ecosystems. Disruptions to global supply chains have highlighted the need in many countries to strengthen local supply chains and, in particular, to explore e-commerce options for supporting supply chains in general.

5. Key remaining knowledge and capacity-building gaps

All five drivers detailed in the present Chapter interact with each other in varying ways. Understanding of these interactions varies and, in particular, understanding of the mechanisms by which interactions between drivers influence the marine environment, although having been recognized as essential for developing holistic approaches to ocean management, is an emerging area of research. Integrated management that takes into account social, economic, ecosystem and cultural values and needs - a whole of system approach - allows for the identification of sustainable pathways that support national economies and human well-being.

Development of modelling frameworks within which scenarios that include changes to population, exploration of governance structures and environmental and economic effects resulting from climate change can be explored is needed. Initial development of integrated socio-ecological models that incorporate the marine environment and fisheries into the shared socioeconomic pathways are now being implemented to explore future structuring of oceanic fisheries (Maury and others, 2017; Bograd and others, 2019). Alternative approaches to integrated models are also being used to explore future states of the marine ecosystem and fisheries (Tittensor and others, 2018). There is a need to advance these efforts not only to expand modelling approaches to explore the effects of multiple drivers and their cumulative effects on marine ecosystems, but also to provide tools that provide an interface between modelling approaches and decision-making frameworks that allow for the planning and implementation of sustainable approaches to the use of the ocean.

The ability to measure and, therefore, understand the key components that contribute to the drivers of change outlined in the present Chapter, that is, the social, demographic and economic developments in societies, including corresponding changes in lifestyles and associated overall consumption and production patterns, is not equal across the planet. There is a need for capacity development, particularly across least developed regions, in collecting observations that provide for understanding of key drivers affecting the marine environment, their interactions and the outcomes of change in each for the marine environment. Similarly, development of capacity to record changes caused by pressures associated with drivers of change and, thereby, understand impacts on the marine environment is also needed (Evans and others, 2019). Finally, capacity to effectively plan, assess and manage ocean activities within frameworks that recognize key drivers of change and their interactions is necessary, particularly in regions where there is little capacity currently to implement such frameworks.

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Chapter 5
Trends in the Physical and Chemical State of the Ocean

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Keynote points

- Thermal expansion from a warming ocean, together with land ice melt, are the main causes of the accelerating global rise in the mean sea level.
- Global warming is also affecting many circulation systems. The Atlantic Meridional Overturning Circulation (AMOC) has already weakened and will most likely continue to do so in the future. The impacts of ocean circulation changes include a regional rise in sea levels, changes in the nutrient distribution and carbon uptake of the ocean, and feedbacks with the atmosphere, e.g. altering the distribution of precipitation.
- More than 90 per cent of the heat from global warming is stored in the world's oceans. The oceans exhibit robust warming since the 1950s from the surface down to 2000m. The rate of ocean heat content has more than doubled since the 1990s as compared with long-term trends. Ocean warming can be seen in most of the global ocean, with a few regions exhibiting long-term cooling.
- The ocean shows a marked pattern of salinity changes during the multi-decadal observations, with surface and subsurface patterns providing clear evidence of a water cycle amplification over the ocean. This manifests in enhanced salinities in the near-surface, high-salinity subtropical regions, and freshening in the low-salinity regions such as the West Pacific Warm Pool and the poles.
- An increase in atmospheric carbon dioxide levels, and a subsequent increase in carbon in the oceans, has changed the chemistry of the oceans to include changes to pH and aragonite saturation. A more carbon-enriched marine environment, especially when coupled with other environmental stressors, has been demonstrated through field studies and experiments to have negative impacts on a wide range of organisms, particularly those that form calcium carbonate shells, and alter biodiversity and ecosystem structure.
- Decades of oxygen observations allow for robust trend analyses. Long-term measurements have shown decreases in dissolved oxygen concentrations for most ocean regions and the expansion of oxygen-depleted zones. A temperature-driven solubility decrease is responsible for most near-surface oxygen loss, though oxygen decrease is not limited to the upper ocean and is present throughout the water column in many areas.
- Total sea ice extent has been declining rapidly in the Arctic, but trends are insignificant in the Antarctic. In the Arctic, the summer trends are most striking in the Pacific Sector of the Arctic Ocean, while, in the Antarctic, the summer trends show increases in the Weddell Sea and decreases in the West Antarctic sector of the Southern Ocean. Variations in sea ice extent results from changes in wind and ocean currents.

1. Introduction

The present Chapter analyses the current physical and chemical state of the ocean and its trends using seven key climate change indicators:

- **Sea level**: Sea level integrates changes occurring in the Earth's climate system in response to unforced climate variability, as well as natural and anthropogenic influences. As such, it **i**s a leading indicator of global climate change and variability.

- **Ocean circulation**: Ocean circulation plays a central role in regulating the Earth's climate and influences marine life by transporting heat, carbon, oxygen and nutrients. The main drivers of ocean circulation are surface winds and density gradients (determined by the ocean temperature and salinity) and any changes in these drivers can induce changes to ocean circulation.

- **Sea temperature and ocean heat content**: The rapid warming of the Earth's ocean over the past few decades affects the weather, climate, ecosystems, human society and economies (IPCC, 2019). More heat in the ocean is manifested in many ways, including, but not limited to, an increasing interior ocean temperature (Cheng and others, 2019b), a rising sea level caused by thermal expansion, melting ice sheets, an intensified hydrological cycle, changing atmospheric and oceanic circulations and stronger tropical cyclones with heavier rainfall (Trenberth and others, 2018).

- **Salinity**: With the advent of improved observational salinity products, more attention has been paid to ocean salinity in Intergovernmental Panel on Climate Change (IPCC) Assessment Reports (AR4, Bindoff and others, 2007; and AR5, Rhein and others, 2013) and in the First World Ocean Assessment (WOA I) (United Nations, 2017). Changes to ocean salinity are important as the global ocean covers 71 per cent of the Earth's surface and contains 97 per cent of the Earth's free water (Durack, 2015). Any global water changes will be expressed in the changing patterns of ocean salinity, a water cycle marker of the largest reservoir of the climate system.

- **Ocean acidification**: Rising concentrations of carbon dioxide (CO_2) in the atmosphere also have a direct effect on the chemistry of the ocean through the absorption of CO_2. The ocean has absorbed roughly 30 per cent of all CO_2 emissions (1870–2015 period; Le Quéré and others, 2016; Gruber and others, 2019) and the increased CO_2 in the water lowers its pH through the formation of carbonic acid.

- **Dissolved oxygen**: Variations in oceanic oxygen have a profound impact on marine life, from nutrient cycling to pelagic fish habitat boundaries (e.g. Worm and others, 2005; Diaz and Rosenberg, 2008; Stramma and others, 2012; Levin, 2018)) and can influence climate change via nitrous oxide emissions, a potent greenhouse gas (e.g. Voss and others, 2013).

- **Sea ice**: Sea ice in the polar regions covers about 15 per cent of the global ocean and affects the global climate system through its influence on global heat balance and global thermohaline circulation. Additionally, sea ice has a high albedo, reflecting more sunlight than the liquid ocean, and its melt releases fresh water which slows the global ocean conveyor belt (the constantly moving system of deep-ocean circulation driven by temperature and salinity).

The present Chapter, through these indicators, details the impacts of climate change on the physical and chemical state of the ocean and its evolution and spatial patterns. The Chapter is to be read in conjunction with Chapter 9 of the present Assessment, which analyses extreme climate events (marine heatwaves, extreme El Niño events and tropical cyclones) and describes in more detail the pressures of some of the physical and chemical changes on marine ecosystems and human populations. Some additional aspects are covered in the section on high-latitude ice in Chapter 7 on trends in the state of biodiversity in marine habitats.

2. Physical and chemical state of the ocean

2.1. Sea level

Since the early 1990s, sea level has been routinely monitored at the global and the regional levels by a series of high-precision altimetry missions (Topex/Poseidon, Jason-1,2,3, Envisat, Saral/AltiKa, Sentinel -3A and B).

The most recently updated global mean sea level curve based on satellite altimetry is shown in Figure 1 (update of Legeais and others, 2018). Since 1993, the global mean sea level has been rising at a mean rate of 3.1 +/- 0.3 mm/yr, with a clear superimposed acceleration of ~ 0.1 mm/yr^2 (Chen and others, 2017; Dieng and others, 2017; Yi and others, 2017; Nerem and others, 2018; the WCRP Global Sea Level Budget Group, 2018). Satellite altimetry has also revealed strong regional variability in the rates of sea level change, with regional rates up to 2–3 times above the global mean in some regions over the altimetry era (Figure 2).

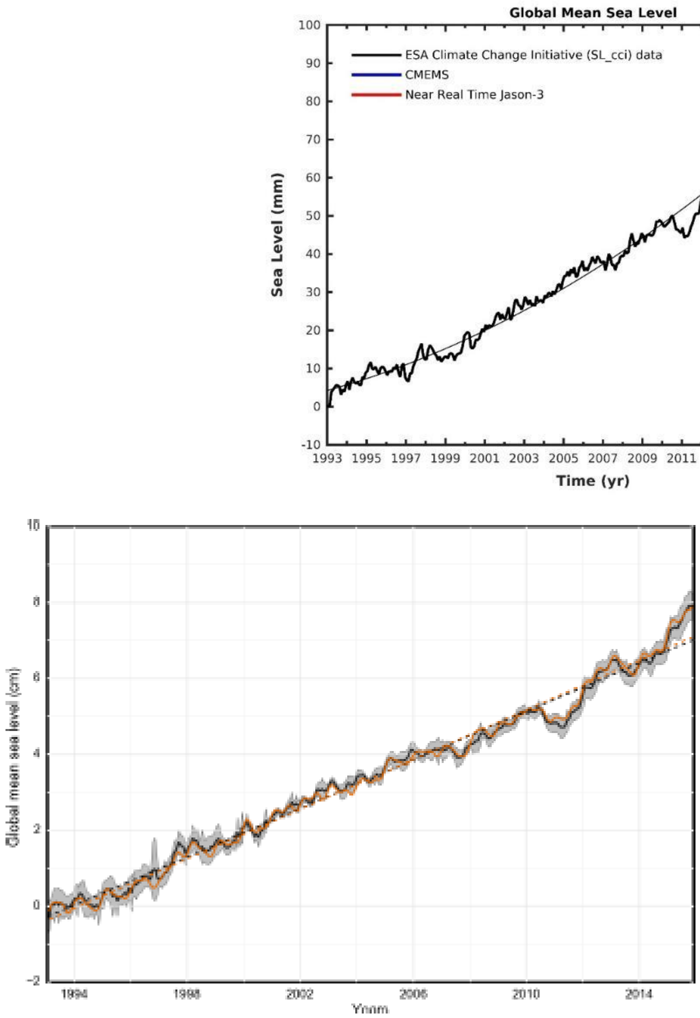


Figure 1. Global mean sea level evolution from multi-mission satellite altimetry (update from Legeais and others, 2018).

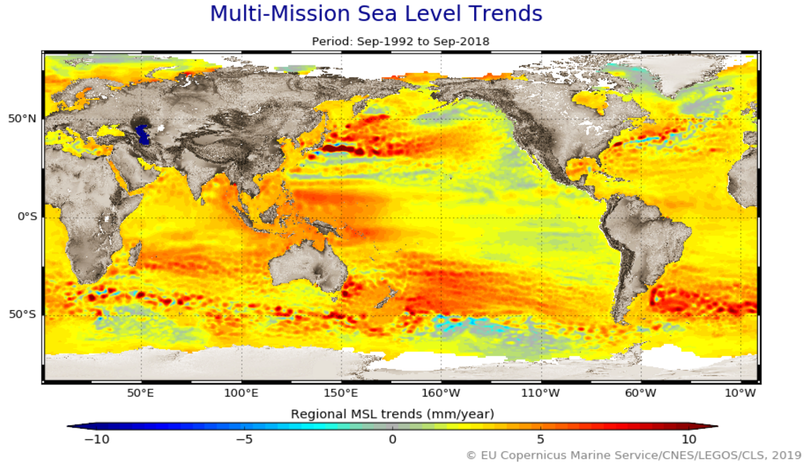


Figure 2. Regional trend patterns in sea level from satellite altimetry (source CMEMS -Copernicus Marine Environment Monitoring Service-).

We now have different observing systems that allow us to quantify the different contributions of the global and regional sea level changes. The Argo system of autonomous profiling floats (http://www.argo.net/) measures sea water temperature and salinity down to 2000m with almost global coverage. The space gravimetry mission GRACE (Gravity Recovery and Climate Experiment) allows for monitoring of ocean mass changes due to glacier and ice sheet mass loss, as well as land water storage change. GRACE also measures individual water mass changes of glaciers, ice sheets and terrestrial water bodies. Other techniques like InSAR and radar and laser altimetry are also used to estimate ice sheet mass balances.

The study of the sea level budget is important as it provides constraints on missing or poorly known contributions such as the deep ocean, under-sampled by current observing systems. Global mean sea level corrected for ocean mass change helps independently to estimate changes in total ocean heat content over time, from which the Earth's energy imbalance can be deduced. Figure 3 presents annual averages since 2005 of the global mean sea level and sum of ocean thermal expansion and ocean mass increase due to land ice melt and terrestrial water storage change (World Climate Research Pool Global Sea Level Budget Group, 2018). Figure 3 shows that annual residuals remain below the 2 millimetre level. In terms of trends, the sea level budget since 2005 is close to 0.3 mm/yr, similar to the mean sea level rise uncertainty. Other studies (Dieng and others, 2017; Nerem and others, 2018) also show closure of the sea level budget over the whole altimetry era (since 1993).

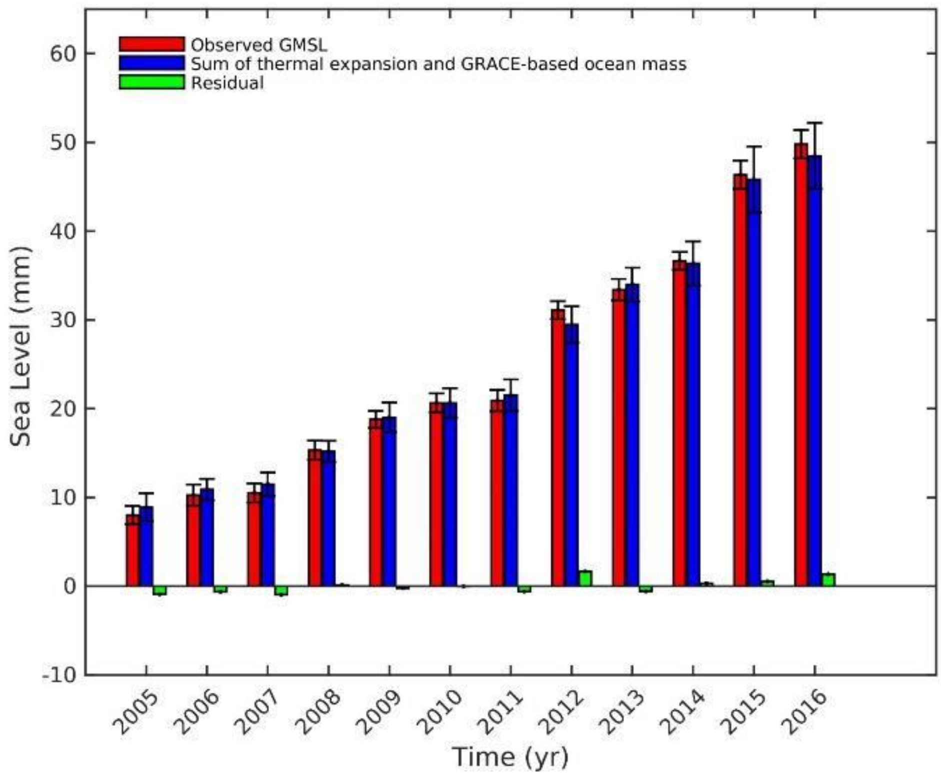


Figure 3. Yearly global mean sea level budget since 2005 (WCRP Global Mean Sea Level Budget Group, 2018).

At local scales, in particular, in coastal areas, additional small-scale processes are added to the global mean and regional sea level components and can make coastal sea level substantially deviate from open ocean sea level rise (Woodworth and others, 2019). For example, changes in wind, waves and small-scale currents close to the coast, as well as freshwater input in river estuaries, can modify the density structure of sea waters, hence the coastal sea level.

2.2. Ocean circulation

The observed changes in the ocean circulation system occur globally and are derived from a variety of data sources. Changes in sea level height, measured with high-precision satellite altimetry since 1993, seem to indicate a widening and strengthening of the subtropical gyres in the North Pacific (Qiu and Chen, 2012) and South Pacific (Cai, 2006; Hill and others, 2008). The data, furthermore, show a poleward movement of many ocean currents, including the Antarctic Circumpolar Current and the subtropical gyres in the Southern Hemisphere (Gille, 2008) as well as western boundary currents in all ocean basins (Wu and others, 2012).

Yet the most severe changes are observed in the Atlantic Ocean: One of the major ocean current systems, the Atlantic Meridional Overturning Circulation (AMOC), has long been predicted to slow down in response to global warming (IPCC, 2013). As this current system transports heat from the Southern Hemisphere and the tropics into the North Atlantic, its evolution can be deduced from the sea surface temperature evolution. The observed cooling in the subpolar North Atlantic since the end of the nineteenth century has already been linked to a slowing AMOC (Dima and Lohmann, 2010; Latif and others, 2006; Rahmstorf and others, 2015). Furthermore, different and largely independent proxy indicators of AMOC evolution published in recent years indicate that AMOC is at its weakest for several hundreds of years (Figure 4) and has been weakening during the last century (Figure 5; Caesar and others, 2018). This weakening can also be seen in the direct measurements of the RAPID research programme[55] (Smeed and others, 2018) over the last decade.

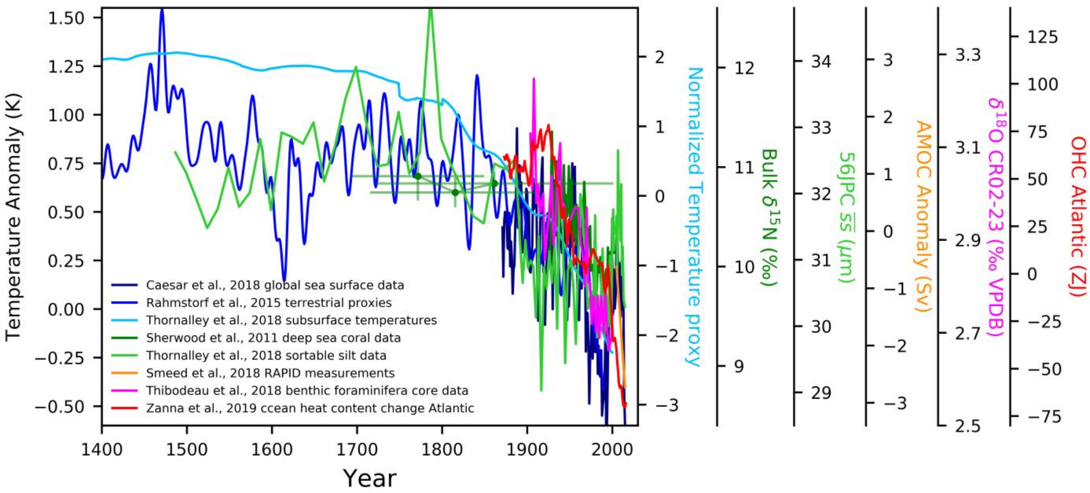


Figure 4. Trend of the strength of overturning circulation (AMOC) in observations since 1400 from various proxies. Shown are the long-term evolution of the sea surface and land temperatures in the North Atlantic region (different shades of blue (Caesar and others, 2018; Rahmstorf and others, 2015; Thornalley and others, 2018), the ocean heat content of the Atlantic (red, (Zanna and others, 2019)), data from deep sea cores (light (Thornalley and others, 2018) and dark (Sherwood and others, 2011) green, magenta (Thibodeau and others, 2018)) and the linear trend of in situ AMOC monitoring by the RAPID project (orange, (Smeed and others, 2018)).

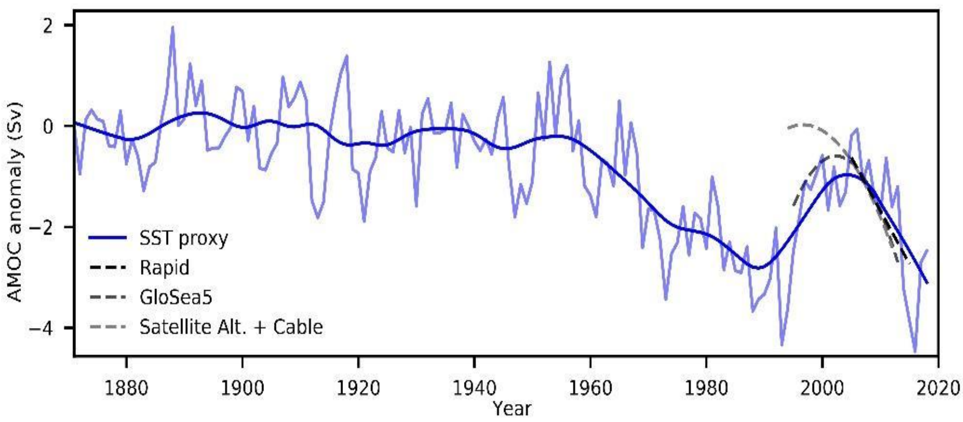


Figure 5. Trend of the strength of AMOC in observations. Shown are the long-term (20-year LOWESS filtering, thin lines are annual values) sea surface temperature proxy (blue), the quadratic trend of an ocean reanalysis product (GloSea5; Jackson and others, 2016), a reconstruction from satellite altimetry and cable measurements (Frackja-Williams, 2015) and the linear trend of in situ AMOC monitoring by the RAPID project. Source: (Caesar and others, 2018).

Information about the circulations and their changes can be inferred from either direct

[55] The RAPID program aims to determine the variability of AMOC and its link to climate. A 2004 deployed array continuously observes the strength of AMOC at about 26°N.

measurements, proxies or model simulations. The main uncertainties regarding the trends in ocean circulation arise from the short timespans of direct, continuous measurements, the incompleteness when representing a circulation through proxies and the inherent uncertainties of the models. It is therefore very important that the existing research programmes of observations like the Global Drifter Program (Dohan, 2010) and the Argo Program (Freeland and others, 2010) are sustained. This also includes the main projects observing AMOC, that is, the RAPID array (Smeed and others, 2014) measuring AMOC strength since 2004 at roughly 26°N, the OSNAP[56] program (Lozier and others, 2017) measuring the overturning that has been feeding AMOC since 2014 and the OVIDE3 line, measuring ocean parameters along a line between Greeland and Portugal (Mercier and others, 2015).

The impacts of the changes in the ocean's circulation system vary. AMOC is crucial for meridional heat transport and therefore strongly influences the climate in the North Atlantic region. Its slowdown can reduce ocean carbon uptake (Zickfeld and others, 2008) and will enhance sea level rise in the United States east coast (Goddard and others, 2015). The stronger North Pacific subtropical gyre, however, leads to regional sea level rise in the western tropical North Pacific Ocean (Timmermann and others, 2010). These are the dynamic responses of the sea level height to changes in ocean circulation. The poleward displacement of the western boundary currents leads to warming in those regions previously unaffected by these warm and strong currents. The consequent thermal expansion will cause a rise in sea level in adjacent coastal areas, for example in the Southern and Indian Ocean (Alory and others, 2007; Gille, 2008). Other possible impacts that need further investigation include changes in marine ecosystems/primary production, as currents transport nutrients, and effects on weather systems, like the occurrence of heatwaves, droughts or flooding, as ocean circulation has a considerable impact on atmospheric circulation, and with that precipitation, patterns (Duchez and others, 2016).

2.3. Sea temperature and ocean heat content

Sea surface temperature

The global sea surface temperature (SST) analyses assessed here are derived from four published data sets (Figure 6). All data sets reveal an increase of global mean SST since the early twentieth century. The globally averaged SST data as calculated by a linear trend over the period 1900–2018 show an incontrovertible warming of 0.60±0.07 °C (COBE1: Centennial In Situ Observation-based Estimates of SST) (Ishii and others, 2005), 0.62±0.11 oC (COBE2) (Hirahara and others, 2014), 0.56±0.07 °C (HadISST: Hadley Centre Sea Ice and Sea Surface Temperature data set) (Rayner and others, 2003), 0.72±0.10 °C (ERSST: Extended Reconstructed Sea Surface Temperature) (Huang and others, 2017) per century, with a 90 per cent confidence interval provided. Considering all data sets, the mean SST rate is 0.62±0.12 °C per century (c^{-1}) over the same period. Differences between these data sets are mainly due to how each methodology treats areas with little to no data, and how each analysis accounts for changes in measurement methods. Among all data sets, the ten warmest years on record have all occurred since 1997, with the five warmest years occurring since 2014. The recent decade (2009–2018) shows a much higher rate of warming than the long-term trend: 2.41±1.79 (COBE1), 2.97±1.81 (COBE2), 2.05±1.85 (HadISST), 2.81±1.98 °C

[56] OSNAP is an international program designed to provide a continuous record of the fluxes of heat, mass and freshwater in the subpolar North Atlantic.

3 The OVIDE project documents the variability of the circulation and water mass properties in the northern North Atlantic.

c[-1] (ERSST). The mean rate is 2.56±0.68 °C c-1 within 2009–2018. In addition to these in situ observations, satellite-based data give consistent changes of SST in the recent periods from 1981 to 2016 (Good and others, 2020, Figure 6)..

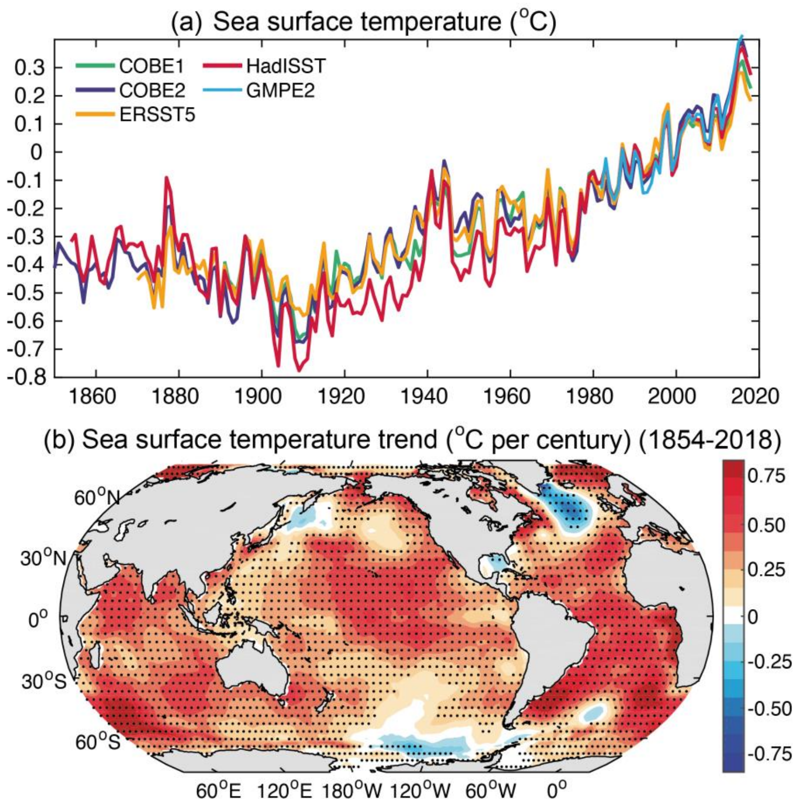


Figure 6. (a) Global average surface temperature anomalies (°C, annual mean). In situ estimates are shown from COBE1, COBE2, ERSST5, HadISST and GMPE2 (GHRSST (Group for High Resolution Sea Surface Temperature) Multi-Product Ensemble dataset, version 2); (b). Spatial pattern of the long-term SST trend (°C per century) from 1854 to 2018 for ERSST data. All data use a common 1981–2010 baseline. Black dot signs (in b) indicate grid boxes where trends are significant (i.e., a trend of zero lies outside the 90 per cent confidence interval).

Most ocean areas around the Earth are warming (Figure 6 b). The broad warming over the global ocean surface is direct evidence of human influence on the climate system (Bindoff and others, 2013). A few regions, such as the subpolar North Atlantic Ocean, have experienced cooling over the last century (often named the "cold blob" or "North Atlantic warming hole"). A number of studies suggest that this "cold blob" indicates a weakening AMOC, possibly in response to increased CO2 concentrations in the atmosphere (Caesar and others, 2018). On other hand, lower warming rates have characterized the Equatorial and Tropical Eastern Pacific. In the South East Pacific, from Central Peru to Northern Chile a multidecadal surface cooling trend has been detected until the late 2000's (Gutiérrez et al., 2016 and references therein), probably associated to coastal upwelling enhancement or remotely-driven circulation changes (Dewitte et al., 2012).

Ocean heat content

Climate change from human activities is mainly due to interference with the natural flows of energy through the climate system, creating an energy imbalance caused by increased heat-trapping (greenhouse) gases (Hansen and others, 2011; Trenberth and others, 2018) in the atmosphere. More than 90 per cent of the energy imbalance accumulates in the ocean (Rhein and others, 2013). This heat imbalance is manifested by the increase of ocean heat content (OHC). Locally, OHC can be estimated by integrating sea temperature (*T*) from ocean depth *z1* to *z2*:

$$\text{OHC} = c_p \int_{z_1}^{z_2} \rho T dz \ .$$

Where ρ is the density of the sea water and C_p is the specific heat capacity of the sea water.

Earth's energy imbalance and OHC are the fundamental metrics for global warming (Hansen and others, 2011; Trenberth and others, 2018; von Schuckmann and others, 2016; Cheng and others, 2018). The OHC record is much less impacted by internal variability in the climate system than the more commonly used sea surface temperature records, so it is better-suited to detecting and attributing human influences (Cheng and others, 2018) than other measures.

Since IPCC-AR5 (Rhein and others, 2013), substantial progress has been made in improving long-term OHC records and a number of sources of uncertainty in prior measurements and analyses have been identified and better accounted for (Abraham and others, 2013; Boyer and others, 2016; Cheng and others, 2016, 2017a; Ishii and others, 2017). At the same time, efforts have made to improve how spatial or temporal gaps are accounted for in historical ocean temperature measurements. For example, a new spatial interpolation method was proposed (Cheng and others, 2017a) and a correction to an existing estimate was made available (Ishii and others, 2017). It is becoming clearer that many traditional gap-filling strategies introduced a conservative bias toward low magnitude changes. Those with less bias include Cheng and others, (2017a); Domingues and others (2008); Ishii and others (2017).

The three recent OHC estimates based on observations show highly consistent ocean warming since the late 1950s (Figure 7). They suggest a linear rate of 0.36±0.06 (Ishii and others (2017), and 0.33±0.10 (Cheng and others, 2017a) W m-2 (averaged over the Earth's surface) within the 1955–2018 period, with the mean rate of 0.34±0.08 W m-2 among all data sets. The new estimates are collectively higher than previous estimates (Rhein and others, 2013) and more consistent with each other (Cheng and others, 2019a). The rate of ocean warming for the upper 2000m has increased in the decades after the 1990s, with linear trends of 0.58±0.06 W m-2 (Cheng and others, 2017a), 0.61±0.08 W m-2 (Ishii and others, (2017), and 0.66±0.02 W m-2 (Domingues and others, 2008; Levitus and others, 2012) over 1999–2018. The mean rate is 0.62±0.05 W m-2. Within the recent decade (2009–2018), the rate of OHC increase is: 0.56±0.06 W m-2 (Cheng and others, 2017a), 0.66±0.09 W m-2 (Ishii and others, (2017), and 0.66±0.03 W m-2 (Domingues and others, 2008; Levitus and others, 2012). The mean rate is 0.65±0.07 W m-2. For OHC, the past ten years are each the ten warmest on record (Cheng and others, 2019a), as OHC is less impacted by natural variability.

Increases in OHC are observed practically throughout the global ocean, down to 2000 m (Figure 7). Some intriguing patterns emerge for long-term OHC change over the 1960–2018 period: stronger warming in the Southern Ocean (70°S~40°S) and Atlantic Ocean (40°S~50°N) than other regions and weaker warming throughout the Pacific and Indian Ocean (30°S~60°N) (Figure 7). The long-term warming of the Southern Ocean has been identified and attributed primarily to greenhouse gases (GHG) (Cheng and others, 2017a; Swart and others, 2018), driven predominantly by air-sea flux changes associated with upper-ocean overturning circulation and mixing (Swart and others, 2018). Southern Ocean warming has important consequences due to its influence on the Southern Hemisphere ice reservoir. Near-surface Southern Ocean heat content is key in limiting the seasonal development of sea ice, and warming can therefore feed back into the global climate by limiting Earth's albedo. Also, ocean warming accelerates the melting of Antarctic ice shelves, threatening the stability of the Antarctic ice sheet, with global implications in terms of sea level rise (Sallée and others, 2018).

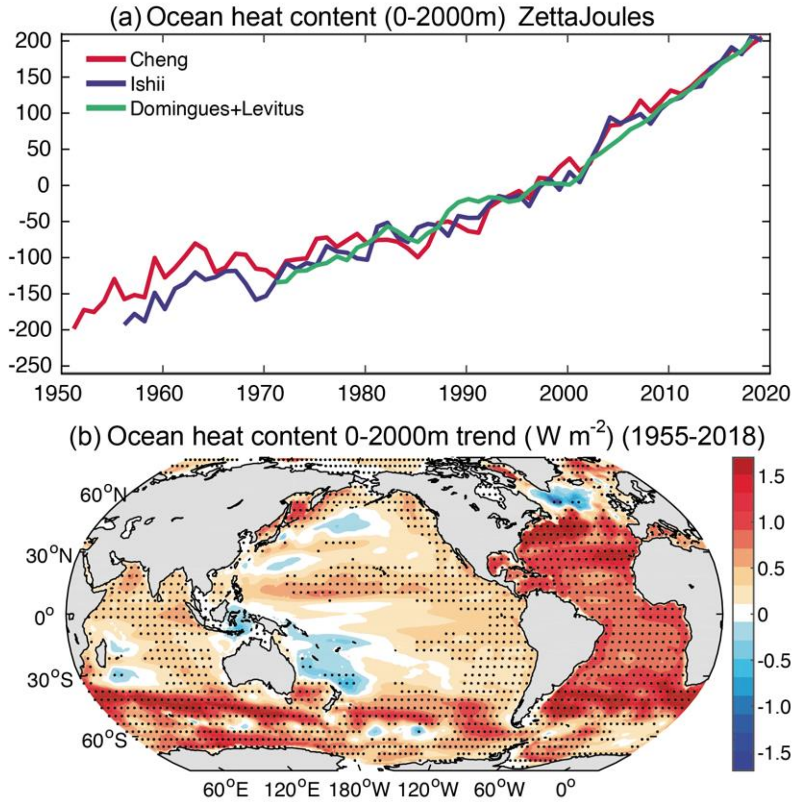


Figure 7. (a) Observational ocean heat content changes (ZettaJoules: 1021 Joules, annual mean) for the upper 2000m (Cheng and others, 2017a; Domingues and others, 2008; Levitus and others, 2012; Ishii and others,. 2017). The Domingues estimate (0- 700m) is combined with the Levitus estimate (700-2000m) to produce a 0-2000m time series, following IPCC-AR5 (Rhein and others, 2013); (b) Spatial pattern of long-term OHC trend (W m-2) 1854–2018 (Cheng and others, 2017a). All data use a common 1981–2010 baseline. Black dot signs (in b) indicate grid boxes where trends are significant (i.e. a trend of zero lies outside the 90 per cent confidence interval).

Over the period 1998–2013, a slowdown in the increase of SST and global surface temperature led to numerous assertions about a “climate hiatus” (Hartmann, 2013). The updated SST record until 2018 (Figure 5) shows that the linear trend of SST for 1998–2018 is $1.25^{o}C \pm 0.52$ per century, greater than the linear trend during the reference (1982–1997) period ($1.00^{o}C \pm 0.46$ per century). This effectively indicates the end of the slowdown in surface temperature increase with the appearance of the extreme 2015/16 El Niño event (Hu and Fedorov, 2017). Besides, it is clear that the rate of OHC increase has increased since the late 1990s (Figure 7). The unabated increase in the rate of SST and OHC refute the concept of a slowdown of human-induced global warming.

2.4. Salinity

The studies described in the fourth and fifth IPCC Assessment Reports documented spatial patterns in near-surface and subsurface salinity that represent long-term change (Bindoff and others, 2007; Rhein and others, 2016). WOA I documented the marked long-term multi-decadal changes to global ocean salinity through the historical period (United Nations, 2017).

These studies provide clear evidence that in the near-surface, high-salinity subtropical ocean regions and the entire Atlantic basin have become more saline, and low-salinity regions, such as the West Pacific Warm Pool, and high latitude regions have become fresher when comparing the earlier historical (~1950s) to present-day salinities (e.g. Boyer and others, 2005; Hosoda and others, 2009; Durack and Wijffels, 2010; Helm and others, 2010; Skliris and others, 2014). The pattern of changes reflects an amplification of the climatological mean salinity and has been linked through model simulations (e.g. Durack and others, 2012, 2013; Terray and others, 2012; Vinogradova and Ponte, 2013; Durack, 2015; Levang and Schmitt, 2015; Zika and others, 2015) to indicate a coincident amplification of the atmospheric water cycle (e.g. Held and Soden, 2006).

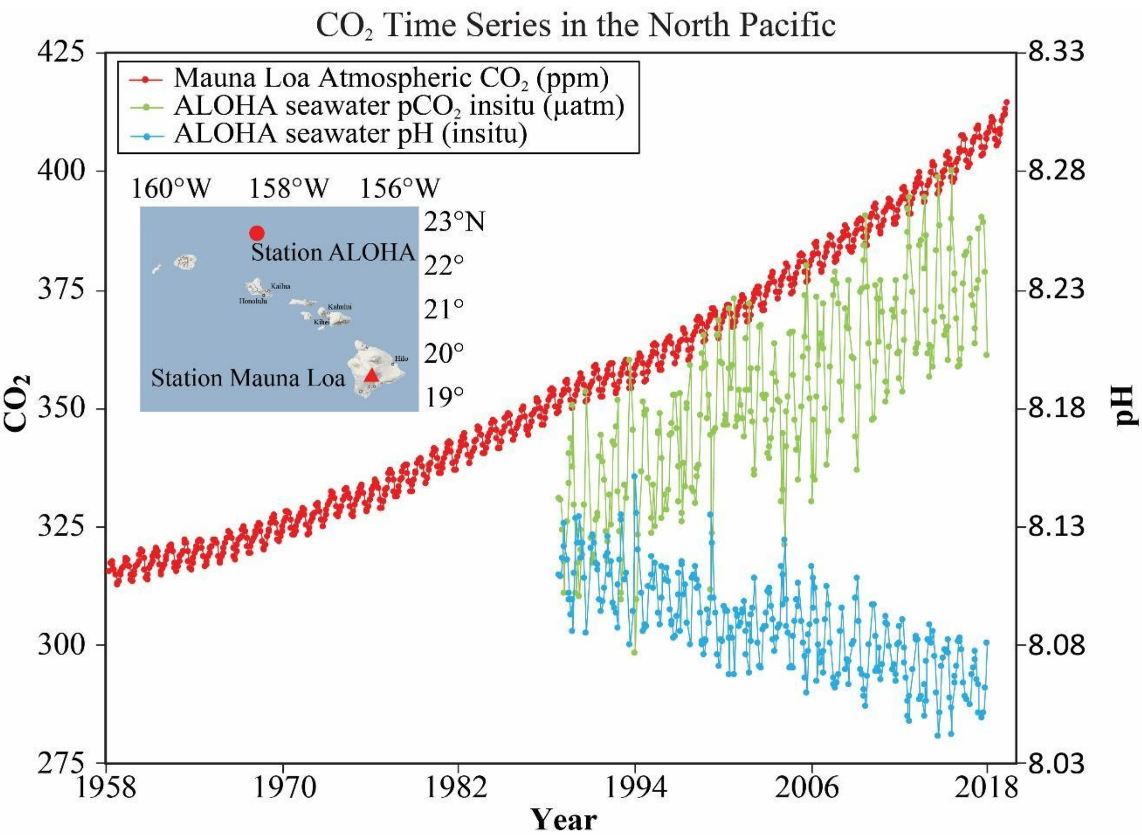
While long-term historical assessments of change are complicated by the sparse observing network extending back into the mid-twentieth century, recent assessments leverage the comprehensive global ocean coverage of Argo profile data from 2008 to near present. As these modern observations provide only ten years of temporal coverage (2008 to present), estimated changes are more strongly impacted by unforced variability modes which influence ocean salinity regionally more than long-term estimates, but their spatial and temporal coverage allows for more accurate estimates of change. The latest Argo-only analyses have shown for the first time that nearly all 2017 Atlantic 0 to 1500m salinity anomalies are positive (> 0.05 PSS-78), mirroring the long-term trends noted above, with the Pacific showing a general freshening, just like long-term trends.

Since WOA I (United Nations, 2017), salinity retrievals from the Soil Moisture and Ocean Salinity (SMOS), Aquarius and Soil Moisture Active Passive (SMAP) satellites (e.g. Berger and others, 2002; Lagerloef and others, 2008; Tang and others, 2017) have become more prominent. While satellite salinity is only available since 2010, and work is ongoing to intercompare and homogenize data products across satellite platforms, these are beginning to provide key insights into ocean salinity variability due to precipitation events (e.g. Boutin and others, 2013, 2014; Drushka and others, 2016). In addition, the comparative high temporal and spatial coverage of satellite salinity, when contrasted to the in-situ platforms (e.g. Argo), for the first time provides insights into the water cycle interactions with the terrestrial and oceanic water cycles, such as the Amazon outlet plume (Grodsky and others, 2014).

Considering all available analyses, it is extremely likely that near-surface and subsurface salinity changes have occurred across the globe since the 1950s. A salinity pattern amplification is apparent, with fresh regions becoming fresher, and salty regions saltier, and is supported by all available observational studies that have considered salinity change since the advent of instrumental records. For example high latitude oceans have shown significant rates of freshening (eg Friedman et al, 2017). More modern assessments are currently too short to confirm consistent changes over the past decade. However, the most recent analyses suggest consistent patterns are beginning to emerge for the Atlantic and, to a lesser degree, the upper Pacific Ocean basins.

2.5. Ocean acidification

Global surface ocean pH has declined on average by approximately 0.1 since the Industrial Revolution (Caldeira and others, 2003), an increase in acidity of about 30 per cent. Ocean pH is projected to decline, approximately, by an additional 0.2-0.3 over the next century (Caldeira and others, 2003; Feely and others, 2009) unless global carbon emissions are significantly curtailed. These changes can be observed in extended ocean time series (Figure 8) and the rate of change is likely unparalleled in at least the past 66 million years (Hönisch and others, 2012; Zeebe and others, 2016). Carbonate chemistry varies according to large-scale oceanic features including depth, distance from continents due to land influence, upwelling regime, freshwater/nutrient input and latitude (Jewett and Romanou, 2017). Due to this variability, as determined by these various characteristics, only longer term, observational time series can detect the predicted long-term increase in acidity at individual sites due to rising atmospheric CO_2 levels. Time of emergence of the signal varies from 8 to 15 years for open ocean sites, and 16 to 41 years for coastal sites (Sutton and others, 2019), making it necessary to commit to long-term observational records, especially in the coastal zone where most commercially and culturally important marine resources reside.



Data: Mauna Loa (ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_mm_mlo.txt) ALOHA (http://hahana.soest.hawaii.edu/hot/products/HOT_surface_CO2.txt)
Ref: J.E. Dore et al, 2009. Physical and biogeochemical modulation of ocean acidification in the central North Pacific. *Proc Natl Acad Sci USA* **106**:12235-12240.

Figure 8. Trends in surface (< 50 m) ocean carbonate chemistry calculated from observations obtained at the Hawaii Ocean Time-series (HOT) Program in the North Pacific over 1988–2018. The figure shows the linked increase in atmospheric (red points) CO_2 concentrations, seawater (green points) pCO_2 concentrations and a corresponding decline in seawater pH (blue points, secondary y-axis). Ocean chemistry data were obtained from the Hawaii Ocean Time-series Data Organization and Graphical System (HOT-DOGS) (Figure source: NOAA PMEL Carbon Program).

It has now been documented that ocean acidification is making it harder for some marine organisms such as corals, oysters and pteropods (Hoegh-Guldberg and others, 2017; Lemasson and others, 2017; Bednarsek and others, 2016; Feely and others, 2004; Orr and others, 2005) to form calcium carbonate shells and skeletons. In some cases, ocean acidification has also been shown to lower fitness in some species such as coccolithophores, crabs and sea urchins (Campbell and others, 2016; Dodd and others, 2015; Riebesell and others, 2017; Munday and others, 2009). Although individual species, when tested, are vulnerable to ocean acidification in laboratory settings, how this is going to translate into changes in actual ecosystems and species populations remains unclear and mostly undocumented (McElhany, 2017). Research efforts over the past decade have begun to build understanding of how marine species, ecosystems and biogeochemical cycles may be influenced by ocean acidification alone and in concert with other stressors, including eutrophication, warming and hypoxia (Baumann, 2019; Murray, 2019). The interactions of ocean acidification in coastal zones with coastal processes, such as upwelling of undersaturated water and land-based nutrient influxes, has become a high priority area of research (Borgesa and Gypensb, 2010; Feely and others, 2008). Natural variability in carbonate chemistry, such as coastal upwelling and seasonal fluctuations in primary productivity, is compounded by anthropogenic changes to create particularly extreme ocean acidification conditions in some regions of the global ocean (Feely and others, 2008; Cross and others, 2014). Intensive national and international efforts focused on carbonate chemistry monitoring, biological observations and biogeochemical/ecological forecast modelling over the past decade have shed light on the status and impacts of ocean acidification on local to global scales. Gaps in the current understanding of ocean chemistry are being addressed through global monitoring capacity-building efforts, such as the Global Ocean Acidification Observing Network (GOA-ON), increased biological impact studies and biogeochemical ecosystem modelling.

2.6. Dissolved oxygen

Since chemical analysis methods have essentially not changed (Carpenter, 1965; Wilcock and others, 1981; Knapp and others, 1991), long-term oceanic oxygen trends can be estimated fairly robustly, in case of sufficient data coverage. Dissolved oxygen samples are analysed by Winkler titration, which was established in 1903 and used since to calibrate all means of oceanic dissolved oxygen measurements. This allows a robust analysis of long-term trends in all areas with sufficient data coverage. Modern Winkler titration is computer aided, providing analysis with higher accuracy, though a bias of historic measurements could not be shown (Schmidtko and others, 2017). The postulated possible bias of 0.5 per cent reagent changes (Knapp and others, 1991) was tested on a global oxygen data set and found very unlikely, since the mapped pattern of oxygen change for a deliberately introduced bias does not match any observed pattern (Schmidtko and others, 2017).

In the open ocean, most regional long-term series data show a small long-term decrease despite temporal variations on many timescales (e.g. Keeling and others, 2010; Whitney, 2007). Increasing oxygen levels are found only in very limited time series (Keeling and others, 2010). Coastal changes have mostly been fuelled by riverine runoff of fertilizers but in some cases may have been affected by the larger-scale oxygen changes. These can lead to an increased occurrence of dead zones with consequences for regional ecology and economy (Diaz and Rosenberg, 2008).

Globally, the ocean has been losing oxygen in recent decades. Both methods, comparing decadal oxygen data snapshots and local regression analyses (Schmidtko and others, 2017; Ito and others, 2017), show large-scale oxygen declines (Figures 9a and 9b). Despite various methods, the derived rates agree within the same water layers and given uncertainties. Deoxygenation rates vary with depth and region, resembling the manifold processes modifying the oxygen content, with isolated regions showing an increase of oxygen. The overall oxygen budget has decreased by 2 per cent in the last five decades, a loss of 4.8± 2.1 petamoles since 1960 (Schmidtko and others, 2017). In the upper water column, temperature-driven solubility decrease is dominating (Figure 9c). For the period 1970–2010, the upper 1000m oxygen concentration has decreased by 0.046±0.047 $\mu mol\ l^{-1}\ yr^{-1}$ including a solubility change of 0.025 $\mu mol\ l^{-1}\ yr^{-1}$ (Schmidtko and others, 2017). Analysing shallower layers increases the solubility-related change significantly (Figure 9c), in accordance with the heat gain in the upper water column (see (c) above,). However, for the full ocean column, solubility-driven changes from 1970–2010 are small, -0.006 μmol l^{-1} yr^{-1} compared to the overall oxygen loss 0.063±0.031 μmol l^{-1} yr^{-1}. Nevertheless, temperature cannot be ruled out as the key source of these changes, via mechanisms other than solubility change. These mechanisms include stratification increase, circulation changes and thermal impacts on biogeochemical cycles (e.g. Keeling and Garcia, 2002; Bianchi and others, 2013; Stendardo and Gruber, 2012).

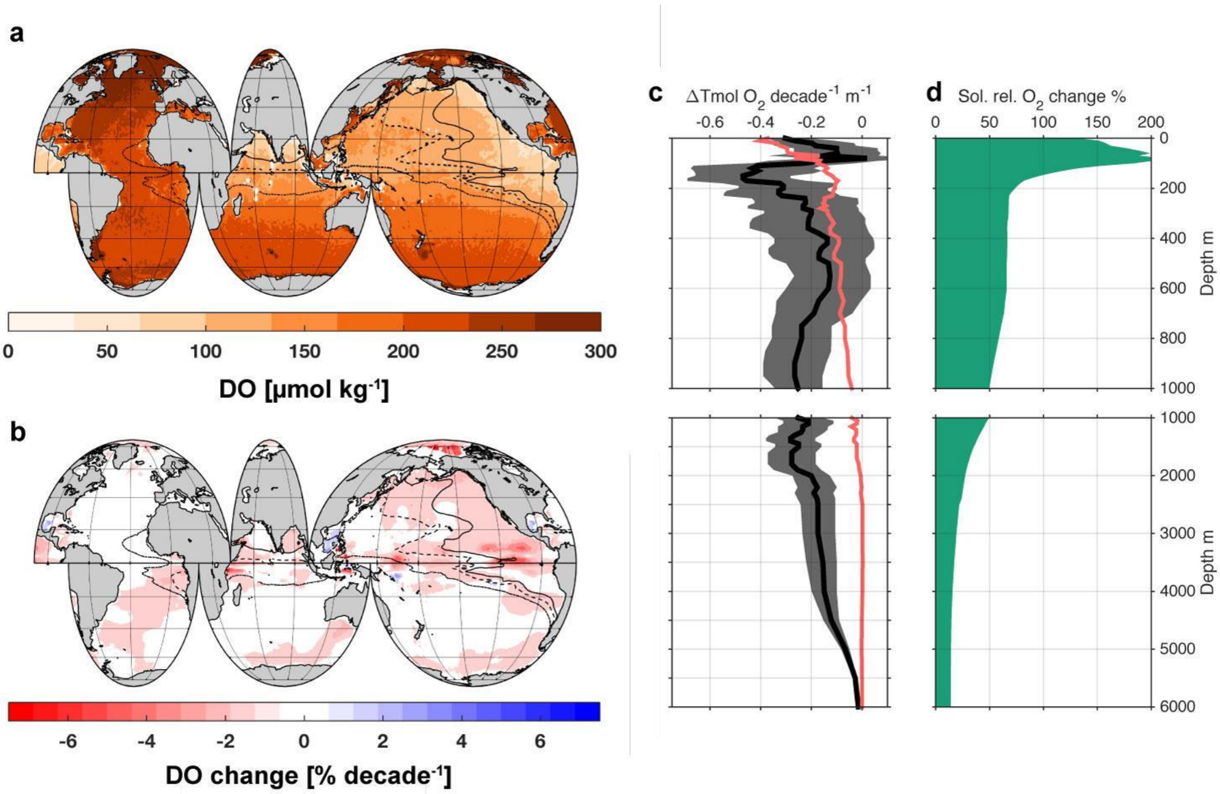


Figure 9. Global oxygen distribution and change based on Schmidtko and others (2017) data. (a) Mean dissolved water column oxygen concentration. (b) Dissolved oxygen changes in per cent per decade. Solid, dotted and dashed lines in (a) and (b) indicate the presence of low oxygen 40, 80 and 120 umol l^{-1} at some depth within the water column. (c) Vertical distribution of oxygen loss per decade oxygen change (black line) with the error as the grey envelope, the red line indicates the loss expected from temperature-driven solubility changes. (d) Water column cumulative oxygen loss due to solubility change as a percentage of observed deoxygenation. Solubility changes above 100 per cent are due to processes that increase upper ocean oxygen content and counteract warming (after Schmidtko and others, 2017).

The area of oxygen minimum zones has typically been expanding in recent decades, although there is significant regional variability (Diazand Rosenberg, 2008). Oxygen minimum zones have potential impacts on climate change because they emit large quantities of nitrous oxide, a potent greenhouse gas, due to denitrification processes under anoxic conditions (e.g. Codispoti, 2010; Santoro and others, 2011). In particular, oxygen minimum zones have increased in the Pacific and Indian Oceans.

2.7. Sea ice

Sea ice in the Arctic has been one of the most iconic indicators of climate change. During boreal winter, the areal extent of Arctic sea ice reaches a maximum area of 15.4 x 10^6 sq. km. in March and, during boreal summer, this area declines to 6.4 x 10^6 sq. km. in September.

Arctic sea ice areal extent is declining by -2.7 +/- 0.4 %/decade during winter (March 1979–2019), and -2.8 ± 2.3 %/decade during summer (September 1979–2018, Figure 10; Feterrer and others, 2017). While the decreasing trends during winter are more evenly distributed around the pole, the summer trends are almost twice as high in the Pacific Sector of the Arctic Ocean (upper right of maps, Figure 10). In this area, the changes in wind related to the Arctic Oscillation have been increasingly blowing the ice away from coastal areas and into the North Atlantic (Rigor and others, 2002), leaving in its wake a much younger and thinner ice pack (Rigor and others, 2004). The thickness of Arctic sea ice has decreased by at least 40 per cent (Rothrock and others, 1999, comparing submarine observations from 1958/76 and 1993797)), and Kwok (2018) shows that these changes persist through today. The observed trends in sea ice extent (area) and thickness together indicate that the volume of Arctic sea ice has decreased by over 75 per cent since 1979. This estimate is coincident with many modelling studies, for example, using the Pan-Arctic Ice Ocean Modeling and Assimilation System (Zhang and Rothrock, 2003; Schweiger and others, 2011) estimate that the average volume of Arctic sea ice of 11.5 x 10^3 km^3 in September, 1979–2017, has decreased by -2.8 × 10^3 km^3 $decade^{-1}$, with the record minimum in total ice volume set in 2010.

In Antarctica, sea ice advances to its maximum extent of 19 - 20 x 10^6 sq. km. in September (austral winter) and decreases to a minimum of 3 x 10^6 sq. km. in February (austral summer). The trends in Antarctic sea ice extent are 0.6 ± 0.6 %/decade during summer (February 1979–2019); 1.1 ± 3.7 %/decade during winter (September 1979–2018). Net Antarctic sea-ice extent showed a statistically significant increase from 1979-2015. From 2016 onwards, net Antarctic sea-ice extent has been consistently below average and set new record low values. Given that this sudden variability in Antarctic sea-ice cover is largely attributed to changes in the ocean mixed layer, it is highly relevant to expand this explanation. See for example, Meehl et al. 2019, and Reid et al. 2019. The net overall changes in sea-ice cover have been very regionally variable. This dichotomy between Arctic and Antarctic sea ice has been attributed to limits imposed by geography. During winter, the maximum extent of sea ice is imposed by the Antarctic Circumpolar Currents and the underlying bathymetry of the Southern Ocean (Nghiem and others, 2016) and, during summer, the sea ice can only retreat to the edge of the Antarctic continent. However, Figure 10 (bottom row), shows that, regionally, the trends are more pronounced. During summer, sea ice extent is increasing in the Weddell Sea but decreasing in the Bellinghausen and Amundsen seas (West Antarctica) where the ice sheet is more vulnerable to ocean processes. These regional trends in sea ice extent have been related to changes in wind (and ocean currents), related to the Southern Annular Mode and ENSO (Parkinson, 2019, and references therein). The 40-y record reveals gradual Antarctic sea ice increases followed by decreases at rates far exceeding the rates seen in the Arctic.

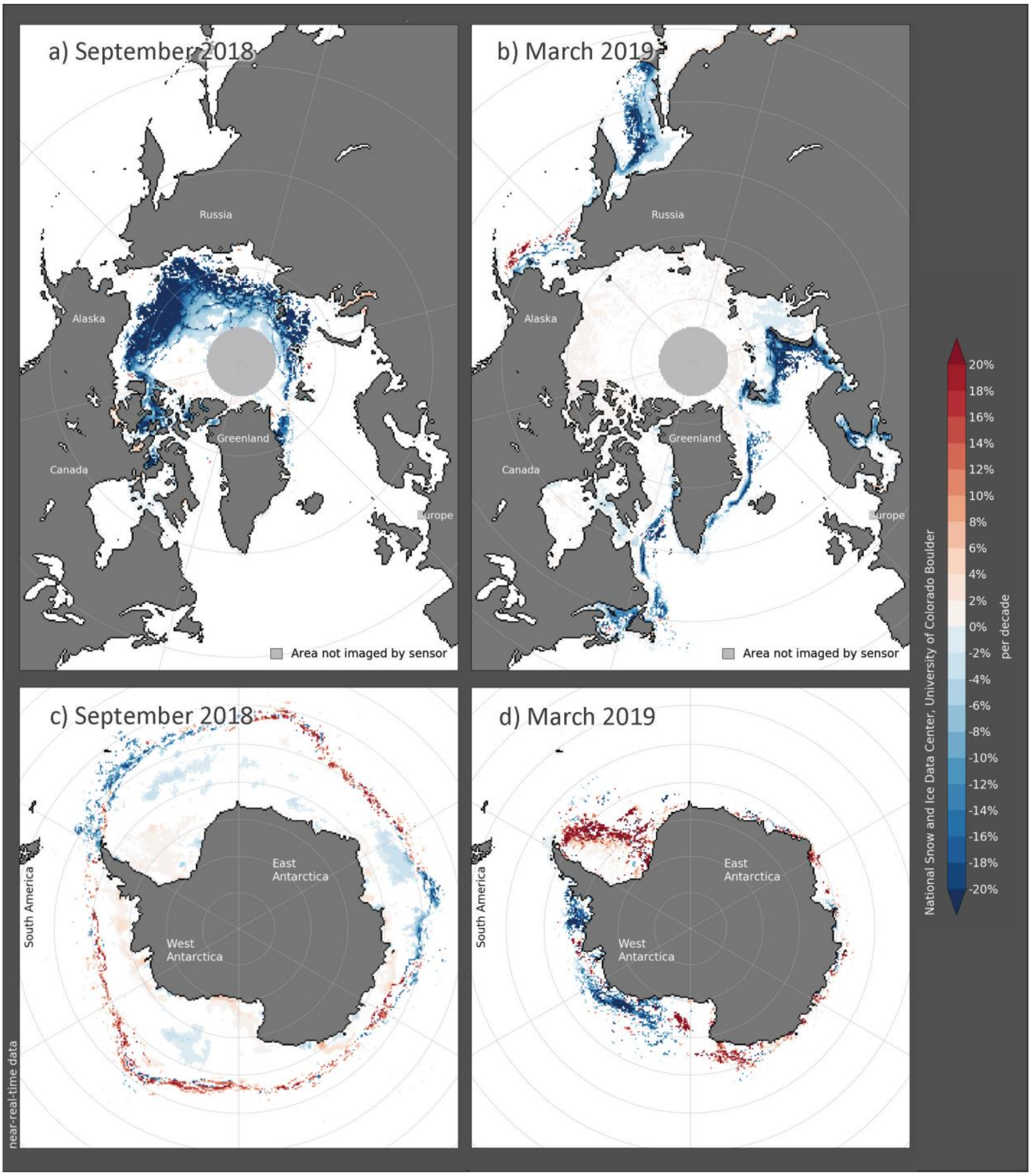


Figure 10. Arctic and Antarctic sea ice concentration trends (per cent per decade). Trends for the Arctic are shown in the top row, for Antarctic in the bottom row, for September 1979–2018 in the left column, and for March 1979–2019 in the right column. Maps were provided by the National Snow and Ice Data Center, University of Colorado, Boulder; Fetterer and others, 2017.

Since sea ice floats on the ocean, the contribution of melting sea ice to sea level rise is negligible. However, sea ice acts as a shield, keeping insolation from warming the ocean, and acts as a buttress for land ice which terminates over the ocean, keeping warm waters and waves from the ocean from eroding the ice sheet (Masson and others, 2018). The loss of sea ice has made many ice sheets more vulnerable and increased the rate of sea level rise due to the melt of these terrestrial ice sheets (e.g. Stewart and others, 2019).

3. Knowledge gaps

3.1. Sea level

Unlike global mean and regional sea level measured by satellite altimetry missions, coastal sea level changes remain poorly known. Coastal zones are indeed highly undersampled by tide gauges and currently unsurveyed (within ten kilometres from the coast) by conventional altimetry missions because of land contamination on the radar signal (Cipollini and others, 2018). However, dedicated reprocessing of the data from these missions now allow for estimating sea level change very close to the coast (Marti and others, 2019). In the near future, systematic use of new synthetic aperture radar technology implemented in recent European Space Agency missions (e.g. CryoSat-2 and Sentinel-3) will also allow for estimating sea level changes very close to the coast.

3.2. Ocean circulation

Some limitations remain for the current ocean observation network, particularly for coastal regions, marginal seas and deep ocean regions below 2000m. It is important to establish a deep ocean system in the future to monitor ocean changes below 2000m, thus to provide a complete estimate of the Earth’s energy imbalance (Johnson and others, 2015). Currently, boundary currents are not fully represented by Argo, as floats can swiftly pass through the energetic regions, e.g. western boundary current and ACC regions, which could induce an inverse cascade of kinetic energy and affect the large scale low-frequency variability (Wang and others, 2017). Achieving adequate sampling will require an observing system design based on a mixture of observing technologies adapted to the different operating environments. There is a need to develop/maintain multiple platform observations for cross-validation and calibration purposes (Meyssignac and others, 2019), including the validation of climate models.

3.3. Sea surface temperature and ocean heat content

Temperature records are regulated by the modes of natural climate such as the Pacific Decadal Oscillation (PDO) (England and others, 2014; Kosaka and Xie, 2013), El Niño-Southern Oscillation (ENSO) (Cheng and others, 2018) and the Atlantic Multi-decadal Oscillation (AMO) (Garcia-Soto and Pingree, 2012). The caveat of observation-based analyses is that the record is still too short: i.e., the typical period of AMO and PDO is 30~70 years, similar to the length of the reliable OHC record (~60 years since the late 1950s). Combined analyses of models and observations are the proposed way forward (Cheng and others, 2018; Liu and others, 2016) to better understand the SST and OHC change and variability on different timescales. Lack of global long-term surface energy flux observations is an additional challenge that prevents fully understanding of the SST and OHC changes. There is insufficient knowledge of ENSO mechanisms and feedbacks as well as ENSO diversity related to global warming. .

3.4. Salinity

While the observed salinity changes appear robustly in all observation-based analyses to date, knowledge gaps exist in the definite source of these changes, particularly in near-coastal regions which are linked to terrestrial and cryospheric water reservoirs. Many observational and model studies have conclusively linked open ocean changes to surface-forced water cycle change, with coincident enhancement of evaporation and precipitation patterns as the primary driver of change. Continued changes will have significant impacts on marine ecosystems, including effects on life-cycle timing, fitness and survivability of ecologically and economically important species.

3.5. Ocean acidification

More research is needed to better inform models and improve predictions of the Earth system response to ocean acidification, its impacts on marine populations and communities and the capacity of organisms to acclimate or adapt to the changes in ocean acidification-induced ocean chemistry. There remains a strong need for more extensive monitoring in coastal regions, and high quality, low-cost sensors to do this monitoring, increased access to satellite data and research into the long-term trends in ocean chemistry beyond the observational record (paleo-OA). A good example is the extension of the Argo Program to include biogeochemical parameters including PH (https://biogeochemical-argo.org/).

3.6. Sea ice

Maintaining the in situ observing networks in the polar regions is a challenge due to the harsh environment and access being typically limited to the spring and summer seasons. Retrievals of geophysical parameters by satellite are improving, but in situ observations are required to validate these retrievals. In particular, in situ measurements of snow on sea ice, and the thickness of sea ice, are invaluable to advancing understanding of physical processes in the polar regions. These measurements are rare in the Arctic, and even more so in the Antarctic.

4. Summary

Ocean warming, together with land ice melt, are the main causes of present-day accelerating global mean sea level rise. The global mean sea level has been rising since 1993 (the altimetry era) at a mean rate of 3.1 +/- 0.3 mm/yr, with a clear superimposed acceleration of ~ 0.1 mm/yr^2. Satellite altimetry has also revealed strong regional variability in the rates of sea level change, with regional rates up to two or three times larger than the global mean in some regions. Due to global warming, many circulation systems also experience changes.

Changes in sea level height, measured with high-precision satellite altimetry, hint to a widening and strengthening of the subtropical gyres in the North and South Pacific. The studies, furthermore, show a poleward movement of many ocean currents, including the Antarctic Circumpolar Current and the subtropical gyres in the Southern Hemisphere, as well as western boundary currents in all ocean basins. One of the major ocean current systems, the Atlantic Meridional Overturning Circulation, has already weakened and will very likely continue to do so in the future. Impacts that follow these changes include regional sea level rise, changes in nutrient distribution and carbon uptake and feedbacks with the atmosphere.

The globally averaged ocean surface temperature data show a warming of 0.62 ± 0.12^{o}C per century over the period 1900–2018. In the recent two decades (2009–2018), the rate of ocean surface warming is 2.56 ± 0.68^{o}C per century. The warming happens in most ocean regions, with some areas, for example in the North Atlantic, showing long-term cooling. Since 1955, the upper 2000m of the ocean has also exhibited signs of robust warming, as evidenced by the increase in ocean heat content.

The spatial patterns of multi-decadal salinity changes provide convincing evidence of global-scale water cycle change over the world's oceans coincident with warming over the period. The resolved changes are replicated in all observed analyses of long-term salinity changes, and more recently have been reproduced in forced climate model simulations. These changes manifest in enhanced salinities in the near-surface, high-salinity subtropical regions and corresponding freshening in the low-salinity regions such as the West Pacific Warm Pool and the poles. Similar changes are also seen in the ocean subsurface, with similar patterns of freshening low-salinity waters and enhanced high-salinity waters represented in each of the ocean basins, Atlantic, Pacific and Indian and across the Southern Ocean.

Global surface ocean pH has declined on average by approximately 0.1 since the Industrial Revolution, an increase in acidity of about 30 per cent. Ocean pH is projected to decline by, approximately, an additional 0.3 over the next century unless global carbon emissions are significantly curtailed. These changes can be observed in extended ocean time series and the rate of change is likely unparalleled in at least the past 66 million years. Time of emergence of the signal varies from 8 to 15 years for open ocean sites, and 16 to 41 years for coastal sites, making it necessary to commit to long-term observational records, especially in the coastal zone where most commercially and culturally important marine resources reside.

Oceanic oxygen levels have declined over the last decades with strong regional variations. While the overall oxygen content has decreased by about 2 per cent in five decades, oxygen in coastal areas or near oxygen minimum zones show larger variations. Coastal changes are mostly fuelled by riverine runoff, and the open ocean changes are likely related to a combination of changes in ocean circulation and biogeochemical cycles. Temperature-driven solubility decrease is responsible for most near-surface oxygen loss, while other processes have to be accountable for deep ocean oxygen loss. A further decrease of oxygen in and near oxygen minimum zones can lead to climate feedback via consequent greenhouse gas emission.

Sea ice covers 15 per cent of the global oceans and affects global heat balance and global thermohaline circulation. Total sea ice extent has been declining rapidly in the Arctic, but trends are insignificant in the Antarctic. Arctic sea ice extent is declining by -2.7 +/- 0.4 %/decade during winter, and -2.8 +/- 2.3 %/decade during summer. In contrast, trends in total Antarctic sea ice extent are insignificant, 0.6 +/- 0.6 %/decade during summer and 1.1 +/- 3.7 %/decade during winter. Regionally, the spatial distribution of these trends is dramatic. In the Arctic, the summer trends are most striking in the Pacific sector of the Arctic Ocean, while in the Antarctic, the summer trends show increases in the Weddell Sea and decreases in the West Antarctic sector of the Southern Ocean. The spatial distribution of the changes in sea ice is attributed to changes in wind and ocean currents related to the Arctic Oscillation in the northern hemisphere, Southern Annular Mode and El Niño in the southern hemisphere.

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Chapter 6
Trends in the biodiversity of main taxa of marine biota

Introduction

In the First World Ocean Assessment (WOA I) published in 2015, biological diversity was considered from three viewpoints: by geographic region, by taxonomic group and by habitats identified as provoking concern. In the Second World Ocean Assessment (WOA II), biological diversity is considered by taxonomic group (Chapter 6) and by habitats (Chapter 7) for all regions where data are available. For the taxonomic groups that were included in WOA I, the focus is on changes that have occurred since the Assessment, including new information. For the taxonomic groups that were not included in WOA I, the focus is on general information in order to establish a baseline on current state.

Chapter 6A expands on information contained in WOA I on plankton by describing the biodiversity of this group, and, in particular, provides information on single-celled phytoplankton, bacteria, viruses and metazoan zooplankton. Information on benthic invertebrates, which were not separately discussed in WOA I, is described in the present assessment in Chapter 6B. Among the pelagic invertebrates, planktonic forms are included in Chapter 6A. Pelagic invertebrates (Cephalopods) remains as gap in this assessment that needs to be filled in the future assessment. Information on this pelagic invertebrate is added as addendum to 6B by the Group of Experts. New and expanded information on fish diversity, particularly in relation to those species not considered by WOA I, is included in Chapter 6C. Chapter 6 also includes information on recent changes in the biodiversity of marine mammals (Chapter 6D), marine reptiles (Chapter 6E), seabirds (Chapter 6F), and marine plants and macroalgae (Chapter 6GH) with the latter incorporating trends in the condition of kelp forests and algal beds. Marine plants are also described in Chapters 7I–7K from the viewpoint of habitats.

Chapter 6A
Plankton (Phytoplankton, Zooplankton, Bacteria and Viruses)

Convener: Thomas Malone; Contributors: Maurizio Azzaro, Russell Hopcroft, Chul Park (Lead Member), Kazuaki Tadokoro, Michael Thorndyke, Sinjae Yoo

Keynote points

- Single-cell microbes are the most abundant and diverse form of marine life. Food webs based on them sustain most ocean biodiversity.

- Marine phytoplankton account for ~ 50 per cent of the Earth's primary production, oxygen supply and N_2-fixation. Diatoms and picoplankton (<2µm) account for most marine primary production.

- Driven by upper-ocean warming, increases in the vertical separation of layers of water (stratification) and decreases in inorganic nutrient inputs to the part of the ocean where photosynthesis is possible (the euphotic zone) are likely to result in:
    - decreases in phytoplankton productivity and cell size;
    - increases in energy flow through microbial food webs relative to that through metazoan food webs (plankton >20µm);
    - decreases in the export of production to the deep ocean. Such decreases would reduce the ocean's capacity to absorb CO_2, accelerating global atmospheric warming;
    - decrease in biological production of higher trophic level.

- Climate-driven ocean acidification may reduce the abundance and distribution of calcareous plankton.

- Current global ocean observations do not explicitly monitor plankton diversity. An international, integrated observing system of ocean life is needed as a component of the Global Earth Observing System of Systems.

1. Introduction

Marine plankton communities are comprised of viruses, prokaryotes (archaea and bacteria) and eukaryotes (protists and metazoa). Prokaryotes and eukaryotes include both primary producers and heterotrophic consumers, and marine plankton represent the most phylogenetically diverse group of organisms on Earth (Colomban and others, 2015; Global Patterns in Marine Biodiversity, 2017). We focus here on plankton assemblages of the upper ocean (0-1000 m) and climate-driven changes in plankton that are most likely to impact ecosystem services.

Unicellular microbes account for most biomass, biodiversity and metabolic activity in the oceans (Gasol and others, 1997; Azam and Malfatti 2007; Salazar and Sunagawa, 2017; Bar-On and others, 2018), and play critical roles in the provision of marine ecosystem services

(Palumbi and others, 2009; Liquete and others, 2013). In particular, phytoplankton account for ~ 50 per cent of the Earth's net primary production (NPP) that fuels marine food webs and for ~50 per cent of the Earth's oxygen supply (Field and others, 1998; Westberry and others, 2008); and planktonic food webs support most fisheries (Blanchard and others, 2012; Boyce and others, 2015), fuel the biological pump[57] (Honjo and others, 2014) and sustain biodiversity (Beaugrand and others, 2013; Vallina and others, 2014). Phytoplankton NPP and the flows of nutrients through planktonic food webs make significant contributions to at least 14 Sustainable Development Goals (Wood and others, 2018), of which "Goal 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development" is the most relevant. [58]

The objectives of this chapter are to (i) describe the current composition of plankton assemblages and past trends in their diversity and productivity at global and regional scales; (ii) summarize predicted, climate-driven trends in these plankton assemblages; and (iii) identify gaps in current knowledge. The climate-driven changes in the upper ocean environment targeted here are ocean warming and ocean acidification.[59] This information is particularly relevant to Chapters 5 (trends in the physical and chemical state of the ocean) and 10 (changes in inputs of nutrients to the marine environment). Subjects addressed here that were not explicitly addressed in Chapter 6 of the First World Ocean Assessment (WOA I) (United Nations, 2017) include past and projected trends in the diversity of plankton.

2. The First World Ocean Assessment (2016), summary of Chapter 6

Regional and global patterns of NPP by phytoplankton and benthic macrophytes, nutrient cycling in the upper ocean, and anthropogenic impacts on these processes were addressed:

- With the exception of coastal waters subject to riverine inputs of nutrients and High Nutrient Low Chlorophyll (HNLC) zones, the global pattern of phytoplankton NPP reflects the pattern of deep-water nutrient (nitrogen and phosphorus) inputs to the euphotic zone.[60]
- Phytoplankton NPP in subtropical gyres decreased from 1998 through 2006 due to climate-driven upper ocean warming and associated decreases in nutrient supply, while NPP has increased in coastal ecosystems due to increases in land-based nutrient inputs. This has led to a global spread of hypoxia in the ocean, a decline in the spatial extent of sea grass beds, and increases in the occurrence of toxic phytoplankton events.
- Phytoplankton species diversity tends to be lowest in polar and subpolar waters, where fast-growing species account for most NPP, and highest in tropical and subtropical waters, where small phytoplankton (< 10 µm) account for most NPP.
- As the upper ocean warms and becomes more stratified, it is likely that small phytoplankton species will account for an increasingly large fraction of NPP resulting in decreases in fish stocks and organic carbon export to the deep sea.

[57] Biologically mediated export of particulate organic matter and calcium carbonate to the deep ocean (> 1000 m).
[58] See United Nations General Assembly resolution 70/1.
[59] Ocean acidification refers to a reduction in the pH of the ocean over an extended period of time, caused primarily by uptake of carbon dioxide from the atmosphere.
[60] The euphotic zone is the upper layer of the ocean over which there is sufficient light for photosynthesis to occur.

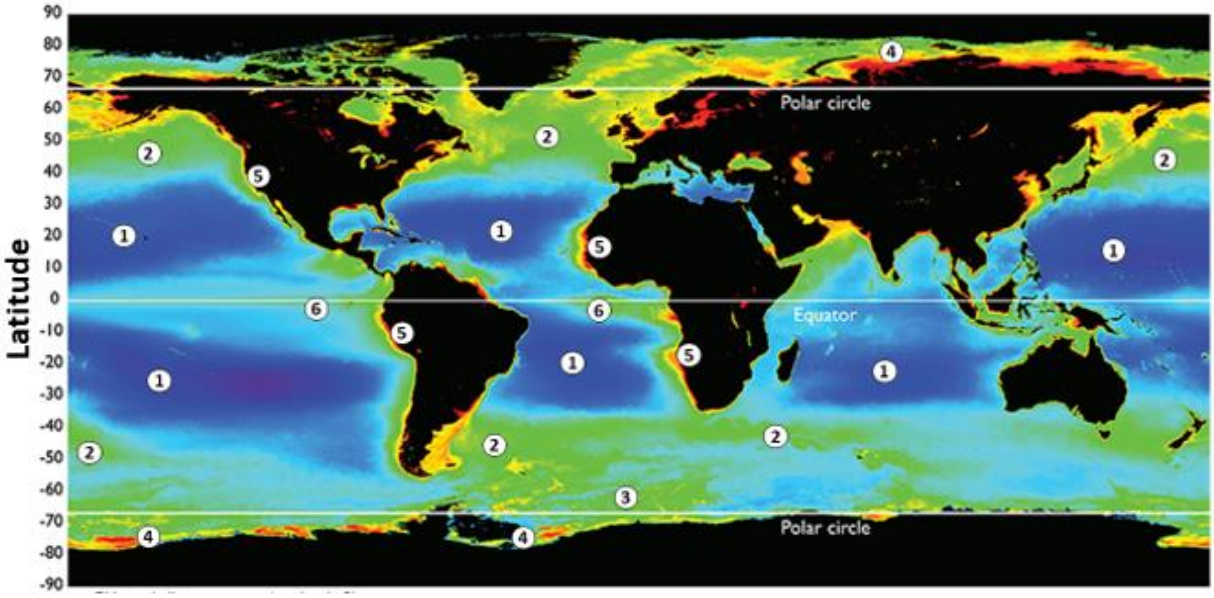
- With increases in upper ocean temperatures at high latitudes, the spatial ranges of copepod species in the North Atlantic have expanded to higher latitudes and seasonal peaks in abundance are occurring earlier in the year for temperate species.

3. Regions targeted for the present Assessment

Phytoplankton NPP varies regionally (Behrenfeld and others, 2006; Uitz and others, 2010; Malone and others, 2016), and the global ocean has been parsed by the Intergovernmental Panel on Climate Change (IPCC) into regions accordingly (Hoegh-Guldberg and Poloczanska, 2017). Of the seven regions specified by IPCC, we target those that represent high and low latitude systems, systems in which the primary input of nutrients is from deep water via vertical mixing or upwelling and systems that exhibit a broad range of trophic states[61] (that do not reflect land-based inputs of nutrients). These are as follows (numbered as in Figure 1):

1) The five subtropical central gyres, the largest biomes of the upper ocean (~ 40 per cent of the ocean's surface, 22 per cent of the ocean's annual NPP);
2) High-latitude spring bloom regions (~ 25 per cent of the ocean's surface, 43 per cent of the ocean's annual NPP);
3) Antarctic circumpolar region of the Southern Ocean (~ 12 per cent of the ocean's surface, ~ 9 per cent of the ocean's annual NPP);
4) Polar sea ice regions of the Arctic and Southern Oceans (~ 4 per cent of the ocean's surface, 1-2 per cent of ocean's annual NPP);
5) Coastal upwelling regions (~ 2 per cent of the ocean's surface, 7 per cent of the ocean's annual NPP); and
6) Equatorial upwelling regions (~ 8 per cent of the ocean's surface, 9 per cent of the ocean's annual NPP).

Collectively, these six regions encompass 90 per cent of the ocean's surface and account for 90 per cent of the ocean's NPP.



[61] From oligotrophic regions with low mean annual chlorophyll-*a* concentrations (< 0.1 mg m^{-3}) to eutrophic regions with relatively high mean concentrations ($1 - 30$ mg m^{-3}).

Figure 1. Mean sea surface chlorophyll-a concentration 1997 – 2010 (adapted from Sundby and others, 2016) and the six targeted regions for this report: 1 – central gyres, 2 – high latitude bloom regions, 3 – Antarctic Circumpolar region, 4 – Polar sea ice region, 5 – coastal upwelling, 6- equatorial upwelling (blue < 0.1 mg m^{-3}, green 0.1 – 1.0 mg m^{-3}, yellow 1 – 3 mg m^{-3}, red > 3 mg m^{-3}).

4. Estimating plankton diversity

4.1. Species diversity

Accurate estimates of plankton species diversity on regional to global scales based on microscopic examination of ocean samples are not possible at this time due to severe undersampling[62] (Appeltans and others, 2012); the rapidly growing number of cryptic species[63] revealed by metagenomics (Delong, 2009; Goetze, 2010; Lindeque and others, 2013; Harvey and others, 2017); larval stages of zooplankton that lack clear diagnostic characteristics (Bucklin and others, 2016); and a lack of consensus among microbiologists on the definition of species (Amaral-Zettler and others, 2010). The problem of undersampling can be addressed only by increasing the time-space resolution of sampling. To this end, we underscore the importance of expanding and sustaining support for the Global Alliance of Continuous Plankton Recorder Surveys (Batten and others, 2019) and for the development of an integrated ocean life observing system (Canonico and others, 2019).

4.2. Functional diversity

Grouping organisms into functional groups that share common characteristics (size and ecological roles) can be more useful ecologically than taxonomic groupings (Litchman and others, 2010; Mitra and others, 2016). The size spectrum of plankton spans over seven orders of magnitude (Boyce and others, 2015; Sommer and others, 2017) and is reflected in the pathways by which phytoplankton NPP is recycled in the upper ocean, channeled to fisheries or exported to the ocean's interior via the biological pump (Ward and others, 2012; Acevedo-Trejos and others, 2018). The size spectrum of plankton has been parsed into picoplankton (0.2 µm to 2 µm), nanoplankton (2 µm to 20 µm), microplankton (20 µm to 200 µm), mesoplankton (200 µm to 20 mm), macroplankton (20 mm to 200 mm) and megaplankton (> 200 mm) (Sieburth and others, 1978; Sommer and others, 2017). On the scale of the major ocean basins, phytoplankton biomass and the fraction of large phytoplankton generally increase as the availability of dissolved inorganic nutrients increase, a pattern that reflects the importance of nutrient supplies as a parameter of phytoplankton NPP and community composition (Mousing and others, 2018).

Functionally, marine food webs can be parsed into two categories based on the size (Fenchel, 1988; Pomeroy and others, 2007):

62 Measurements are too sparse in time and space to accurately estimate plankton biodiversity on regional to global scales.

63 Genetically distinct species, operational taxonomic units (OTUs), that do not exhibit clear morphological differences. OTUs are used to estimate species richness based on genetic differences (Caron and others, 2009).

- Microbial food webs populated by picophytoplankton and nanophytoplankton, heterotrophic bacteria and protozoan consumers that are fueled primarily by picophytoplankton NPP (including the release of dissolved organic matter by primary producers and consumers), and
- Metazoan food webs populated by microphytoplankton and metazoan plankton that are fueled primarily by microphytoplankton productivity as well as by microbial food webs.

Microbial food webs account for most living biomass and nutrient recycling in the ocean (Del Giorgio and Duarte 2002; Sunagawa and others, 2015), while metazoan food webs support most fisheries and the biological pump (Legendre and Michaud, 1998; Sommer and others, 2002). Thus, changes in the balance between these two food webs are likely to have major impacts on the provision of ecosystem services (Müren and others, 2005; Worm and others, 2006; Sommer and others, 2016).

5. Microbial plankton

5.1. Phytoplankton

Major taxa in terms of their contribution to global NPP include prokaryotic cyanobacteria and eukaryotic diatoms, coccolithophores and chlorophytes (Not and others, 2007; Simon and others, 2009; Uitz and others, 2010; Flombaum and others, 2013).

5.1.1. Diversity and functional groups of phytoplankton

Five functional groups of phytoplankton have been recognized based on their size and roles in pelagic food webs and nutrient cycles (Chisholm, 1992; Le Quéré and others, 2005; Marañón and others, 2012): photosynthetic picoplankton; silicifying microplankton; calcifying nanoplankton; nitrogen fixing mesoplankton; and dimethyl sulphide-producing nanoplankton. For the purposes of this chapter, toxic microplankton have been added to this list. Changes in the relative abundance, productivity and toxicity of these functional groups have major repercussions for capacity to support ecosystem services.

5.1.1.1. Picoplankton

Picoplankton include two genera of cyanobacteria (*Prochlorococcus* and *Synechococcus*) and a diverse ensemble of picoeukaryotes from several phyla (Not and others, 2007; Kirkham and others, 2013). They are globally ubiquitous, account for ~ 50 per cent of the ocean's NPP (Agusti and others, 2019) and fuel microbial food webs (Marañón and others, 2001, 2015). It is estimated that *Prochlorococcus* accounts for 17–39 per cent, *Synechococcus* for 12–15 per cent and picoeukaryotes for 49–62 per cent of picoplankton biomass globally (Buitenhuis and others, 2012). *Prochlorococcus* dominates the phytoplankton in warm (>15 °C), nutrient-poor waters (Chisholm, 2017). *Synechococcus* has a broader, more uniform distribution and is more abundant than *Prochlorococcus* under cooler, nutrient-rich conditions (Follows and others, 2007; Flombaum and others, 2013). Picoeukaryotes tend to increase in abundance with increasing nutrient levels, often dominating the phytoplankton at high latitudes (Li, 1994; Worden and Not, 2008; Kirkham and others, 2013). Underlying their broad geographic distribution, these organisms exhibit extraordinary amounts of genomic diversity (Vaulot, 2008; Kent and others, 2016).

5.1.1.2. Silicifying microplankton: Diatoms

Diatoms dominate microphytoplankton in cold, turbulent, nutrient-rich waters (Malone, 1980; Rousseaux and Gregg, 2015). They account for 40–50 per cent of global marine NPP, fuel metazoan food webs and account for ~ 40 per cent of carbon export via the biological pump (Honjo and others, 2014; Tréguer and others, 2018). Diatoms are, therefore, important players in the global carbon cycle.

5.1.1.3. Calcifying nanoplankton[64]

Coccolithophores (dominated by *Emiliania huxleyi*) are globally ubiquitous, function as both a sink for CO_2 (photosynthesis) and a source of CO_2 (calcification) and are, therefore, important players in the global carbon cycle (Sarmiento and others, 2002; Balch and others, 2016). *E. huxleyi* forms the "great calcite belt" that surrounds Antarctica between the subantarctic and polar fronts (Balch and others, 2016; Nissen and others, 2018). There is evidence that *E. huxleyi* produces more biogenic $CaCO_3$ than any other organism on Earth (Iglesias-Rodríguez and others, 2002). Blooms tend to occur following seasonal diatom blooms (Brown and Yoder, 1994; Smith and others, 2017). *E. huxleyi* harbors a pan genome of extensive genetic variability that underpins its cosmopolitan distribution and its capacity to bloom under a wide variety of environmental conditions (Read and others, 2013).

5.1.1.4. Nitrogen fixing mesoplankton[65]

Planktonic cyanobacteria account for about half of the Earth's N_2-fixation (Karl and others, 2002; Landolfi and others, 2018) and are the largest source of fixed nitrogen in the global ocean (Galloway and others, 2004; Gruber, 2004). The group includes unicellular symbionts (diatom-diazotroph associations) and colonial genera (e.g., *Trichodesmium*) (Delmont and others, 2018; White and others, 2018). Most marine nitrogen fixation occurs in the subtropical gyres (Gruber, 2019) where *Trichodesmium* is most abundant at temperatures above 20°C (Breitbarth and others, 2007; Monteiro and others, 2010).

[64] Calcifying plankton include taxa that create shells, skeletons or other structures from calcium carbonate. This is taxonomically diverse group that includes phytoplankton such as coccolithophores, zooplankton such as pteropods and the larval stages of benthic bivalve molluscs and echinoderms.
[65] N-fixation is not limited to mesozooplankton. There is evidence that there are non-cyanobacterial diazotrophs (bacteria and archaea) in the oceans (Benavides and others, 2018).

5.1.1.5. DMSP[66] producing nanoplankton

Over 90 per cent of DMS emissions to the atmosphere come from DMSP produced in the ocean, most of which is produced by Prymnesiophyceae (e.g., *Phaeocystis* spp. and *E. huxleyi*) and Dinophyceae (e.g., *Prorocentrum minimum*) during blooms (Keller and others, 1989; Bullock and others, 2017). *Phaeocystis* is a cosmopolitan genus with a life cycle that alternates between free-living nanoplankton (3-9 µm) and large (> 2 mm) gelatinous colonies (Schoemann and others, 2005). The latter develop during massive summer blooms in high-latitude spring bloom regions and during summer blooms in polar sea ice regions and in the Antarctic circumpolar region (Schoemann and others, 2005; Vogt and others, 2012). Blooms of *P. minimum* occur in regions with relatively high anthropogenic nutrient inputs, and its global distribution is expected to expand given that anthropogenic nutrient inputs are projected to more than double by 2050 unless inputs are controlled more effectively on a global scale (Glibert and others, 2008).

5.1.1.6. Toxin producing microplankton

Among the 5,000 species of extant marine phytoplankton (Sournia and others, 1991), some 80 or so species have the capacity to produce potent toxins that find their way through fish and shellfish to humans (Hallegraeff and others, 2004). Most toxic species are dinoflagellates that cause paralytic shellfish poisoning (PSP, e.g., *Alexandrium* spp.), diarrhetic shellfish poisoning (DSP, e.g., *Dinophysis* spp.), neurotoxic shellfish poisoning (NSP, e.g., *Karenia* spp.), azaspiracid shellfish poisoning (AZP, e.g., *Protoperidinium crassipes*), and ciguatera fish poisoning (CFP, e.g., *Gambierdiscus toxicus*). One diatom genus (*Pseudo-nitzschia* spp.) causes amnesic shellfish poisoning (ASP) (Lelong and others, 2012). Toxin producing microplankton have a cosmopolitan distribution (Hallegraeff and others, 2004).

5.2. Protozoan consumers

Most heterotrophic protozoa fall into the nano- and micro-zooplankton size classes and are major consumers in microbial food webs and important links to metazoan food webs (Landry and Calbet, 2004; Mitra and others, 2016). Their diversity can be described in terms of three basic body plans that broadly determine their ecological roles: amoeboid, flagellated and ciliated forms (Fuhrman and Caron, 2016).

Amoeboid foraminifera are most abundant in high latitude spring bloom regions and least abundant in subtropical gyres (Berger, 1969). They are major producers of marine calcareous shells deposited on the ocean floor (Schiebel and Hemleben, 2005). Radiolaria are common in the euphotic zone in tropical and subtropical oceanic regions globally and are much less abundant in coastal upwelling, high latitude spring bloom and polar regions (Caron and Swanberg, 1990).

[66] Dimethylsulphoniopropionate (DMSP) is the biogenic precursor of dimethyl sulfide (DMS) which represents a large source of sulfur going into the Earth's atmosphere where it helps to drive the formation of clouds that block solar radiation from reaching the Earth's surface and reflect it back into space.

Heterotrophic nanoflagellates are the most abundant protozoan consumers and they control the abundance of bacterioplankton (Fenchel, 1982; Massana and Jürgens, 2003). While nanoflagellates are important grazers of picophytoplankton in oligotrophic habitats, heterotrophic microflagellates (e.g., dinoflagellates) can be important consumers of microphytoplankton, including bloom-forming diatoms (Sherr and Sherr, 2007; Calbet, 2008).

Microzooplankton (dinoflagellates and ciliates) have been estimated to graze over half of daily global phytoplankton NPP and exert significant top-down control on phytoplankton blooms in ecosystems from the Southern (Swalethorp and others, 2019) and the western Arctic Oceans (Sherr and others, 2009) to temperate coastal ecosystems (Pierce and Turner, 1992).

5.3. Heterotrophic bacteria and archaea

Bacterial assemblages are typically dominated by a small number of phylotypes[67] (Yooseph and others, 2010), the 20 most abundant of which fall into one of four groups (Amaral-Zettler and others, 2010; Luo and Moran, 2014): α-Proteobacteria (SAR 11, Rhodobacteraceae), γ-Proteobacteria (SAR 86), Bacteroidetes (Flavobacteriaceae), and Actinobacteria, most abundant of which are α-Proteobacteria (Lefort and Gasol, 2013; Giovannoni, 2017). Species richness tends to decrease toward the poles as observed for both the animal and plant kingdoms (Wietz and others, 2010).

Four major groups of archaea are abundant in the ocean (Church and others, 2003; Danovaro and others, 2017): MG-I, MG-II, MG-III and MG-IV. MG-I are among the most abundant and widely distributed group from polar to tropical waters (Karner and others, 2001; Santoro and others, 2019). Although bacteria tend to outnumber archaea, archaea make an important contribution to microbial biomass in deep waters (Danovaro and others, 2015).

5.4. Viruses

Viruses play important roles in marine food webs and nutrient recycling via their control of the abundance of microbial populations and the release of dissolved organic matter by cell lysis (Rohwer and Thurber, 2009; Sieradzki and others, 2019). Viruses, including free living virions, are the most abundant biological entities in the oceans and are a major reservoir of genetic diversity (Suttle, 2007; Simmonds and others, 2017). The majority of viruses are bacterial phages (Coutinho and others, 2017), and their abundance is correlated with the abundance of bacteria from regional to global scales (Fuhrman and Caron, 2016). Metagenomic analyses indicate that there are thousands of different virions in a few liters with the most abundant genotypes represented by a relatively small fraction of the entire assemblage (Breitbart and others, 2004; Angly and others, 2006). However, despite recent advancements in metagenomics such as these, it is clear that this is the "tip of the iceberg" in terms of viral biodiversity (Paez-Espino and others, 2019).

[67] A group of organisms that are genetically similar that may be grouped at different taxonomic levels, e.g., species, family, class, or phylum.

6. Metazoan Zooplankton

6.1. Holoplankton[68]

Metazoan holoplankton have been described from 15 phyla (Bucklin and others, 2010; Wiebe and others, 2010). As a group, they exhibit diverse feeding types (Kiørboe, 2011), from filter feeders (e.g., copepods, euphausiids, tunicates) to passive ambush predators (e.g., ctenophores and some pteropods) and active ambush predators (e.g., chaetognaths and some amphipods). Like other groups of animals, the diversity of holozooplankton tends to decrease toward the poles (Lindley and Batten, 2002; Burridge and others, 2017). Diversity also tends to be higher when biomass is low (e.g., subtropical gyres) and lower when biomass is high (e.g., coastal upwelling and high latitude spring bloom regions) (Global Patterns in Marine Biodiversity, 2017).

6.1.1. Crustaceans

About half of the known species of holoplankton are crustaceans (Verity and Smetacek, 1996; Global Patterns in Marine Biodiversity, 2017). With over 10,000 species (Khodami and others, 2017), copepods are by far the most abundant and are a key trophic link between phytoplankton and fisheries (e.g., Möllmann and others, 2003; Beaugrand, 2005). While copepod abundance is generally highest in regions where high NPP occurs seasonally, biodiversity is generally highest in warm water regions where NPP is relatively low (Rombouts and others, 2009; Valdés and others, 2017).

With nearly 100 documented species (Baker and others, 1990), euphausiids (krill) occur throughout the global ocean and, like copepods, are most abundant during periods of high phytoplankton productivity (Baker and others, 1990). They are especially abundant in the Southern Ocean, where they play a crucial role in the food web and are a target for fisheries (Mangel and Nicol, 2000; Boopendranath, 2013).

There are ~ 200 described species of planktonic ostracods (Angel and others, 2007) and ~300 species of hyperiid[69] amphipods (Vinogradov, 1996; Boltovskoy and others, 2003). Ostracod species richness tends to be highest in the mesopelagic zone at low latitudes (< 50°N) and in the epipelagic zone at higher latitudes. The majority of hyperiids spend at least part of their life cycle living as commensals with salps, jellyfish, ctenophores or siphonophores (Madin and Harbison, 1977; Gasca and Haddock, 2004), and their species richness is highest in regions where gelatinous zooplankton are most abundant.

6.1.2. Gelatinous zooplankton

[68] Species that live their entire life cycle as plankton.
[69] An order of amphipods that is exclusively marine.

This diverse group includes cnidarians (jellyfish),[70] ctenophores (comb jellies), chaetognaths (arrow worms), tunicates (salps, doliolids and appendicularians), and molluscs (pteropods and heteropods) (Alldredge, 1984; Jennings and others, 2010). As a group, tunicates are well adapted to life in oligotrophic oceans where their diversity and abundance are often greater than planktonic crustaceans (Alldredge and Madin, 1982; Madin and Harbison, 2001). Species richness is highest in jellyfish (> 1,000 species) (Purcell and others, 2007; Pitt and others, 2018), followed by molluscs (250 species) (Jennings and others, 2010), ctenophores (200 species (Harbison, 1985; Madin and Harbison, 2001), tunicates (145 species) (Deibel and Lowen, 2012) and chaetognaths (100 species) (Daponte and others, 2004).

6.2. Meroplankton

Meroplankton are larval stages of benthic and pelagic adults (e.g., shellfish and fish) and are, therefore, temporary members of the plankton. Their contribution to plankton diversity occurs episodically or seasonally, and their abundance relative to holoplankton decreases with increasing depth and increasing latitude (Silberberger and others, 2016; Costello and Chaudhary, 2017). The distribution, diversity and fecundity of adults that have a planktonic larval stage are inextricably linked to the abundance and diversity of their meroplanktonic larvae which, in turn, influence the distribution and diversity of their adult stage (Miron and others, 1995; Hughes and others, 2000).

7. Documented trends

7.1. Global

Based on a satellite time series (1998-2015) of sea surface chlorophyll-a (Chl), a long-term trend in NPP has yet to be observed on a global scale (Gregg and others, 2017). However, microplankton diatom biomass has declined relative to picophytoplankton during this period in most regions (Rousseaux and Gregg, 2015; Gregg and others, 2017), a trend that appears to be related to upper ocean warming, increases in vertical stratification[71], and decreases in nutrient supplies from the deep sea (Daufresne and others, 2009; Basu and Mackey, 2018).

A comparison of known toxic events prior to 1970 with those observed by 2015[72] suggests that the public health and economic impacts of toxic events have increased in frequency and have spread globally (Hallegraeff and others, 2004):

- PSP events caused by *Alexandrium tamarense* and *Alexandrium catenella* increased from 19 coastal sites (including 12 in North America and 4 in western Europe) to 118 coastal

[70] Although jellyfish have a life cycle with a benthic polyp stage and a planktonic medusa stage, they are considered to be holoplankton because the sexually reproducing stage (medusa) is planktonic.

[71] A water column becomes vertically stratified when a less dense body of water develops (due to an increase in temperature and/or a decrease in salinity) over deeper, denser water. This process limits mixing between the surface mixed layer and the deep ocean.

[72] Available at www.whoi.edu/website/redtide/regions/world-distribution.

sites (including 26 in North America, 25 in western Europe, 36 in the western Pacific, 9 in Australia and New Zealand, 7 in South America, 7 in Africa and 4 in India).

- DSP events caused by *Dinophysis* spp. increased from 15 coastal sites (including 13 in western Europe) to 71 coastal sites (including 8 in North America, 37 in western Europe, 9 in South America, 7 in Australia and New Zealand, 6 in Japan and 4 in India).
- ASP events caused by *Pseudo-nitzschia* spp. increased from 1 coastal site in North America to 31 coastal sites (including 12 in North America, 9 in western Europe and 9 in Australia and New Zealand).

While there is reason to suspect that the combined effects of increases in coastal eutrophication, sea surface temperature and vertical stratification may favor the growth of dinoflagellates, the underlying causes of these trends remain a matter of speculation (Wells and others, 2015).

Upper ocean warming is influencing the biogeography and phenology of plankton species (Hays and others, 2005; Thackeray and others, 2010; Mackas and others, 2012). On average, seasonal spring peaks in biomass have advanced by 4.4 ± 0.7 days per decade (± SE) and the leading edges of species distributions have extended poleward by 72.0 ± 0.35 km per decade (1920 – 2010) (Hoegh-Guldberg and others, 2014). While holoplankton show large shifts in both biogeography and phenology in response to upper ocean warming, meroplankton show relatively small shifts in distribution but have greater changes in phenology (Edwards and Richardson, 2004), changes that are likely to have feedback effects on the abundance of adult populations.

7.2. Polar sea ice regions

7.2.1. Southern Ocean

A significant interannual trend in NPP in the Southern Ocean as a whole has not been documented (Arrigo and others, 2008a). However, opposing trends in NPP in the Ross Sea (increasing) and West Antarctic Peninsula (WAP) (decreasing) coincided with increases (Ross Sea) and decreases (WAP) in sea ice extent[73] (Montes-Hugo and others, 2009; Ducklow and others, 2013). The decrease in NPP was associated with a shift in the size spectra of phytoplankton from microplankton-dominated (diatoms) assemblages to nanoplankton and picoeukaryotes as sea surface temperature increased (Moline and others, 2004; Montes-Hugo and others, 2009). Warming and the shift to smaller phytoplankton have also been associated with a range extension of *E. huxleyi* from the Antarctic circumpolar region into the polar sea ice region (Cubillos and others, 2007).

Inter-annual variations in the extent of sea ice off the Antarctic Peninsula also appear to be reflected in the relative abundance of two dominant grazers: krill (*Euphausia superba*) and salps (*Salpa thompsoni*). Krill recruitment, which depends on the survival of larval krill during winter, is the most likely population parameter to be impacted by climate change (Flores and others, 2012). *E. superba* has been found to be more abundant following winters

[73] Available at https://earthobservatory.nasa.gov/features/SeaIce.

with extensive sea ice cover while salps were more abundant following winters when the spatial extent of sea ice is relatively low (Loeb and others, 1997). Thus, while krill populations may have suffered from sea ice decline, salps appear to have benefited from warming surface waters during the last century (Loeb and Santora 2012). The observed decrease in sea ice extent portends a long-term shift from a food web dominated by *E. superba* to one dominated by salps with unknown cascading effects on the abundance of vertebrate predators (Henschke and others, 2016).

7.2.2. Arctic Ocean

The Arctic Ocean is in the process of transitioning to a warmer state (cf., Buchholz and others, 2010). Unlike the Antarctic, sea ice extent has decreased (1998–2015) in all sectors of the Arctic due to increases in sea surface temperature (Kahru and others, 2016), a trend that is associated with increases in NPP (Arrigo and van Dijken, 2011; Hill and others, 2017) and increases in the biomass of picoeukaryotes at the expense of microplankton diatoms as vertical stratification of the water column increased (Li and others, 2009).

As in coastal waters of WAP, krill are an important prey for a number of species including smelt. Between 1984–1992 and 2007–2015, krill abundance increased in the southwestern and central Barents Sea, despite high smalt predation, probably as a result of increasing temperatures, stronger advection of krill into the Barents Sea (Slagstad and others, 2011), and increases in phytoplankton NPP (Dalpadado and others, 2014). Warming has also influenced the relative abundance of krill species with the boreal species *Meganyctiphanes norvegica* increasing and the cold water species *Thysanoeassa raschii* decreasing (Rasmussen, 2018).

7.3. North Atlantic high-latitude spring bloom region

In these seasonally nutrient-rich waters, upper ocean warming and an earlier setup of the seasonal pycnocline[74] combine to increase the length of the growing season and the availability of sunlight. As a result, NPP has been increasing in recent decades (1979-2010) (Dalpadado and others, 2014; Raitsos and others, 2014), increases that have been accompanied by increases in picoeukaryotes and coccolithophores relative to diatoms (Li and others, 2009), a reduction in the average size of phytoplankton and zooplankton and an increase in biodiversity of plankton assemblages (Hoegh-Guldberg and Bruno, 2010; Edwards and others, 2013).

Poleward expansions in the range of plankton species in response to upper ocean warming have been well documented (Poloczanska and others, 2013), especially in the North Atlantic: *Emiliana huxleyi* into the Barents Sea (Smyth and others, 2004); *Calanus helgolandicus* replacing *C. finmarchicus* in the North Sea (Edwards and others, 2013); and a poleward expansion of the ranges of calcifying species of plankton (foraminifera, coccolithophores, and

[74] A pycnocline is a vertical zone over which an increase in density separates a surface layer of relatively low density from a deeper layer of relatively high density. A seasonal pycnocline begins to form in these regions as solar heating begins to warm the surface layer during late winter-early spring, a process that increases the availability of solar energy for photosynthesis.

pteropods) (Beaugrand and others, 2013; Winter and others, 2014).

Phenologies[75] of phytoplankton and zooplankton species are also changing in response to upper ocean warming (1958 – 2002) (Edwards and Richardson, 2004). For example, the seasonal abundance of the copepod *C. finmarchicus* in the North Atlantic peaked ~10 days earlier in the year than in previous years while its food (microplankton diatoms and dinoflagellates) peaked ~30 days earlier (Hays and others, 2005). Likewise, diatom blooms in the North Sea are occurring earlier in the year than their macrozooplankton grazers (Hays and others, 2005). Such uncoupling of trophic levels has also been documented in the Baltic Sea where the duration of the growing season during 1988–2017 increased at a rate of 4.5 days per year, resulting in an earlier spring bloom, a prolongation of the summer biomass minimum and a later and more prolonged autumn bloom (Wasmund and others, 2019).

7.4. Upwelling regions

Diatom production has been increasing (1996-2011) in eastern boundary upwelling systems (Kahru and others, 2012) while NPP increased in Pacific equatorial upwelling (Chavez and others, 2011), apparently due to increases in upwelling (Tim et al., 2016). However, ocean acidification in coastal upwelling systems is proving to be corrosive to pteropod shells (*Limacina helicina*) (Bednaršek and others, 2014). As the habitat suitability for pteropods declines, metazoan food webs are likely to be impacted (Bednaršek and others, 2012; Lischka and others, 2011), and similar impacts of ocean acidification are likely to occur in the Southern and Arctic Oceans (Comeau and others, 2009; Negrete-García and others, 2019).

7.5. Subtropical gyres

Due largely to declines in diatoms and chlorophytes (Gregg and others, 2017), a significant downward trend in Chl (1998–2013) has been documented in all gyres except in the South Pacific (Signorini and others, 2015). Rates of decline were greatest in the northern hemisphere and lowest in the South Atlantic and the Indian Ocean, trends that correspond to expansions of the gyres in the Atlantic and North Pacific Oceans (Polovina and others, 2008)

Downward trends in NPP were observed in all five gyres that coincided with upper ocean warming and decreases in phytoplankton cell size (Polovina and Woodworth, 2012). The latter is consistent with observed increases in the relative abundance of *Prochlorococcus* and *Synechococcus* (Flombaum and others, 2013; Agusti and others, 2019), trends that most likely reflect both warming (Daufresne and others, 2009; Morán and others, 2010) and decreasing nutrient supplies as the euphotic zone becomes more isolated from nutrient-rich deep water (Marañón and others, 2015; Sommer and others, 2016).

8. Outlook

[75] Phenologies refer to the timing of the biological events in plants and animals (e.g., reproduction and migration) in relation to changes in season and climate.

Climate change during the course of this century is expected to continue driving changes in the upper ocean that impact the diversity and productivity of plankton assemblages on regional to global scales. These include expansion of the subtropical gyres (Polovina and others, 2011), ocean warming and acidification, decreases in salinity, increases in vertical stratification and decreases in inorganic nutrient supplies to the euphotic zone in the open ocean (Bopp and others, 2013). Predicted biological responses to these changes on a global scale include the following:

- A decrease in NPP and an increase in the relative abundance of picophytoplankton (Daufresne and others, 2009; Morán and others, 2010) at the expense of microplankton diatoms (Bopp and others, 2005; Moore and others, 2018).
- These trends are likely to propagate through food webs resulting in decreases in the ocean's carrying capacity for fisheries (Worm and others, 2006; Chust and others, 2014) and in the ocean's capacity to sequester carbon via the biological pump (Boyd, 2015).
- Expansion of the subtropical gyres may promote increases in N_2-fixation (Boatman and others, 2017; Follet and others, 2018), a trend that could further perturb the global nitrogen cycle (Jiang and others, 2018).
- Plankton food webs in the polar oceans and coastal upwelling regions will be the most affected by ocean acidification due to the high solubility of CO_2 in cold waters (Bednaršek and others, 2014; Gardner and others, 2018).

Regional exceptions during the course of this century are predicted to occur poleward of the subtropical gyres due to environmental changes in the euphotic zone, including increases in the availability of sunlight as the surface mixed layer shoals in nutrient rich environments (promoting increases in NPP), increases in temperature and decreases in salinity (favoring the growth of small phytoplankton) (Tréguer and others, 2018). Notable examples include:

- An increase in NPP and a decrease in phytoplankton size in the Arctic Ocean (Mueter and others, 2009; Kahru and others, 2011; Dalpadado and others, 2014).
- Increases in NPP, export production and the abundance of diatoms during the first half of the century in the polar sea ice region of Antarctica (Bopp and others, 2001; Kaufman and others, 2017; Moore and others, 2018).
- Expansion of the range of *E. huxleyi* into the polar oceans (Winter and others, 2014) and increases in the frequency of coccolithophore blooms in high-latitude spring bloom regions (Bopp and others, 2013; Rivero-Calle and others, 2015).
- An increase in NPP and a decrease in the relative abundance of diatoms in the North Atlantic high-latitude bloom region (Bopp and others, 2005, 2013; Sundby and others, 2016).

Projections of future trends in NPP in coastal upwelling regions are less certain due to uncertainty concerning how interactions between increases in upwelling-favorable winds (increases in upwelling, NPP and the relative abundance of diatoms) and upper ocean warming (decreases in upwelling, NPP and the relative abundance of diatoms) will play out (Chavez and others, 2011; García-Reyes and others, 2015).

In this context, we emphasize that our analysis of the impacts of climate change on plankton communities does not consider transgenerational adaptation to climate-driven changes in the upper ocean environment (e.g., Schlüter and others, 2014; Thor and Dupont, 2015).

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Chapter 6B
Marine Invertebrates

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Keynote points

- As of 2019, 153,434 marine benthic invertebrate species were described globally.
- Since 2012, researchers described 10,777 new marine benthic invertebrate species; at the same time biodiversity is changing globally at rates unprecedented in human history, creating the potential for species extinction before they have been described.
- The deep sea covers 43 per cent of Earth's surface, with around 95 per cent of marine invertebrate species still undescribed.
- Major pressures on marine invertebrates include temperature increase, ocean acidification physical impacts on the seabed, extraction of living/non-living resources, coastal use, invasive species, and pollution.
- Large areas of the globe, including areas beyond national jurisdiction, still lack effective, adequate long-term ecosystem monitoring and/or protection for marine invertebrates.
- Despite new research regarding many important ecosystem processes, functions, goods and services, huge knowledge gaps remain in understanding how reductions in benthic invertebrate biodiversity impact human well-being and ecosystem dynamics.

1. Introduction

This chapter focuses on benthic shrimps, worms, gastropods, bivalves and other invertebrates living on or in the sea floor, which provide important food sources for fishes, marine mammals, seabirds, and humans; some commercial fisheries target invertebrate species. These taxa form the basis for some of the most productive ecosystems on the planet (e.g. estuaries, coral reefs), rivalling tropical forests (Valiela, 1995) and habitats covering more of Earth's surface than all other habitats combined (Snelgrove and others, 1997). Changes in ocean use, harvesting of organisms, climate change, pollution and invasive species contribute to global alteration in nature at rates unprecedented in human history. Historically, coastal biota experienced greater pressures and impacts than the deep sea, but depletions of coastal marine resources and new technologies create both the capacity and incentive to fish, mine, and drill in some of the deepest parts of the ocean (McCauley and others, 2015). Alterations of biodiversity often erode economies, livelihoods, food security, health and quality of life worldwide (IPBES, 2019).

2. Summary of the situation recorded in the First World Ocean Assessment (WOA I)

The First World Ocean Assessment (WOA I) (United Nations, 2017) identified major drivers and patterns of marine invertebrate biodiversity from regional to global scales. Complex interactions among drivers, and their individual and collective impacts on marine biodiversity at multiple scales of biological organization and observation, limit our current capacity to predict regional diversity with confidence. Globally, coastal and oceanic patterns differ. Globally, coastal benthic species richness generally peaks near the equator and declines poleward, in contrast to mid-latitude peaks in oceanic species. However, strong longitudinal gradients complicate coastal patterns, with localized hotspots of biodiversity across many taxa in areas such as the tropical Indo-Pacific and the Caribbean.

Areas of low oxygen, bottom instability, variation in ocean chemistry, habitat variables and maritime activities complicate prediction of marine invertebrate diversity patterns in space and time. The multiple drivers of change, often acting in tandem, make it extremely difficult to disentangle natural changes from human-induced pressures. Biodiversity hotspots often attract and support human extractive activities, directly linking ocean biodiversity and ecosystem services. Moreover, these hotspots also often support important ecosystem functions, such as nutrient recycling, food web support and habitat creation that, in turn, contribute to ecosystem services of direct benefit to humans.

3. Description of the environmental changes (between 2010 and 2020)

3.1. Marine invertebrate biodiversity

Records in the World Register of Marine Species (Vandepitte and others, 2018; WoRMS Editorial Board, 2019), indicate 10,777 new valid marine benthic invertebrate species were described between 2012 and 2019, bringing the total number of marine benthic invertebrate species described globally to 153,434. The Mollusca contain the highest numbers of described marine benthic invertebrate (31 per cent), followed by Arthropoda (24 per cent).

The Ocean Biodiversity Information System (OBIS), contains distribution information for 124,372 marine species, representing 56.4 million distribution records. Of all these, WoRMS currently identifies 80,132 species as marine benthic invertebrates, representing 8.1 million occurrence records.

Based on available OBIS and WoRMS data in 2019 (Figure 1), the well-sampled North Atlantic Ocean contains the highest numbers of recorded marine benthic invertebrate species (24,214 species), followed by the comparatively under sampled South Pacific Ocean (23,245 species), including the Coral Sea (18,224 species), which will certainly yield many more undiscovered species.

Based on different bathymetric zones (Figure 1), the Coral Sea contains the highest number of species recorded at depths shallower than 200m (11,353 species), followed by the Indian Ocean (9,971 species), the North Atlantic Ocean (9,915 species) and the South Pacific Ocean (7,498 species). In some instances (e.g. Bering Sea, Arctic Ocean, Norwegian Sea) similar latitudes differ in benthic diversity. Below 1,000m, the better-sampled North Atlantic Ocean relative to other basins, contains the highest numbers (8,027 species).[76]

[76] Not all species described in WoRMS have distribution information available. OBIS constantly receive input from many data providers and shows exactly ocean locations where marine species were recorded. Because WoRMS documentation of benthic traits is ongoing, about 11,000 of the invertebrate species in OBIS still lack functional group designations, the overview therefore omits these marine benthic invertebrate species.

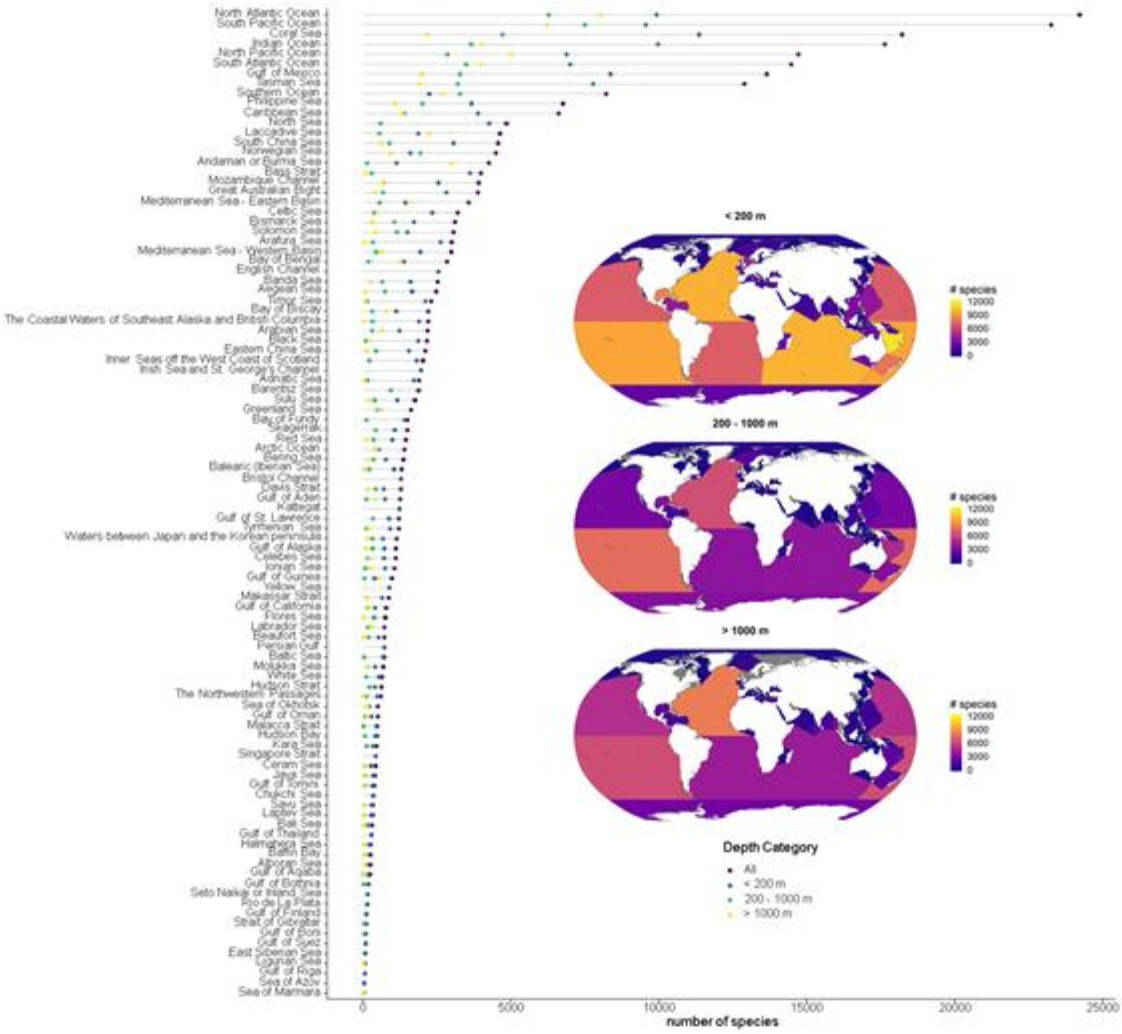

Figure 1. The total numbers of recorded marine invertebrate benthic species are represented as three depth categories (<200m, 200-1000m, >1000m). Information based on Claus and others (2014), Flanders Marine Institute (2018), International Hydrographic Organization Sea Areas version 3 (available online at http://www.marineregions.org/. https://doi.org/10.14284/323), species occurrences (OBIS, 2019), species group information (WoRMS), and bathymetry data (EMODnet, 2016; GEBCO, 2015; Provoost and Bosch, 2018).

3.2. Assessment and state of marine invertebrate biodiversity

Globally, multiple pressures and drivers simultaneously affect marine benthic invertebrates (Table 1). Many studies around the globe address these impacts, but the section below only highlights some recent targeted or valuable time series studies in Table 1 that illustrate increased understanding since WOA I.

Table 1. Selected national case studies and related natural and anthropogenic drivers and pressures (described in the text below the table).

	Arctic			North Atlantic							South Atlantic	Indian Ocean		North Pacific			South Pacific		Indian - South Pacific Ocean boundary
	Norway Barents Sea	**Russia Arctic Seas**	**USA Arctic**	**Canada North East**	**Greenland W and SE**	**England North Sea**	**Portugal South West**	**Greece bays, gulfs**	**Malta coast**	**Trinidad and Tobago**	**Brazil, coast, bays**	**Bangladesh coast**	**Australia West**	**Vietnam coast**	**South China Sea**	**Russia Eastern Seas**	**Australia North-east**	**New Zealand East**	**Australia South**
Climate warming	X	X	X	X	X	X									X	X			X
Temperature events (e.g. El Niño)													X	X			X		
Sedimentation								X		X	X	X		X					
Storms and wave action										X		X	X				X		
Bottom trawl fisheries	X	X		X	X	X	X	X				X		X	X	X		X	X
Overharvesting of invertebrates											X								
Spreading of new species	X	X	X	X			X		X		X								
Outbreaks of species										X							X		X
Pollution								X			X	X		X	X				
Eutrophication (agriculture, aquaculture, sewage)								X			X				X				
Oil and Gas exploitation and extraction				X		X				X	X				X				X
Offshore wind farms						X													
Large ship breaking activities												X							
Anchoring								X	X		X								
Coastal infrastructure development								X	X		X				X				
Tourism								X	X		X	X							

Climate warming: Strong evidence indicates unabated warming of the global ocean since 1970, which has taken up more than 90 per cent of the excess heat in the climate system. Since 1993, the rate of ocean warming has likely more than doubled (IPCC, 2019). Impacts on marine benthos are particularly striking for polar and subpolar regions. Sea ice reduction in the Arctic will increase ship access to this region, potentially increasing local anthropogenic pressure on benthic communities, particularly in harbors.

Recent updates include:

- In the Arctic[77], the Barents Sea (Jørgensen and others, 2019), other seas to the north of Eurasia and the far Eastern Seas in the North Pacific (Lobanov and others, 2014) marine invertebrates are shifting northward due to warming waters (Table 1). Invertebrate biomass has declined in areas of the Alaska Seas (Table 1) (Grebmeier and others, 2015) with consequences for higher trophic levels (Grebmeier, 2012); native elders link this change to decreased sea ice coverage, movement of sand bars, and alterations in ocean currents (Metcalf and Behe in Jørgensen and others, 2017).
- In the North Atlantic, climate warming (SSD) has enabled the arrival of warm-water species in English inshore areas (Table 1) influenced from the Gul-stream (Birchenough and others, 2015).
- In the Pacific, marine heatwaves led to severe bleaching and mass mortality of corals around Australia (Le Nohaïc and others, 2017; Hughes and others, 2018; Stuart-Smith and others, 2018), the Central American coast (Cruz and others, 2018) and the South China Sea (Table 1).

Some researchers predict increasing frequency and severity of marine heatwaves (Frölicher and Laufkötter, 2018) in the coming decades, even if emission-reduction targets established by the Paris Agreement[7879] are met. This warming could eliminate key biogenic habitats in coastal regions of temperate and Arctic seas worldwide (Krumhansl and others, 2016) and affect reef ecosystems located in poorly monitored waters with unknown damage (Genevier and others 2019).

Bottom trawl fisheries are the most widespread source of anthropogenic physical disturbance to global seabed habitats and almost one quarter of global seafood landings were caught by bottom trawls (Hiddink and others, 2017). Trawl gear removes 6–41 per cent of faunal biomass per pass and median recovery times are 1.9–6.4 years (excluding the deep sea), depending on the specific fisheries and environmental context (Hiddink and others, 2017). Trawling impact studies demonstrates that decreases in the relative abundance of long-lived fauna (>10 years) in trawled areas are greater than those of fauna with shorter life spans (1-3 years) Hiddink and others, 2019).

Recent findings include:

- Bottom trawling alters native benthic communities, with impacts characterized as “some modifications” in the North Sea. Studies elsewhere in the North Atlantic and beyond report similar changes in benthic communities resulting from aggregate dredging (Cooper and others, 2017), with “removal and decline in benthic population size or target species” along the Canadian east coast (Pierrejean and others 2020), imposition of “one of the largest footprints per unit of biomass landed” in south-west

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[77] See www.arcticbiodiversity.is/index.php/findings/benthos.

[78] Available at: https://unfccc.int/sites/default/files/english_paris_agreement.pdf

Portugal (Ramalho and others, 2018) and "with negative impact on macro-epibenthic composition" in southern Greenland (Yesson and others, 2016).
- On bathyal seamounts in the South Pacific, east of New Zealand, the recovery of coral communities, after the use of heavy ground gear, will likely take many decades (Clark and others, 2019).
- In the North Pacific, negative impacts of bottom trawling on macro-epibenthic composition were reported in the East China Sea (Wang and others, 2018).
- Discarded or lost fishing gear impacts cold water coral assemblages significantly (Deidun and others, 2015) at depths of hundreds of metres.
- Invertebrate fisheries catches (see also Chapter 15) have rapidly expanded globally to more than 10 million tons annually and contribute significantly to global seafood provision, export, trade and local livelihoods. On average, 90 per cent of invertebrate catch can be achieved at 25 per cent depletion, requiring less fishing effort and thereby raising profits, while strongly reducing impacts on other trophic groups (Eddy and others, 2017).
- Harvesting of scallops (*Chlamys islandica*) in the Arctic (Barents Sea) (Nosova and others, 2018) and sea cucumbers, scallops, and crabs in the Russian Eastern Seas (Lysenko and others, 2015) is altering biogenic habitats.

Invasive species (see also Chapter 25 and [80]) occasionally become a dominant pressure to native benthos;

Recent updates include:

- Documentation of expanding range of the commercial, predatory snow crab, (*Chionoecetes opilio*) (Zalota and others, 2018) in the Arctic; studies estimate that *C. opilio* removes < 30,000 tons of macrobenthos in the eastern Barents Sea (Table 1) annually (Zakharov and others, 2018).
- In the North Atlantic, invasive green crab (*Carcinus maenas*) has impacted seagrasses and sea floor invertebrates in some Canadian[81] coastal areas (Table 1) (Garbary and others, 2014, Matheson and others, 2016). Extensive invasions of *Sargassum* algae (see also Chapter 6G) now cover beaches and inshore coastal habitats of Trinidad and Tobago and other Caribbean islands (Gobin, 2016). Extensive *Sargassum* beds can alter the abundance of many native marine invertebrates and may provide a suitable habitat for species not previously represented in the local benthic community.
- In the Mediterranean, >500 non-indigenous marine invertebrate species have been recorded (Tsiamis and others, 2019) and many have become established, at least locally, at many sites
- Outbreaks of sea urchins (*Centrostephanus rodgersii)* are degrading kelp forests off the coast of Tasmania (Ling and Keane, 2018).
- In the South Atlantic, invasive species frequently dominate some Brazilian coastal reefs (Creed and others, 2016, Mantellato and others, 2018) (Table 1).

The consequences of pollution on seabed communities were well documented in the World Ocean Assessment Report I and in IPBES (2019). To interpret the environmental state and the

[80] Available at: https://www.invasivesnet.org/news/
[81] Available at: https://www.dfo-mpo.gc.ca/species-especes/ais-eae/about-sur/index-eng.html

resilience of the benthic invertebrates, their behavior, dynamics and multiple interactions with the environment need to be studied (Neves and others, 2013, Pessoa and others, 2019).

Recent updates include:

- Agricultural run-off and disposal of municipal waste into the ocean add nutrients that produce algal blooms that eventually sink to the bottom, creating hypoxic conditions and low pH that typically reduce benthic species diversity. Since WOA I, researchers have reported additional occurrences in the Indian Ocean, the Bangladesh coast (Kibria and others, 2016, Mallick and others, 2016; Molla and others, 2015) and in the South Atlantic**,** along coastal Brazil (Cruz and others, 2018) (Table 1).
- In the North Atlantic, outflow (sedimentation) from the Orinoco River (Trinidad and Tobago) (Table 1) increases potential contamination and mortality of benthic invertebrate communities (Gobin, 2016), while a metalliferous discharge caused a multi-year decline in benthic "ecological status" along coastal Greece (Simboura and others, 2014) (Table 1).

Storms and wave action cyclones and tsunamis are among the most critical variables in shaping marine benthic communities' biological richness and structure, and significantly challenging their resilience and stability (Betti and others 2020). Hurricane frequency and intensity have increased during recent decades along the tropical Atlantic in close association with climate change-related influences (see references in Hernández-Delgado and others, 2020)

Mining of deep-sea minerals (see also Chapter 19) is a potential new industry that can help to support an expanding "green" economy based on new battery technology for electric vehicles, wind turbines and improved telecommunications and computing technology (Hein et al. 2013). Although no deep-sea mining currently operates in the high seas, the International Seabed Authority administers 30 exploration licenses (1.5 million km^2) in the Pacific and Indian Oceans and along the Mid-Atlantic Ridge. In mining operations, direct physical removal of sea floor fauna and secondary effects from sediment plumes or release of ecotoxins will potentially impact benthic environments and will require careful evaluation (Miller and others, 2018). Lack of knowledge of deep-sea biodiversity is a major constraint to ensuring environmental sustainability (Glover and others, 2018).

Human recreational activities, **coastal infrastructure development, and ship anchoring and bunkering** continue to impact vulnerable habitats and associated invertebrate assemblages, as discussed in WOA I, with additional records from near Malta (Table 1) in the Mediterranean (García-March, and others, 2007; Mifsud and others, 2006). Also, ship-breaking activities in coastal Bangladesh (Table 1), in the Bay of Bengal, have reduced benthic species diversity (Hossain, 2010).

Crime and smuggling of marine species occur globally, as illustrated by crime groups that smuggle abalone out of South Africa across the borders of the Indian and South Atlantic Oceans. A request for assistance from law enforcement agencies in receiver countries may provide a solution (Warchol and Harrington, 2016).

Consequences of changes in marine invertebrate biodiversity on human communities, economies, and well-being: Biodiversity changes have both direct and indirect impacts on human well-being (IPBES, 2019). Unfortunately, we lack large-scale and long-term monitoring for large marine areas, although some Arctic and North Atlantic nations have established long-term monitoring of invertebrate fisheries and by-catch from trawls within existing scientific national fish-assessment surveys (Jørgensen and others, 2017).

Limited publications document specifically how marine benthic invertebrates contributes to human well-being (e.g. Officer et al. 1982; Snelgrove et al. 1997). However, WOA I and the present Assessment document the importance of benthic invertebrates to marine food webs and the many habitat-forming or habitat-engineering benthic species. Here, we briefly illustrate some key issues:

- Under a business-as-usual emissions scenario, the United Nations Educational, Scientific and Cultural Organization predicts that Australia's Great Barrier Reef, along with other World Heritage coral reefs, will cease to exist as a functioning coral reef ecosystem by 2100 (Heron and others, 2017).
- Corals, oysters, and other living reefs (see also Chapter 7G) can dissipate up to 97 per cent of the wave energy reaching them, thus protecting structures and human lives (Ferrario and others, 2014). This is potentially an important mitigation factor as sea levels rise. Artificial coastal barriers to protect coastal infrastructure and human communities from climate-related sea level rise will cost an estimated hundreds of billions of dollars by the latter decades of this century (IPCC SROCC, 2019).
- Increased risk to food security with decreases in seafood availability varies greatly on local and cultural scales. However, for many coastal indigenous peoples and local communities, harvesting of benthic invertebrates, particularly intertidal species, contributes significantly to their culture and to community-scale food security (IPBES, 2018 a, b; IPCC, 2019).
- Elevated sea surface temperatures have contributed to range extensions of species globally and also into South Pacific Tasmanian waters (Pecl and others, 2014), which will likely affect fisheries and possibly tourism in the region, as well as ecosystem services.
- Climate-induced changes in distribution of many benthic invertebrates cause increase, decrease, local extinction of or even new food resource species for dependent coastal communities (IPCC, 2019).
- Several studies report poleward range changes of sessile invertebrates at a slower rate than for fishes, but also consider benthic invertebrates more likely to respond directly to changes in temperature and pH (IPCC, 2019).
- Invasive species, such as snow crab, support increased commercial harvesting in the Arctic Barents Sea (Jørgensen and others, 2019), whereas the crab *Portunus segnis*, a Lessepsian migrant spreading in the Mediterranean Sea, feeds on fish, shelled molluscs, crustaceans and organic matter, thus significantly impacting trophic processes in native ecosystems, besides hosting a variety of parasites (Rabaoui and others, 2015).
- In Africa and Asia-Pacific regions, impacts from invasive benthic invertebrates increasing risk failure in meeting food security needs (IPBES b, c).
- In the Mediterranean, infrastructure development (e.g. habitat modification for vessels), which impacts directly on protected (e.g. *Cladocora caespitosa*) and commercially important species, diminish the value of marine ecosystem services.

Despite some progress, the need to address the huge knowledge gap concerning the effects of biodiversity loss on human communities, economies and well-being remains. Understanding the underlying causes of change requires repeated time series studies.

4. International and governmental responses

There are several ongoing initiatives that reflect a growing priority for protecting marine biodiversity, both in areas within and beyond national jurisdiction. These initiatives include science processes such as the "World Ocean Assessment" and legal processes such as the "Intergovernmental conference on an international legally binding instrument under the United Nations Convention on the Law of the Sea on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction", [and initiatives of Intergovernmental Organizations such as the International Seabed Authority.

General Assembly resolution 61/105 of 8 December 2006 on sustainable fisheries, which calls for fisheries using bottom-contacting gears to avoid serious adverse impacts to vulnerable marine ecosystems, has been particularly influential on marine fisheries. The expert Guidance in 61/105 in FAO (2008), supported States and Regional fisheries Management Organizations (RFMOs) in identifying vulnerable marine ecosystems (VMEs) and operating fisheries in ways compliant with the resolution.

Actions motivated by Resolution 61/105 enhanced existing efforts of RFMOs, to manage biodiversity impacts of fisheries. Targeted spatial and temporal closures and move-on rules, triggered by indicators of the presence of VMEs, are now applied in combination with a variety of target and limit catch levels spatial management approaches and gear and effort regulations. This is done to try to keep the impacts of fisheries on target species, bycatches species, seabed habitats and ecological communities within safe ecological levels (Garcia et al 2014). Performance of RFMOs in delivering this mandate to protect seabed habitats and species has been variable over time and among RFMOs (Gianni et al 2016), but the frameworks are considered sound and progress is being made (Bell et al 2019).

Recent governmental actions:

- Some Arctic and North Atlantic nations have established time and cost efficient, long-term monitoring of invertebrate by-catch from trawls within existing scientific national fish/shrimp-assessment surveys (Jørgensen and others, 2017).
- In the South Pacific, New Zealand government policies[82] prohibit bottom trawling and dredging to conserve the deep-sea environment in Seamount Closure Areas and Benthic Protection Areas, and there is evidence that benthic species of concern have benefited (Kelly and others 2000)
- In the Arctic, in 2019, the Norwegian government closed 442,022 km^2 in the Barents Sea to bottom trawling.[83]
- In the North Pacific Sea and the Bohai Sea of China, strict ecological restoration and fishery resources conservation were introduced in 2018.[84]
- At the inlet of the Indian Ocean, despite rules and regulations to protect the marine ecosystem from hazards and destructive activities, actual implementation remains minimal.

[82] Available at https://www.mpi.govt.nz/dmsdocument/7242-compliance-fact-sheet-7-benthic-protection-areas-and-seamount-closures.
[83] Available at https://lovdata.no/dokument/SF/forskrift/2011-07-01-755.
[84] Available at http://www.mee.gov.cn/xxgk2018/xxgk/xxgk03/201812/t20181211_684232.html.

- In the Mediterranean, the conservation status of sponges has recently been locally assessed in the Aegean ecoregion (Gerovasileiou and others, 2018).
- Authorities in EU countries are implementing the Marine Strategy Framework Directive. Here, the sea floor integrity shall be kept at a level that safeguards the structure and function of the ecosystems and does not adversely affect benthic ecosystems.[85] Phase II implementation plans[86] include further protection from fishery impacts on seabed features important to benthic invertebrates. This includes, among other, the banning of mobile bottom-contacting gears at depths shallowed than 50m, to protect vulnerable habitats such as seagrass beds.

Another major global policy initiative, the Convention on Biological Biodiversity (CBD) Aichi Biodiversity Target 11, has direct relevance for benthic invertebrates. This initiative calls for a robust conservation strategy based on an effectively and equitably managed, ecologically representative and well-connected system of protected areas (see also Kenchington and others, 2019) and other effective area-based conservation measures (OECMs), integrated into wider seascapes (see also Chapters 29 and 30). This target includes identifying and spatially delineating areas of protection, ensuring scales matching the spatial and temporal needs of the biodiversity features.

This approach was intended to achieve positive and sustained long-term outcomes for conservation of biodiversity, and particularly seabed invertebrate diversity and associated ecosystem functions and services and, where applicable, cultural, spiritual, socioeconomic, and other locally relevant values.[87]

Benthic invertebrate biodiversity could particularly benefit from these developments given that, as this chapter documents, seabed habitats experience pressures and impacts from many sectors and their associated activities, and has such a diversity of characteristics that effectiveness of specific types of conservation measures vary greatly with specific environmental conditions, history, and mixes of human pressures, including climate change.

In general, increasing coverage MPA network coverage should reduce pressures on benthic invertebrates and facilitate recovery of impacted areas. Acknowledging the potential for sectoral management measures to contribute to conserving benthic invertebrates may stimulate both more prominent consideration of the health of benthic invertebrate communities in managing uses of the ocean and better quantification of the outcomes of using such measures and factors that influence their effectiveness.

5. Achievement of relevant Sustainable Development Goals (SDGs)[88]

Current negative trends in biodiversity and ecosystems will undermine progress towards achievement of the CBD and Aichi Biodiversity Target 11. These Goals aim to conserve 10 per cent of coastal and marine areas of particular importance for biodiversity and ecosystem services by 2020 through effectively and equitably managed, ecologically representative and

[85] Available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0056.

[86] Available at https://mcc.jrc.ec.europa.eu/main/dev.py?N=24&O=202&titre_chap=D6%20Sea-floor%20integrity&titre_page=Implementation#2016331103713.

[87] Available at https://www.cbd.int/sp/targets/rationale/target-11/

[88] See United Nations General Assembly resolution 70/1.

well-connected systems of protected areas and OECMs, and integrated into the wider landscape and seascape.

6. Key remaining knowledge gaps and capacity-building gaps

6.1. Knowledge gaps

- Studies on the effect of protected areas remain limited.
- Reviews do not break down impacts (e.g. climate change, resource exploitation, pollution) on marine biodiversity by species group. This grouping limits documentation regarding invertebrate value and importance for human well-being.
- Baseline biodiversity (ecoregions, or for habitats that are hotspots for biodiversity) studies are lacking for the mesophotic zone, underwater caves, and many of the thousands of global seamounts.

6.2. Capacity-building gaps in the field

- Large-scale protection of seabed, national and international, must continue in order to sustain benthic biodiversity and extirpating species before they have ever being recorded.
- Lists of species with restricted geographic ranges, often arising from specialized habitat requirements, represents the most urgent need. Even describing 100 taxonomic units every year over the next decade would add just 1000 species within the time period before some experts expect commercial scale deep-sea mining will begin (Glover et al 2018).
- To increase knowledge on biodiversity and ecosystem understanding, marine national regular assessment cruises should report both target and non-targeted scientific catch.
- Prioritize integrated oceans management to coordinate conservation and management among all relevant activities.
- Managers should develop and implement common, well-defined measures to identify and respond to declining benthic habitats in national and international waters.
- Undertake studies needed to determine ecosystem effects of reduced or lost benthos, particularly in the context of food webs interactions.
- Undertake studies needed to determine the effect on food supply if harvested benthic harvested disappear.
- To assess cumulative impact of drivers and pressures that can have a combined effect to marine biodiversity.

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Addendum by the Group of Experts

Status of the Pelagic Invertebrates: Cephalopods

Of the 750 species considered by the International Union for Conservation of Nature (IUCN), only one species is classified as Critically Endangered, two as Endangered, and another two as Vulnerable, all of which are deep-sea umbrella octopuses (IUCN 2020).

However, more than 419 species are considered data deficient, which include many deep-sea dwellers (IUCN 2020). Ten nautilus species were added to the Convention of International Trade in Endangered Species (CITES) Appendix II in 2017[1] to prevent their illegal trade.

Although information on many deep-sea dwellers is still scarce, recent advances in deep-sea research has increased understanding of the ecology and biology of deep-sea cephalopods. In the central Pacific Ocean, a rare observation of the mating and reproduction behaviors of the deep-sea squid *Chiroteuthis* spp. has been recorded (Vecchione 2019). The largest (up to 12~13 m) and one of the most enigmatic species, giant squid was filmed in the Gulf of Mexico in 2019, which was only the second time it had been recorded since it was first observed in 2012. Analysis of the mitochondrial DNA of 43 specimens collected from giant squid from the North Pacific Ocean, Atlantic Ocean and Oceania, support the hypothesis that giant squids are a single species, *Architeuthis dux* (Winkelmann et al, 2013). Ontogenetic changes in the feeding strategy of vampire squid (*Vampyroteuthis infernalis*) have been established using stable isotope analyses (Golikov et al. 2019)

Recent work has identified a common multi-decadal increasing trend in the catch rates of dozens of cephalopods species with different biological and ecological strategies (demersal, benthopelagic, pelagic) in diverse oceanic regions (Doubleday and others 2016). This proliferation has been attributed to their high adaptability and resilience against environmental fluctuations based on their rapid growth and flexible development. As an example, shoaling of the oxygen minimum zone in the California Current system has been thought to optimize feeding conditions for the Humboldt squid (*Dosidicus gigas*). This has allowed the species to thrive and expand its distribution north up to the Gulf of Alaska (Stewart et al, 2014). In North Sea, decadal warming trend from the mid 1980s to the mid 2010s is thought to have been responsible for an increase in overall abundance and expansion of several squid species distribution to the north (van der Kooij et al, 2016). Future warming of the Arctic Ocean may facilitate a European cuttlefish (*Sepia officinalis*) trans-Arctic expansion into the North Canadian water by 2300 (Xavier et al, 2016). In Australian waters, warming waters associated with an extension of the Eastern Australian Current polewards are facilitating the expansion of the distribution of gloomy octopus (*Octopus tetricus*) (Ramos et al, 2018).

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Chapter 6C
Fish

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Keynote points

- Mobilization of existing data and development of tools and open, global repositories provide a global picture of the diversity of the 17,762 known species of marine fishes, including 238 species described since the First World Ocean Assessment (WOA I) (United Nations, 2017e).
- While knowledge of the biodiversity of marine fishes exceeds that of many other marine taxa, not only further improvements in taxonomic and biosystematic infrastructure but also in exploration and characterization of the oceans will be required to obtain a complete inventory.
- Over half of known marine fish species have had their conservation status assessed by the IUCN, with approximately a third of these assessments occurring since WOA I.
- Of the fish species with conservation assessments, around 6 per cent of bony fishes, nearly 50 per cent of elasmobranchs, 10 per cent of chimaeras, and both species of Coelacanth are threatened or near threatened with extinction.
- Capacity for documenting and understanding marine fish diversity continues to grow, but significant gaps remain for certain ecosystem groups (e.g. mesopelagic fishes) and in predicting responses to multiple simultaneous external stressors.

1. Introduction

This Chapter covers marine fish taxonomy, distribution, habitat and conservation status, emphasizing how the overall state of knowledge has changed since WOA I. Consequences of changing fish diversity for humanity are briefly considered, and perspectives for specific regions are provided. The Chapter concludes with an outlook for fish biodiversity, including continuing knowledge and capacity gaps. All 17,762 taxonomically valid species within the World Register of Marine Species (WoRMS) Superclass Pisces (WoRMS, 2019) are considered, including bony fishes (Class Actinopterygii, 16,503 species), sharks and rays (Elasmobranchii, 1,202 species), chimaeras (Class Holocephali, 55 species) and coelacanths (Class Coelacanthi, 2 species).

The global biomass of marine fishes is approximately 4 times the total biomass of all birds and mammals, and fishes constitute and important part of marine biodiversity. Approximately 70 per cent of the marine fish biomass is comprised of mesopelagic fishes, though with wide estimate ranges, found in depths of 200-1,000m (Irigoien and others, 2014, Hidalgo and Browman, 2019). Fishes occur throughout the world's oceans and in a wide range of depths. For example, the deepest fish seen alive is the snailfish *Pseudoliparis swirei*, formally described in 2017 and found in depths greater than 8,000 m in the Mariana Trench in the Pacific Ocean (Linley and others, 2016, Gerringer and others 2017). Fishes play a key role in marine food webs as both predators and prey, with many species moving through food webs throughout ontogeny, such as from planktonic larvae into predatory adults. Fish biodiversity varies between habitats. Habitat affiliations in Fishbase for 17,246 (97 per cent) species show that most bony fishes are demersal or reef-associated, while most species of sharks and rays, chimaeras and coelacanths are demersal or bathydemersal (Table 1).

Fish biodiversity is changing, and fishes are sensitive to environmental change due to multiple external pressures (Comte and Olden, 2017) and to exploitation via fisheries (see Chapter 15), which has important implications for human well-being (FAO, 2018). WOA I included chapters on the conservation challenges faced by the 1088 species of sharks and other elasmobranchs (United Nations, 2017c) and the 25 species of tunas and billfishes (United Nations, 2017d). In addition, overall synthesis chapters revealed fishes to be among the best-known marine groups (United Nations, 2017a, b), with clear latitudinal and depth gradients in diversity. The mechanisms driving fish diversity are complex and include ecosystem stability and age, niche partitioning and predator-mediated dampening of dominance (Rabosky and others, 2018).

Overexploitation and habitat loss and degradation were recently identified as major threats to marine fish biodiversity, while the impacts of climate change were becoming more apparent, but pollution was not considered to be a significant threat (Arlington and others 2016). Subsequently, evidence has emerged that scientific assessment and effective fisheries management can reverse the effects of overexploitation, leading to increases in abundance on average for well-managed stocks constituting half of the reported global fish catch, although overexploitation remains a significant threat in regions with less-developed fisheries management (Hilborn and others 2020). The impacts of climate change and thermal stress on marine fishes, particularly coral reef fish communities, have become more severe (Robinson and others 2019) while novel threats, for instance from microplastic pollution, are also now attracting increased research interest, although considerable uncertainty remains about their population-level effects (Villarrubia-Gómez and others 2018).

Table 1. Number of valid marine species in each taxonomic class of fishes according to the WoRMS taxonomy, in each broad habitat category. Percentages are the percentage of species in a class occurring in each habitat category. Numbers of species described since 2015 are shown in italics. Source: WoRMS Editorial Board (2019), Froese and Pauly (2019).

Habitat	**Actinopterygii**	**Elasmobranchii**	**Holocephali**	**Coelacanthi**
Bathydemersal	1785 (11%) *4*	314 (26%) *2*	38 (69%)	
Demersal	5691 (34%) *11*	449 (37%) *5*	11 (20%) *3*	2 (100%)
Benthopelagic	1422 (9%) *18*	131 (11%) *13*	4 (7%)	
Bathypelagic	1346 (8%) *3*	33 (3%) *1*	2 (4%)	
Pelagic-Neritic	807 (5%) *38*	34 (3%) *10*		

Pelagic-Oceanic	378 (2%) *1*	83 (7%) *11*		
Reef-Associated	4618 (28%) *93*	98 (8%) *1*		
Unknown	456 (3%) *22*	60 (5%) *2*		
Totals:	16503 *190*	1202 *45*	55 *3*	2 *0*

2. Documented change in state of fish biodiversity

Documenting changes in fish biodiversity requires considerations of fish taxonomy, including the description of new species; spatial distribution, which can be assessed using occurrence records to reveal contractions or expansions in species ranges; and formal assessments of conservation status, to highlight species of conservation concern. Summarising findings across higher taxonomic groups, and across groups of species occurring in similar habitat zones, is also necessary. Primary data sources used to quantify all these aspects of change are listed in Table 2.

Table 2. Major global aggregations of data on the taxonomy, systematics, geographic distribution, habitat affinities and conservation status of marine fishes.

Data type	**Source**	**Reference**
Taxonomy and systematics	World Register of Marine Species; California Academy of Sciences	WoRMS Editorial Board, 2019; van der Laan and others, 2019
Global occurrence data	Ocean Biogeographic Information System	OBIS, 2018
Habitat affinities	Fishbase	Froese and Pauly, 2019
Conservation status	IUCN Red List 2019	IUCN, 2019

2.1 Taxonomy

Since 2015, 238 new marine fish species have been described and added to WoRMS (Table 1). Almost half (49 per cent) of the newly described bony fishes are reef-associated, whereas most of the newly described elasmobranchs are pelagic (Table 1). This rate of description is around 6-7 times lower than the one species per day described between 1999 and 2013 (United Nations, 2017a). This taxonomic effort is supplemented by recent phylogenetic studies of bony fishes (Rabosky and others, 2018) and of sharks, rays and chimaeras (Stein and others, 2018).

2.2 Occurrences

Fishes continue to be well represented in global occurrence databases, providing insight into distributions, biogeography, and macroecological analyses. Collectively, the Ocean Biodiversity Information System (OBIS) (OBIS, 2018) includes occurrence records for 15,101 marine fish species, with fishes making up over a third (20,302,222) of occurrence records for all marine species. Occurrence records are now available from OBIS for 85 per cent of bony fishes, 84 per cent of elasmobranchs, 78 per cent of chimaeras, and one of the two Coelacanth species. A total of 306,913 of these occurrences have been added since WOA I, covering 4,099 (23 per cent) fish species, including 3,857 (23 per cent) bony fishes (total 241,385 new records), 233 (19 per cent) sharks and rays (65,480 new records), eight (15 per cent) chimaeras (46 new records) and one of the two coelacanths (two new records). Seventy-six species (68 bony fishes and eight elasmobranchs, 153 total occurrence records) have been recorded in OBIS for the first time since 2015. These species are primarily demersal (N = 32) or reef-associated (13). Five of the 238 species added to WoRMS since WOA I already have occurrences in OBIS.

2.3 Conservation status

Marine fishes are among the well-assessed marine taxonomic groups in terms of conservation status (Webb and Mindel, 2015). Fifty-three per cent (9,372 species) of all marine fishes have been assessed by the International Union for Conservation of Nature (IUCN) in the 2019 Red List (IUCN, 2019),[89] with 44 per cent (7,756 species) assigned to a category other than Data Deficient (DD). Thirty-two per cent (3,008 species) of all assessments of marine fishes have occurred since WOA I (2015). So far, no marine fish species has repeat assessments from both pre- and post-WOA I, so the IUCN Red List cannot yet be used to assess change in status of individual species. However, proportions of species in each threat category are shown for each taxonomic class in Table 3, and for each habitat affiliation in Table 4. Ecological and trait-based methods for predicting the conservation status of DD species suggest that, at least for Europe's sharks and rays, around a half to two-thirds of species in this category should also be considered at risk of extinction (Walls and Dulvy, 2019). Recent evidence suggests that 24% of the mean monthly space used by sharks falls under the footprint of pelagic longline fisheries and that pelagic sharks have limited spatial refuge from current levels of fishing effort in marine areas beyond national jurisdictions (Queiroz and others, 2019)

[89] Search focused on species in taxonomic Classes Actinopterygii, Cephalaspidomorphi, Chondrichthyes, Myxini, or Sarcopterygii with global scope, in the Marine Oceanic, Marine Deep Benthic, Marine Intertidal, Marine Coastal/Supratidal or Marine Neritic habitats, to ensure all species within WoRMS Superclass Pisces were included. Available at https://www.iucnredlist.org/search?permalink=c53bbf34-fec3-4549-8a83-d7630d2bc6bd.

Table 3. Number of species in each class assessed by the IUCN in each IUCN category. Pre-WOA 1 is the number of species that were most recently assessed before 2015; Since WOA 1 is the number of species most recently assessed since 2015. Also shown are the total number of species in each category for each class and the percentage of assessed species in the class in that category. The final row shows total species assessed pre- and since WOA 1 in each class, and the percentage of all species in that class that have been assessed.

Class / Status	**Actinopterygii**			**Elasmobranchii**			**Holocephali**			**Coelacanthi**		
	Pre WOA 1	Since WOA 1	Total (%)	Pre WOA 1	Since WOA 1	Total (%)	Pre WOA 1	Since WOA 1	Total (%)	Pre WOA 1	Since WOA 1	Total (%)
Least Concern	4642	2071	6713 (80.6%)	117	201	318 (31.8%)	9	16	25 (54.3%)			
Near Threatened	70	27	97 (1.2%)	85	22	107 (10.7%)	2		2 (4.3%)			
Vulnerable	171	39	210 (2.5%)	80	27	107 (10.7%)		1	1 (2.2%)	1		1 (50%)
Endangered	45	18	63 (0.8%)	29	15	44 (4.4%)						
Critically Endangered	25	2	27 (0.3%)	14	24	38 (3.8%)				1		1 (50%)
Extinct in the Wild / Extinct	2		2 (0.02%)									

Data Deficient	746	467	1213 (14.6%)	310	75	385 (38.5%)	15	3	18 (39.1%)			
Totals	**5701 (34.5%)**	**2624 (15.9%)**	**8325 (50.3%)**	**635 (52.5%)**	**364 (30.1%)**	**999 (82.6%)**	**26 (47.3%)**	**20 (36.4%)**	**46 (83.6%)**	**2 (100%)**	**0 (0%)**	**2 (100%)**

Table 4. Number of marine fish species in each IUCN category grouped by habitat affiliation. Percentages for ‘Not Assessed’ are the percentage of all known species with a given habitat affiliation that have not been assessed by IUCN. Percentages in the other columns are percentages of IUCN-assessed species falling into that category. IUCN categories ‘Least Concern and Lower Risk/Least Concern’ are combined as ‘Non Threatened’, and categories ‘Near Threatened, Vulnerable, Endangered, Critically Endangered, Extinct in the Wild, Extinct’ are combined as ‘Threatened’.

	Not Assessed	**Data Deficient**	**Not Threatened**	**Threatened**
Bathydemersal	1325 (61.9%)	285 (34.9%)	491 (60.1%)	41 (5.0%)
Demersal	3060 (49.7%)	617 (19.9%)	2169 (69.9%)	317 (10.2%)
Benthopelagic	936 (60.0%)	124 (19.8%)	440 (70.4%)	61 (9.8%)
Bathypelagic	594 (42.7%)	140 (17.6%)	452 (81.9%)	4 (0.5%)
Pelagic (Neritic)	351 (41.6%)	120 (24.4%)	335 (68.1%)	37 (7.5%)
Pelagic (Oceanic)	187 (40.5%)	41 (14.9%)	202 (73.5%)	32 (11.6%)
Reef-associated	1561 (33.0%)	262 (8.3%)	2712 (85.5%)	198 (6.2%)
Unknown	425 (82.2%)	27 (29.3%)	55 (59.8%)	10 (10.9%)

2.4 Advances in knowledge and capacity contributing to evaluation of change in state

Evaluation of change of state since WOA I is possible due to new data from ongoing long-term monitoring programmes (e.g. ICES international bottom trawl surveys), contribution of fishery observers to science data collection, global compilations of fish stock assessments (e.g. RAM Legacy Stock Assessment Database) and conservation assessments (e.g. 2019 IUCN Red List), as well as improvements in technology allowing sampling in novel environments (Linley and others, 2016) and monitoring of individual movements using satellite tagging (Curtis and others, 2018). Dramatic increases in knowledge of fish diversity have been made possible by increased deep-water fishing (to 1,200m) by commercial and research vessels, coupled with an increase in shallow-water sampling enabling discovery of many cryptic reef fish species in some regions (Gordon and others, 2010). Data infrastructure (e.g. WoRMS, OBIS and ICES data portal) providing the backbone for assessments has been supplemented by new analytical tools to interact with them (Boettiger and others, 2012; Chamberlain, 2018; Chamberlain and Salmon, 2018; Provoost and Bosch, 2019; Millar and others, 2019). These developments and tools have facilitated the use of marine fish data products as indicators of the status of marine ecosystems (ICES 2018, 2019).

3. Consequences of biodiversity change on human communities, economies and well-being

Changes in fish biodiversity have direct and immediate consequences for human communities, economies and well-being through their impacts on commercial, recreational and subsistence fisheries, as well as on alternative sources of income derived from marine ecosystems, including tourism (FAO, 2018). Fishes are integral to the achievement of United Nations Sustainable Development Goal 14 of conserving and sustainably using marine resources, with several indicators relating directly to the role that fishes play in sustainable food provision (see Chapter 15). In particular improved knowledge of the distribution and abundance of marine fishes is key to monitoring progress toward target 14.4 to effectively regulate harvesting. Increasing the economic benefits to Small Island Developing States and least developed countries through tourism (target 14.7) will involve understanding the distribution and status of charismatic fish species, such as manta rays (Kessel and others, 2017) or fish assemblages, such as coral reef fish (Wabnitz and others, 2018).

4. Key region-specific changes and consequences

4.1 The North Atlantic Ocean

In the Northern Atlantic and adjacent areas, pressure on fish stocks (F/Fmsy) shows an overall downward trend over the period 2003-2017, with the median fishing mortality stabilised at 1.0. The F/Fmsy indicator for the Mediterranean and Black Seas has remained at 2.2. The number of stocks within safe biological limits has almost doubled, from 15 in 2003 to 29 in 2017, with the largest increase in the Bay of Biscay and the Iberian waters – from 2 to 8 stocks. The overall biomass volume has continued to develop positively, increasing by around 36%. In the Mediterranean and Black Seas, the 2016 spawning stock biomass showed no significant increase compared to 2003. The Northwest Atlantic saw a marked change in fish community structure with the collapse of cod and mackerel stocks due to overfishing (Shelton and Sinclair, 2008; Van Beveren and others, 2020).

In the Baltic Sea, gradual long-term trends, rather than abrupt changes in functional diversity and multi-trait community composition were observed between 1971–2013 (Törnroos and others, 2018). There are three sub-assemblages along a strong west-east salinity gradient, with low functional redundancy in the Baltic Proper compared with other sub-areas, suggesting an ecosystem more susceptible to external pressures (Frelat and others, 2018). In the North Sea, taxonomic and trait-based indicators provide new evidences of fish assemblage structure and highlight the multifaceted effects of drivers responsible for these changes. Specifically, the central North Sea displayed a decrease in community size structure linked to changes in fishing, and the Norwegian trench region displayed an increase in community size structure with primarily linkage to climate change while no change was observed along the eastern

Scottish coast where the community size structure was most strongly associated to net primary production (Marshall and others, 2016). In the Mediterranean, dynamics of small and medium pelagic fish populations exhibit synchrony with climate variability: while the North Atlantic Oscillation is affecting their dynamics in the western and central Mediterranean anchovy and sardine populations follow the signal of the Atlantic Multidecadal Oscillation in the eastern and central Mediterranean. Thus, there are strong sub-regional patterns in the temporal dynamics of pelagic fish in the Mediterranean Sea (Tsikliras and others, 2019).

4.2 The South Atlantic Ocean

The Wider Caribbean is highly biodiverse, and an important region of fish endemism, with approximately 50 per cent of its bony fishes occurring nowhere else (Linardich and others, 2017). Diverse oceanographic and hydrographic features yield an array of subtropical and tropical habitats, including 8 per cent of the world's coral reefs and 6 per cent of seamounts (Oxenford and Monnereau, 2018). Fish biodiversity is negatively affected by overfishing, habitat destruction (particularly of coral reefs) and climate change (Jackson and others, 2014; Oxenford and Monnereau, 2018). Several large-bodied fish species have become commercially extinct or critically endangered (Linardich and others, 2017). The reduction in fish biodiversity is impacting the functioning of Caribbean coral reefs (Lefcheck and others, 2019), with socioeconomic consequences, especially for small island developing States, where up to 22 per cent of the workforce is employed in the fisheries sector (CARICOM, 2019).

A significant emerging phenomenon is the unprecedented bloom of pelagic *Sargassum* seaweed across the equatorial Atlantic which, since 2011, has been advecting into the Caribbean Sea (Wang and others, 2019). This has negatively impacted critical fish habitats and associated fish biodiversity nearshore (van Tussenbroek and others, 2017, Rodríguez-Martínez and others, 2019), although it has had positive effects on some pelagic reef-associated species, which have increased and are now supporting fisheries (e.g. e.g. yellow jack *Carangoides bartholomaei*, almaco jack *Seriola rivoliana*) (Ramlogan and others, 2017; Monnereau and Oxenford, 2017). Landings of offshore pelagic species appear to have been disrupted by the presence of *Sargassum* with some being more readily available, but often as small juveniles (e.g. dolphinfish *Coryphaena hippurus*), whilst others (e.g. flyingfish *Hirundichthys affinis*) are more difficult to catch (Oxenford and others, 2019; CRFM-JICA, 2019).

4.4 The South Pacific Ocean

The South Pacific Ocean includes several highly biodiverse tropical, sub-tropical and temperate marine ecosystems, modulated directly by the El Niño-Southern Oscillation and monsoons. There is high inter-annual variability of primary production that leads to a rich diversity of marine fishes , including reef fishes, pelagic species and highly migratory species (e.g. tuna, sharks, manta rays). Fish biodiversity in this region is impacted by fishing (incl. bycatch) on small pelagics, sharks and tuna, as well as by climate change and pollution, which threaten nursery habitats and drive species from tropical to temperate waters. Destruction of strategic habitats, such as mangroves, can change the distribution and abundance of fish species that use these areas for reproduction and feeding.

Areas of the South-West Pacific that have been explored, including ocean ridges and seamount chains, support a rich marine fish diversity (Clark and Roberts, 2008; Roberts and others, 2015). The fish faunas of the tropical islands of Melanesia and Polynesia in the northern South-West Pacific are predominantly Indo-West Pacific in nature, with high diversity but relatively low levels of endemism. In contrast, New Caledonia is a centre of fish endemism, with 107 of 2,341 recorded species endemic to the exclusive economic zone (Fricke and others, 2011; 2015). Off New Zealand, the number of known marine fish species has grown from around 1,000 species in 1993 to over 1,294 in 2019 (Roberts and Paulin, 1997; Roberts and others, 2015, 2019), with 22 per cent endemic to the New Zealand region and half of the additional species new to science. Australia is positioned southwest of the previously mentioned tropical archipelagos, spans the junctions of two major oceans, and has around 2,000 known marine fish species.

4.3 The North Pacific Ocean

The North Pacific Ocean, extending from arctic to tropical waters, has the highest fish species diversity in the world, with more than 6,000 species. This rich diversity is derived from and supported by strong water currents flowing northward and southward along the north-western continental shelf. Such currents have functioned both to transfer fishes and isolate fish populations, thereby facilitating speciation (Motomura, 2019). The northern region is a major fishing ground, contributing to about 30 per cent of global catches, mainly targeting pollock, tuna, sardines, and anchovy. The southern region includes the northern part of the Coral Triangle, identified as a marine biodiversity hot spot, and has a higher species richness of shore fishes than any other large marine area on the globe (Roberts and others, 2002). Most fishes in the southern part are associated with coral reefs and have seen population declines due to intense fishing pressure and habitat degradation (Nañola and others, 2011).

5. Outlook

Positive outlooks for fish biodiversity come from the evidence that individual fish populations respond positively to effective fisheries management (Hilborn and others, 2020) and that fish diversity and biomass increases within effective Marine Protected Areas (Sala and Giakoumi, 2018). However, the global extinction of the smooth handfish *Sympterichthys unipennis* (Last and others 2020) is a reminder that fish biodiversity continues to face significant threats as well. Both positive and negative outcomes are known because fishes continue to be among the most systematically studied and monitored components of marine ecosystems, mostly due to their economic value. Nonetheless, considerable fish diversity remains to be discovered: expert estimates indicate that at least another 700 fish species (a ~50 per cent increase over the number of currently known species) are yet to be described from the New Zealand exclusive economic zone and extended continental shelf alone (Gordon and others, 2010; Roberts and others, 2019). Further increase in capacity in taxonomy and biosystematics (Taxonomy Decadal Plan Working Group, 2018), integration of data from the existing biodiversity collections (Nelson and others, 2015) and other sources (Edgar and others, 2016), would pave the way for more comprehensive, synthetic analyses of fish biodiversity over the near to medium term. In addition to improving our understanding of fish biodiversity, improved estimates of fish biomass are needed for some ocean zones, such as the pelagic zone. While mesopelagic fish are estimated to dominate global fish biomass, biomass estimates span orders of magnitude and therefore are still poorly understood (Irigoien and others, 2014; Hidalgo and Browman, 2019). Additionally, while there are no current estimates of species richness or biomass of bathypelagic fish, which reside in the world's largest environment (by volume), it is highly likely that these fish comprise a large portion of global fish biomass (Sutton and others, 2017). Since WOA I, the disposal of deep-sea mining water after ore removal has emerged as a significant threat to bathypelagic fish (Drazen and others, 2019). Summary of key knowledge and capacity gaps in fish biodiversity can be found in Table 5.

Table 5. Key gaps in our understanding of the biodiversity of marine fishes, with examples of remedial steps and capacity building activities that have been employed to address them.

Knowledge/capacity gap	**Examples of remedial steps taken to address gaps**
Taxonomic/biosystematics infrastructure and capacity	National/international plans to support and develop core taxonomic activities, workforce and infrastructure (e.g. Taxonomy Decadal Plan Working Group, 2018)
Mobilization of existing data into open, global repositories	Historical data rescue, digitization of museum specimens and historical biodiversity literature (e.g. Faulwetter and others, 2016)
Understanding of mesopelagic and deep sea fish diversity	More and better sampling regimes, employing novel technologies (e.g. Linley and others, 2016; Hidalgo and Browman, 2019)
Response of fishes to multiple simultaneous stressors	Better linking of relevant data across disciplines (e.g. Hodgson and others, 2019)

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Chapter 6D
Marine Mammals

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Keynote points

- Marine mammals play a key role in marine ecosystems in terms of biomass, consumption and energy transfer, and continue to provide significant economic and cultural contributions to coastal communities.
- The number of species for which a conservation status is available has increased, with eight species moving from a status of data deficiency as a result of new information. Of baleen whales, 36 per cent of species are increasing in abundance. Overall, the status of coastal dolphins, sirenians and marine otters is deteriorating, with the vacquita close to extinction. Many species lack population abundance information.
- Fisheries bycatch continues to be a dominant conservation threat for many species. Indirect threats such as habitat alteration, including overfishing of prey, land-based pollution, anthropogenic noise, ship strikes and disturbances are becoming more prevalent, particularly in coastal zones.
- There is apparent increasing consumption of hunted and bycaught small marine mammals in some coastal developing nations.

1. Introduction

There are 132 extant species of marine mammals (cetaceans, pinnipeds, sirenians, otters, polar bears) with varied habits, ranging from cosmopolitan, comprising multiple discrete local populations (e.g. some dolphin species), to endemic to specific ecoregions (e.g. freshwater dolphins). The First World Ocean Assessment (WOA I) (United Nations, 2017) recognized direct takes (including commercial and subsistence harvest), fisheries interactions, (including entanglement and bycatch), and habitat alteration (including disturbance, coastal and riverine developments and climate change) as key pressures linked to trends in the abundance of marine mammals.

In the present Chapter, we report changes in the global status of marine mammals since WOA I on the basis of the International Union for Conservation of Nature (IUCN) Red List assessments carried out by the IUCN Species Survival Commission Specialist Groups for marine mammals (IUCN, 2019). These assessments (Figure 1) are complemented, where needed, using primary literature. We also report changes in Conservation Threats (IUCN, 2019) faced by species calculated over two decades: 1999–2008 and 2009–2018.

Overall, fewer marine mammal species are of a data deficient (DD) status due to more information on populations becoming available (Figure 1). Since WOA I, the status of eight marine mammal species has improved, while the status of four species has declined (Figure 1). These trends give a picture of cautious optimism, showing that, on a global scale, the individual management measures put in place for well-known conservation threats, together with increased efforts to gather data and information on marine mammal species, are showing signs of effectiveness.

Since WOA I, advances in the understanding of the role of marine mammals in the state and productivity of marine systems have been made (Roman and others, 2014), including in nutrient cycling and carbon storage (Doughty and others, 2016), trophic cascades (Estes and others, 2016; Burkholder and others, 2013; Kiszka and others, 2015) and ecosystem engineering. Decreases in marine otter populations have had profound impacts on coastal ecosystems in the eastern Pacific (Estes and others, 1998; Estes and others, 2016). It is likely that the continued recovery of baleen whale abundances, following their overexploitation in the nineteenth and twentieth centuries, will influence marine food webs in multiple ways, through consumption, but also vertical (through the water column) and horizontal (between foraging and calving ground) transfer of nutrients (Roman and others, 2014). Similar to all predators in marine systems, marine mammal populations are affected by variability in the timing and location of productivity in ocean basins. Some species are likely to be more resilient than others to changes to marine productivity dynamics caused by climate change and overexploitation as a result of more flexible behaviours (Sydeman and others, 2015; Moore and Reeves, 2018).

Intentional takes for subsistence or for commercial harvest and bycatch and entanglement in other fisheries continue to be identified as the main conservation threats for all groups of marine mammals under assessments conducted by the IUCN (Figure 2; IUCN, 2019). The diversification of human activities in the oceans, including for energy production and mining as part of expanding "blue economies" in many marine regions (Eikeset and others, 2018), poses new conservation challenges for marine mammals. Climate change and associated changes to marine ecosystem dynamics, anthropogenic noise, ship strikes, habitat modification and behavioural disruptions, are now emerging as influencing a wider range of species (Figure 2; IUCN, 2019). Crucially, individual threats can interact and lead to cumulative effects, compounding their impacts on species (National Academies of Sciences, Engineering and Medicine, 2017; see also Chapter 28 of the present Assessment).

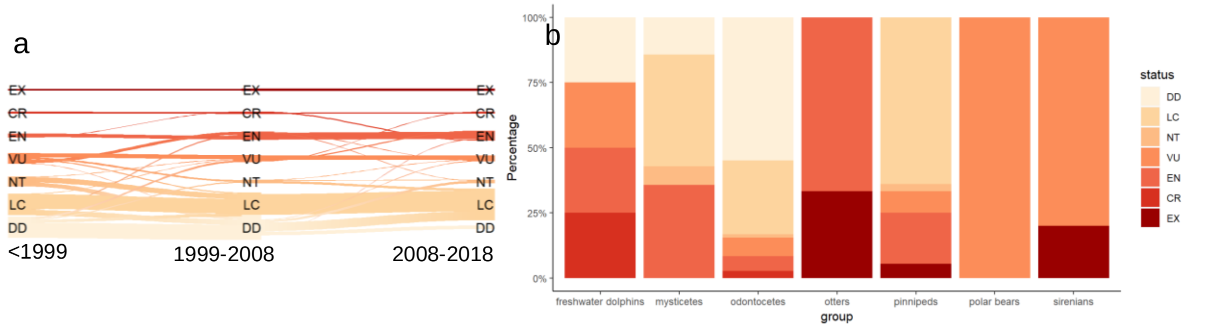

Figure 1. (a) Change in the conservation status of marine mammals before 1999, 1999-2008 and after 2008 on the basis of IUCN Red List assessments; (b) Composition of current conservation status of marine mammal species by groups. DD: Data Deficient; LC: Least Concern; NT: Near Threatened; VU: Vulnerable; EN: Endangered; CR: Critically Endangered; EX: Extinct.

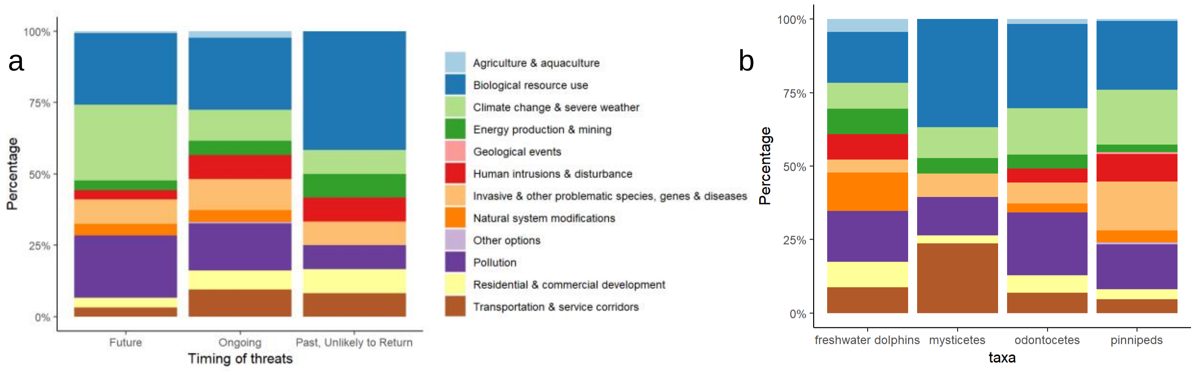

Figure 2. (a) Currently identified main conservation threats for all marine mammals categorized by the timing of their impact on those species; (b) Conservation threats for specific groups. Threat categories are IUCN Red List threats where anthropogenic noise is categorized as pollution and fisheries impacts as biological resource use (IUCN, 2019).

2. Cetaceans

2.1. Baleen whales (Mysticetes)

2.1.1. Diversity

Fourteen extant species of baleen whales are currently recognized. They are distributed among four families (Balaenidae, Balaenopteridae, Neobalaenidae, and Eschrichtiidae).

2.1.2. Abundance and main threats

Of the Balaenidae species, the bowhead whale (*Balaena mysticetus*) and the southern right whale (*Eubalaena australis*) are assessed as Least Concern (LC) reflecting increasing population trends. For the latter, however, not all geographically defined populations are increasing (George and others, 2018). The North Atlantic right whale (*E. glacialis*) has most recently been assessed as endangered (EN). Although the population of this species was estimated to have increased from 1990 to 2010, it is now estimated to have declined 16 per cent in the following years (Pettis and others, 2018). No range-wide population size or trend is available for the North Pacific right whale (*E. japonica*) (EN).

Of the Balaenopteridae species, new information on Antarctic minke whales (*Balaenoptera bonaerensis*) and Bryde's whales (*B. edeni*) has resulted in a change in status from Data Deficient (DD) to Near Threatened (NT) and LC, respectively (Figure 3a). Globally, increasing population trends have been estimated for blue (*B. musculus*; EN), sei (*B. borealis; EN*) and humpback (*Megaptera novaeangliae; LC*) whales, with populations recovering from industrial whaling exploitation (IUCN, 2019). These increases have resulted in fin whales (*B. physalus*) being uplisted from EN to Vulnerable (VU). The gray whale (*Eschrichtius robustus*) is listed as LC and considered stable, and the pygmy right whale (*Caperea marginata*) is LC with an unknown population abundance or trend.

Main ongoing threats for baleen whales identified by IUCN Red List assessments include entanglement in fishing gear (fin, gray, humpback and North Atlantic right whales), harvesting (common (*B. acutorostrata*) and Antarctic minke whales[90] and sei whales) and

[90] It is noted that with the cessation of whaling operations in the Southern Ocean this threat has likely been reduced

ship strike (blue, fin, gray, humpback and northern and southern right whales) (IUCN, 2019). Climate change effects on biological productivity and, consequently, prey availability (Cabrera and others, 2018) are a concern. However, observations for some species are not consistent with projections. For example, the bowhead whale, endemic to the Arctic, is increasing despite current rapid ice loss (Moore and Reeves, 2018) and associated projected declines in prey. Importantly, environmental change can interact with other anthropogenic threats to cause unforeseen synergistic impacts (Moore and others, 2019; Seyboth and others, 2016). For example, climate-driven shifts in habitat use by North Atlantic right whales into unprotected shipping and commercial fishing areas have resulted in increases in mortality associated with entanglement and ship strike (Corkeron and others, 2018; Meyer-Gutbrod and Greene, 2018). Direct take of baleen whales through commercial and subsistence harvest are generally within sustainable limits.

2.2. Toothed whales, dolphins and porpoises (Odontocetes)

2.2.1. Diversity

Seventy-five species of toothed cetaceans distributed across ten families are recognized globally. The Delphinidae family is the most diverse and includes some of the most threatened species (Figure 3c).

2.2.2. Abundance and main threats

Pelagic toothed whales, dolphins and porpoises

Due to their wide-ranging distributions, trends in the abundance of pelagic cetacean populations, and threats are often difficult to assess. As a result, most oceanic species continue to be listed as LC, except for the sperm whale (*Physeter macrocephalus*; VU) and the false killer whale, (Pseudorca crassidens; moved from DD to NT). A recent global population size or trend estimate for sperm whales does not exist. Beaked whales consist of 22 pelagic deep diving species that are still poorly known, with a new species (*Berardius minimus*) proposed and currently being considered (Yamada and others, 2019). All species within this group remain DD, except for the southern bottlenose whale (*Hyperoodon planifron*s) and Cuvier's beaked whale (*Ziphius cavirostris*), both listed as LC. The killer whale (*Orcinus orca*), a cosmopolitan species, is DD globally, but the small coastal southern resident population in the eastern North Pacific is listed as EN in the United States of America and Canada as a result of threats associated with prey availability, vessel and acoustic disturbance, and accumulation of contaminants (Southern Resident Orca Taskforce, 2019).

Entanglement in fishing gear is identified as a threat for several oceanic species (IUCN, 2019). Other interactions with fisheries, such as catch depredation and bait stealing by false killer, killer and sperm whales can result in deterrent actions, such as shooting and subsequent mortality (Tixier and others, 2019; Werner and others, 2015; Hamer and others, 2012). Anthropogenic noise derived from, in particular, mid-frequency active sonar is of concern for deep diving species, such as beaked whales, *Kogia* spp. and sperm whales (Pirotta and others, 2018; Harris and others, 2018). Decreasing sea ice and warmer waters has increased interactions between ice-dwelling species such as the narwhal (Monodon monoceros) and more boreal mammal species, such as the killer whale, and reduced accessibility to foraging habitat (Breed and others, 2017).

Coastal and estuarine dolphins and porpoises

This group is represented mostly by inshore and regionally restricted species or populations, including endemic species (Möller, 2012) and is the most susceptible to human interactions because of these characteristics. This susceptibility is reflected in the fact that ten of the 35 species show decreasing trends, with two CR, four EN, and four VU (Figure 3b). Regionally restricted populations can result in locally varying states. For example, bottlenose dolphins (*Tursiops truncatus*) are assessed as LC globally, but the Fiordland, New Zealand, regional population is currently assessed as CR; the Mediterranean Sea population as VU; and the Black Sea population as EN. Populations of coastal and estuarine dolphins are predominantly threatened by intentional and non-intentional capture from fisheries. Despite management plans, failure to reduce captures to sustainable levels have led to severe declines in abundance, particularly for the vaquita (*Phocoena sinus*) (Jaramillo-Legorreta and others, 2019) and the Māui dolphin (*Cephalorhynchus hectori maui*) (Baker and others, 2016). In particular, the vaquita is at a high risk of extinction over the next ten years (Rojas-Bracho and others, 2019). Other threats to coastal dolphins and porpoises include climate change, and associated changes to marine ecosystem dynamics, pollution, ship strike, novel diseases, and disturbances caused by industrial and recreational human activities.

Freshwater dolphins

This group of dolphins (Figure 3d) includes the Baiji River dolphin (*Lipotes vexillifer*). which is currently classified as CR (possibly extinct) (IUCN, 2019); the Amazon River dolphin (*Inia geoffrensis*), which has declined by 70 per cent in the Mamirauá Reserve in Brazil over less than one dolphin generation (da Silva and others, 2018); and the Ganges (*Platanista gangetica*) and Indus (*Platanista gangetica minor*) dolphins, all of which are currently classified as EN. Species-level abundance estimates are lacking for these species. Key threatening processes affecting all species include water development projects, which fragment habitats, pollution from run-off, bycatch, direct takes and other anthropogenic habitat modification, all of which lead to continued population declines (IUCN, 2019). Most freshwater dolphin species belong to single species families and their loss, therefore, represents the loss of entire evolutionary lineages.

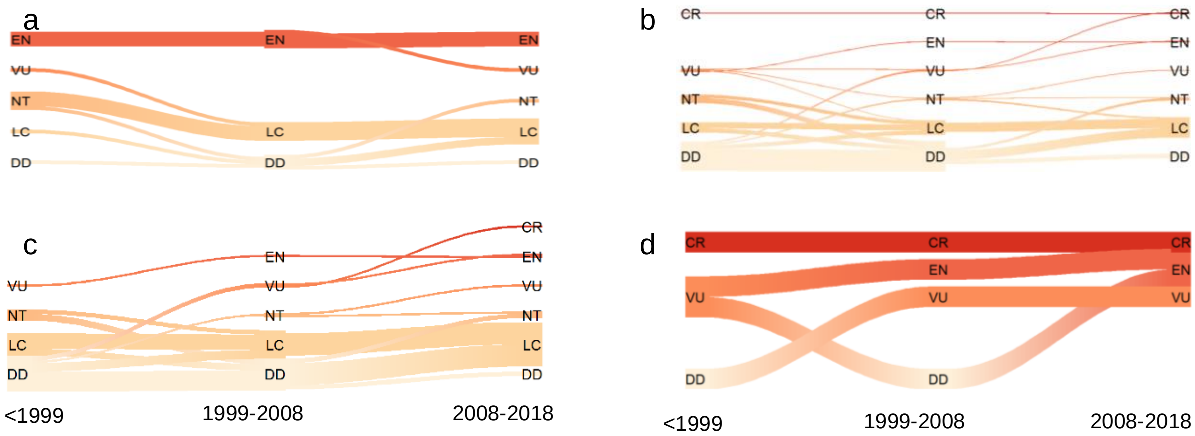

Figure 3. Change in the conservation status of (a) baleen whales, (b) toothed whales, (c) delphinids and (d) freshwater dolphins before 1999, 1999-2008 and after 2008on the basis of IUCN Red List assessments. DD: data deficient; LC: Least Concern; NT: Near Threatened; VU: Vulnerable; EN: Endangered; CR: Critically Endangered.

3. Pinnipeds

3.1. Diversity

Thirty-three extant and two recently extinct species are recognized from three families of pinnipeds (Otariidae, Phocidae and Odobenidae). Most pinnipeds are range limited, with seven species limited to cold temperate and Arctic waters in the Northern Hemisphere and four limited to Antarctic waters in the Southern Hemisphere. A further four species are restricted to the Caspian Sea, Lake Baikal, the Hawaiian Islands and the Mediterranean Sea.

3.2. Abundance and main threats

Phocidae

Global trends are available for eight species of phocids: four species are increasing in abundance, including the Mediterranean monk seal (*Monachus monachus*; uplisted from CR to EN); one is decreasing, namely the EN Hawaiian monk seal (*Neomonachus schauinslandi*); and three are stable (Figure 4). The most numerous species in the Antarctic is the crabeater seal (*Lobodon carcinophaga*) with 4 million adults. In the Arctic, the most numerous is the harp seal (*Pagophilus groenlandicus*) with 4.5 million adults (IUCN, 2019).

Threats to phocids are consistent across species, and include habitat loss and alteration (loss of pupping and resting areas), fisheries interactions (intentional killing, entanglement and competition) and disease transfer potentially from pets and feral terrestrial mammals (Figure 4b; IUCN, 2019). The recent change in trend in the Mediterranean monk seal may be due to successful local adaptations of the species in part due to avoidance of human interactions (e.g. utilisation of refuges, changes in environmental stewardship and declining interactions (Notarbartolo di Sciara and Kotomatas, 2016)).

Otariidae

Currently threatened otariids (e.g. the New Zealand *Phocarctos hookeri* sea lion, the Australian *Neophoca cinerea* sea lion, and the Galapagos *Zalophus wollebaeki* sea lion) are continuing to decrease in abundance, while those that are LC are increasing (e.g. the New Zealand fur seal, *Arctocephalus forsteri*, and the California sea lion, *Zalophus californianus*). Steller sea lions (*Eumetopias jubatus*) are the exception, with the species uplisted from EN to NT in 2012 (IUCN, 2019). This improvement has been largely driven by a doubling of the subspecies Loughlin’s Steller sea lion (*Eumetopias jubatus monteriensis*) since the 1980s after protection from hunting. Western Steller sea lions (*Eumetopias jubatus jubatus*), although increasing in parts of their range, continue to decline in the Aleutian Islands. Otariid species currently identified as threatened tend to have more limited ranges and are therefore sensitive to rapid changes in marine productivity caused by climate change (Atkinson and others, 2008; McClatchie and others, 2016) (Figure 4b). Other threats include interactions with fisheries (bycatch and competition for prey) (Chilvers, 2012; Hamer and others, 2013). Although bycatch management has reduced fisheries-related mortality for some species, other factors may be interacting with this conservation threat, leading to reduced survival of particular life stages and cohorts, resulting in a lack of recovery (Hamilton and Baker, 2019).

Odobenidae

The single species in the family Odobenidae, the walrus (*Odobenus rosmarus*), is currently assessed as VU. There are an estimated 225,000 individuals although trends are unknown (IUCN, 2019). Although they were unsustainably harvested in the past, current management approaches are yielding sustainable catches. Climate change and associated habitat modification is expected to affect sustainable harvest levels for the species (MacCracken, 2012), with consequences for human food security. The development of human industrial activities in the Arctic linked to sea ice loss further compounds conservation threats for this species (Moore and Reeves, 2018).

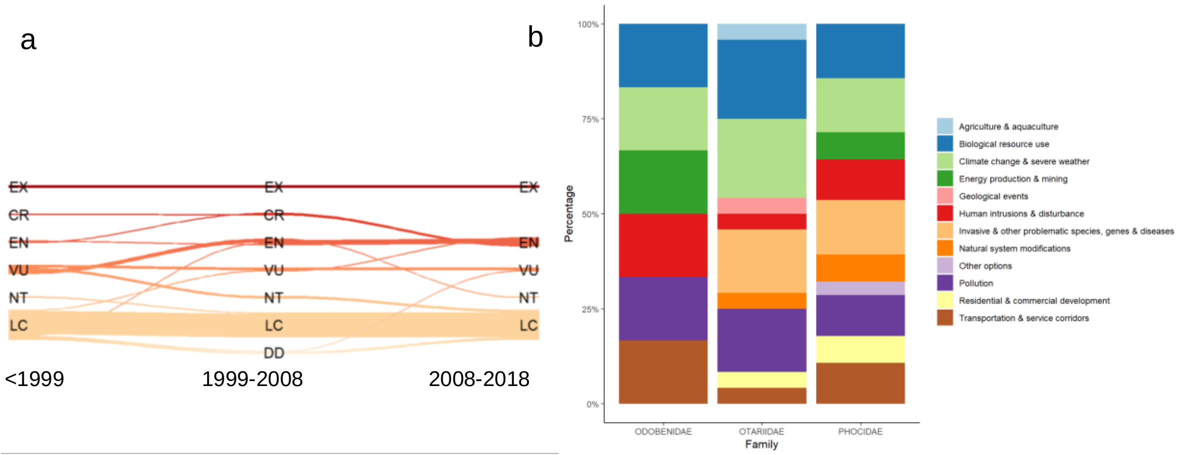

Figure 4. (a) Change in the conservation status of pinnipeds before 1999, 1999–2008 and after 2008on the basis of IUCN Red List assessments; and (b) Composition of ongoing and future threats to the three pinniped families. DD: data deficient; LC: Least Concern; NT: Near Threatened; VU: Vulnerable; EN: Endangered; CR: Critically Endangered; EX: Extinct. Threat categories are IUCN Red List threats where anthropogenic noise is categorized as pollution and fisheries impacts as biological resource use (IUCN, 2019).

4. Sirenians

4.1. Diversity

There are four extant species in the order Sirenia (African manatee, *Trichechus senegalensis*; American manatee, *Trichechus manatus*; dugong, *Dugong dugon*; and Amazonian manatee, *Trichechus inunguis*), with some evidence of genetic partitioning between populations across their range (Hunter and others, 2010).

4.2. Abundance and main threats

There continues to be a lack of species abundance estimates for the four species. Indirect evidence indicates decreasing population trends and all species are classified as VU (IUCN, 2019). Overall, main drivers associated with decreasing populations have been habitat loss, direct and incidental catch and boat collisions (IUCN, 2019). In the north-east of Brazil, high neonate and calf mortality has been connected with decreasing calving habitats associated with the development of shrimp farms and silting of estuaries (Balensiefer and others, 2017).

5. Otters and polar bears

5.1. Diversity

The family Mustelidae includes two extant marine otter species (marine otter, *Lontra felina;* and sea otter, *Enhydra lutris*). The family Ursidae includes one extant marine species, the polar bear (*Ursus maritimus*).

5.2. Abundance and main threats

Marine and sea otters.

Although global abundance estimates are not available for both species, they are regarded as decreasing overall as a result of failures fully to recover from past overexploitation for fur. As a result, both species are currently listed as EN. However, several remnant populations are now increasing as a result of conservation management programmes. New threats limiting recovery include: disease; offshore oil exploitation and transport (including spills); poaching; bycatch; intentional killing; and disturbance from recreational activities (Duplaix and Savage, 2018). Variability in abundance has been linked to El Niño events and associated effects on Pacific coastal ecosystems. Although projected changes to the El Niño Southern Oscillation are unclear, any changes in occurrence and intensity may impact this species (Vianna and others, 2010).

Polar bears

Polar bears remain listed as VU with trends in abundance unknown. A global estimate of 16,000 to 31,000 individuals was recently produced (Hamilton and Derocher, 2019). The most serious threat to this species is the loss of Arctic ice habitat for key demographic functions caused by climate change (Regehr and others, 2016). Pressures from new pathogens as a result of the reduction of sea ice and intensifying industrial and recreational activities as accessibility to the region increases are haing a greater influence on populations (Hamilton and Derocher, 2019).

6. Consequences of changes on human communities, economies and well-being

6.1. Consumption and competition

The recovery of several marine mammal populations is generating the potential for conflicts in some regions and opportunities in others. Marine mammals can learn to associate fishing activities with food availability leading to development of behaviours to depredate catches from fishing vessels (Tixier and others, 2019) and creation of conflict with aquaculture operations (Guerra, 2019).

Following an increase in minke whale catches and a resumption of commercial fin whaling prior to WOA I, north Atlantic commercial catches of minke whales have since decreased and stabilised[91] and commercial catches of fin whales was suspended in 2019 and 2020 (small numbers have been taken since WOA1 as part of regulated subsistence catches). Over the same period, catches of pinnipeds and other cetaceans in the Northern Hemisphere have remained relatively stable overall (NAMMCO, 2019; IWC, 2019). Commercial catches in the western north Pacific have remained broadly stable since WOA I (IWC, 2019, catches taken under Special Permit) and catches in Antarctic waters were suspended in 2019 (IWC, 2019). Regulated subsistence hunting of marine mammals remains stable (NAMMCO, 2019; IWC,

[91] see https://nammco.no/

2019). Two intergovernmental organizations continue to provide a forum for the discussion, assessment and management of catches of marine mammals; the International Whaling Commission (IWC) established in 1946 and the North Atlantic Marine Mammal Commission (NAMMCO) established in 1992.

Bycaught marine mammals can complement fishery catches for human consumption. This practice can be further complemented by hunting or the use of stranded animals in some countries (Robards and Reeves, 2011). Such use of marine mammals has been termed “marine bushmeat”. This is an analogy with ‘bushmeat’ in supporting food security in deprived regions (Cosentino and Fisher, 2016; Clapham and Van Waerebeek, 2007). Catch and consumption of coastal species in lower latitudes is likely to have increased (Robards and Reeves, 2011), particularly in south-east Asia and west Africa (Porter and Lai, 2017; Liu and others, 2019; Mintzer and others, 2018; Van Waerebeek and others, 2017), where the sustainability of such practices is often unknown. As habitat change associated with climate change redistributes species and potentially impacts population abundances (Moore and Reeves, 2018), communities relying on the harvesting of marine mammals for food are also likely to be impacted, resulting in future food security challenges (Brinkman and others, 2016).

Marine mammals remain culturally significant with objects created from body parts, and as part of the imagery of coastal traditions and cultures. This cultural heritage is key to community cohesion and identity and includes unique elements such as cooperative fishing between people and dolphins in Brazil (Daura-Jorge and others, 2012).

6.2. Non-lethal activities

Marine mammals continue to be a key feature of marine tourism (see also Chapter 24 of the present assessment), which has increased and diversified (Hoyt, 2018). There is anecdotal evidence of expansion of tourism focused on marine mammals in novel locations or of increased sighting rates in mature touristic activity locations as a result of distributional shifts associated with population recovery and climate change (e.g., Accardo and others, 2018; Halliday and others, 2018). Tourism is now listed as a conservation threat for 11 cetacean and 13 pinniped species (Figure 2; IUCN, 2019). Tourism activities offer the opportunity of income generation for coastal communities as long as appropriate management schemes are developed to ensure that marine mammal populations are not overexploited (Christiansen and Lusseau, 2015; Pirotta and Lusseau, 2015), investment is responsible, and profits remain in the community (Higham and others, 2016). Quantification of the socio-ecological contribution of marine mammal related tourism to global coastal communities remains outstanding.

7. Outlook

Marine mammal conservation successes include an end to overharvesting of large whales and unsustainable bycatch in large-scale pelagic drift net fishing (Reeves and others, 2013). We can expect continued improvements of stocks as long as management efforts are maintained (Bejder and others, 2016) and not impaired by climate change (Tulloch and others, 2019).

The number of species listed as EN or CR (22 species) clearly demonstrates urgent management and conservation challenges. Almost all critically endangered species and subpopulations of species, including the vaquita, Baiji River dolphin, Māui dolphin and

Atlantic humpback dolphin (*Sousa teuszii*), have very limited distributions. Despite detailed knowledge of the risks to them, decades of management interventions have not improved their population status (Figure 3c). Unless management measures for these species can reduce current threats, current assessments estimate that within ten years, those CR species/subpopulations will have further deteriorated and may become extinct (CIRVA, 2019, IUCN 2019).

Global initiatives are required to develop comprehensive management plans for far-ranging species. Since WOA I, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has established a marine protected area (MPA) in the Ross Sea (CCAMLR, 2016). The multiple objectives of the MPA include protection of core foraging areas of Weddell seals (*Leptonychotes weddellii*) and Type C killer whales. Fixed spatial management, such as an MPA, has been identified as effective for species conservation (Gormley and others, 2012). The current shifts in threats observed (Figure 2), alongside rapid changes in marine ecosystems driven by climate change, however, make MPAs a less flexible tool, especially for ensuring that highly mobile species can be conserved and used sustainably (Pinn, 2018; see also Chapter 30 of the present Assessment).

Since WOA I, it has become apparent that cumulative impacts from multiple sectors (see also Chapter 28) are increasingly influencing the conservation status trajectories of marine mammals (National Academies of Sciences, Engineering and Medicine, 2017). In the coming decades, climate change will influence marine mammals in multiple ways (Figure 2), including habitat and food web modifications. In addition, increased exposure to human activities and associated stressors will contribute to cumulative effects, potentially curtailing recent recoveries (Tulloch and others, 2019). Trophic amplification may strengthen climate change impacts up the food web, with proportionally stronger impacts on the higher trophic levels occupied by marine mammals (Lotze and others, 2019).

New technological and analytical developments have helped to design frameworks to quantify the population consequences of multiple stressors using observational data (see Chapter 28). We are, therefore, better equipped to estimate the conservation impact of non-lethal and indirect stressors such as anthropogenic noise, tourism and offshore renewable energy systems. Ecosystem approaches to risk assessments (Holsman and others, 2017) are increasingly being used as critical elements of Integrated Ecosystem Assessments (see also Chapter 30). These approaches also place risks within the wider socio-ecological context of the communities using marine mammals.

8. Key remaining knowledge gaps

The world is changing rapidly, challenging our ability to forecast marine mammal status and exploitation patterns based on retrospective analyses. These rapid changes require new mechanistic approaches to forecasting how species and populations will respond to climate change and the sustainability of current and future direct and indirect human impacts. Specifically, there is a need: (i) to develop approaches to assess and forecast how marine mammals respond and adapt to climate change and associated changing marine ecosystems, ii) for greater understanding of the cumulative effects of multiple anthropogenic pressures on marine mammals, including ongoing and new exploitations; (iii) to develop processes to identify and implement management actions that successfully secure critically endangered marine mammal species from extinction and (iv) greater understanding of DD populations that allows for quantification of their abundances thereby facilitating their classification and movement out of the DD category. In addition, further work is needed to better understand the role of marine mammals in ocean processes, including in the spatial transfer of nutrients and carbon[92]

9. Key remaining capacity-building gaps

A broad understanding of the human dimensions that lead to successful and unsuccessful management interventions and the capacity and resources to engage in them is currently lacking. Where marine mammals are abundant, there is often a gap in institutional capacity for maximizing opportunities for access to these highly valued resources and their sustainable use. Associated tools for assessing trade-offs between sectors utilizing marine mammals through incidental bycatch or non-lethal cumulative impacts and traditional industries exploiting those species (e.g. fisheries and tourism) are lacking. Incentivization techniques are being developed for other natural resources, such as forests, in order to diversify how they are sustainably used, as well as better to connect local “nature-wealthy” communities with potential remote markets (Dao, 2018). This could potentially be applied to marine mammals. There is a need to assess how these approaches could be used to diversify current marine mammal exploitation and offer opportunities to develop derivatives.

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[92] see https://www.imf.org/external/pubs/ft/fandd/2019/12/natures-solution-to-climate-change-chami.htm

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Chapter 6E
Marine Reptiles

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Keynote points

- Changes in conservation status of marine turtles since the First World Ocean Assessment (WOA I) (United Nations, 2017b) are highly variable, with some populations experiencing positive growth rates, while others have experienced catastrophic declines.
- Most sea snake and marine iguana populations remain at similar conservation status to WOA I, though huge data gaps remain.
- The main threats to marine reptiles remain similar to WOA I. Bycatch is the most significant threat, although targeted harvesting, marine pollution, habitat loss, coastal development, disease and climate change are also key threatening processes.

1. Introduction

Chapter 39 of WOA I outlined the conservation status of marine reptiles, the major threats to these taxa and the most pressing conservation needs as of 2012 (United Nations, 2017a).

The present Chapter provides an updated assessment at a global scale, and identifies regional trends in the conservation status of marine turtles and sea snakes, with a focus on changes that have occurred since WOA I. It also relates to several other Chapters in the present Assessment, in particular, Chapters 4, 7, 15 and 24.

1.1. Frameworks

The primary frameworks used in WOA I to assess the status of marine reptiles were the International Union for the Conservation of Nature and Natural Resources (IUCN) Red List assessments and the IUCN Marine Turtle Specialist Group (MTSG) conservation priorities portfolio (Wallace and others, 2010). The present Chapter takes a similar approach and, where updates on conservation status were not available, incorporates updated information from MTSG regional reports and peer-reviewed publications.

2. Conservation status of marine reptiles

2.1. Marine turtles

Since WOA I, the status of two global populations and four subpopulations of marine turtles has been updated. (Table 1). The global status of loggerhead turtles (*Caretta caretta*), based on data from 90 per cent of the total global nesting population (comprising 6 of 10 recognized subpopulations), has improved from Endangered to Vulnerable (Table 1). However, the status of each subpopulation varies considerably, ranging from Least Concern (Northwest Atlantic, Mediterranean, Southwest Atlantic and North Pacific) to Near Threatened (Southwest and Southeast Indian), to Endangered (Northeast Atlantic) to Critically Endangered (Northwest and Northeast Indian and South Pacific) (Casale and Tucker, 2017).

Kemp's ridley turtles (*Lepidochelys kempii*) have been uplisted from Endangered to Critically Endangered, based on a greater than 80 per cent reduction in total population from historic levels. This constitutes a reversal of recoveries observed in the 1990s and 2000s, the causes of which are unknown, but may be related to fisheries bycatch and the Deepwater Horizon oil spill (Wibbels and Bevan, 2019). Similarly, the Northwest Atlantic subpopulation of leatherback turtles (*Dermochelys coriacea*) has been uplisted from Least Concern to Endangered (Northwest Atlantic Leatherback Working Group, 2019). This change in status is primarily the result of updated regional nesting trend analyses.

Subpopulations of green turtles (*Chelonia mydas*) in the North Indian (Vulnerable), and South Atlantic (Least Concern) have been assessed for the first time (Mancini and others, 2019; Broderick and Patricio, 2019) with the Hawaiian subpopulation re-assessed, remaining of Least Concern (Chaloupka and Pilcher, 2019). Although green turtles were not reassessed globally by the IUCN since WOA I, a global assessment under the United States Endangered Species Act ranked most subpopulations with a very low likelihood of quasi-extinction risk within the next 100 years (Seminoff and others, 2015). Of subpopulations assessed, the Mediterranean population was ranked as having the highest risk of extinction.

2.2. Sea snakes

Since WOA I, the status of 26 of the 71 currently recognized species has been updated, including three of four newly described species. Two species (*Aipysurus apraefrontalis* and *Aipysurus foliosquama*), previously assessed as Critically Endangered, were reclassified as Data Deficient due to changes in their known range (D'anastasi and others, 2016, Udyawer and others, 2020).

Declines in dusky sea snake (*Aipysurus fuscus*) abundance at Ashmore Reef have reduced the known range to three reef systems in the Timor Sea. Currently classified as Endangered, high rates of hybridization with the more common species *Aipysurus laevis* across their reduced range has raised concerns of high levels of introgression of this species (Sanders and others, 2014).

More generally, increased documentation of sea snakes has provided updated records of species assemblages and distribution globally (Rasmussen and others, 2014; Rezaie-Atagholipour and others, 2016; Sarker and others, 2017; Buzás and others, 2018; Ganesh and others, 2019). Expanded genetic evaluation of species across their global range has resulted in the restructuring of the Hydrophiinae phylogeny (Sanders and others, 2013), the reclassification of cryptic species (Sanders and others, 2013; Ukuwela and others, 2013; Ukuwela and others, 2014; Lukoschek, 2018) and the description of four novel species since WOA I (Ukuwela and others, 2012; Sanders and others, 2012, Nankivell and others, 2020).

Table 1. Species of marine turtles and sea snakes that have had a change in IUCN Red List status since WOA I. IUCN Red List categories: CR = Critically Endangered, EN = Endangered, VU = Vulnerable, NT = Near

Threatened, LC = Least Concern, DD = Data Deficient.

Taxa	Common name	Change in IUCN Red List status
Marine turtles	Loggerhead turtle	Downgraded in 2015 from EN to VU (subpopulations range from CE to LC).
	Green turtle	Hawaiian subpopulation was assessed as remaining at LC in 2019. North Indian and South Atlantic subpopulations were listed as VU and LC respectively in 2019. The rest of the global population is EN (no change, but see Seminoff and others, 2015).
	Kemp's ridley turtle	Up-listed from EN to CR in 2019.
	Leatherback turtle	Northwest Atlantic subpopulation was uplisted from LC to EN in 2019. The global population has not been assessed since 2013, and remains at VU, although all other subpopulations are either CE or DD (no change).
Sea snakes	Short-nosed sea snake	Listing revised from CR to DD in 2018.
	Leaf-scaled sea snake	Listing revised from CR to DD in 2018.
	Mosaic sea snake	Assessed at DD in 2018.
	Shark Bay sea snake	Assessed at DD in 2018.
	Rough-scaled sea snake	Assessed at DD in 2018.

The remainder of sea turtle species have not been reassessed since WOA I.

Twenty-six Australian sea snake species were reassessed under the IUCN Red List assessment in 2018. Apart from the updates of the five species listed in the table above, listings for the remaining 21 Australian species were unchanged. All other species found outside Australia (45) have not been reassessed since WOA I.

2.3. Marine iguanas

The marine iguana (*Amblyrhynchus cristatus*) was reassessed under the IUCN Red List assessment in 2020 and its status remains Vulnerable (MacLeod and others, 2020). A recent taxonomic review of the species based on morphological and genetic information resulted in a reclassification of two subspecies into one subspecies and the addition of five new subspecies, resulting in a total of 11 subspecies (Miralles and others, 2017).

3. Regional trends

A variety of sources provide information on local and regional population trends for turtles and sea snakes. Because these sources vary widely in how they report population trends, we provide a brief summary in Table 2 and refer the reader to the specific references for details on assessment and reporting methods used. Where there are population trend data for a regional management unit (RMU) as a whole, we include citations for reports on smaller regions within the RMU. In some instances, smaller nesting beaches or areas may differ in trend direction from the RMU; in these instances they are reported separately. This table includes only data on trends since WOA I, so we rely on sources published from 2015 through January 2020. Additional data unknown to the compilers or published after January 2020 may alter the trends reported here.

Table 2. Regional trends in abundance and distribution for sea turtles and sea snakes. CC – loggerhead turtles, *C. caretta*; CM – green turtles, *C. mydas*; DC – leatherback turtles, *D. coriacea*; EI – hawksbill turtles, *E. imbricata;* LK – Kemp's ridley turtles, *L. kempii*; LO – Olive ridley turtles, *L. olivacea;* and ND – Flatback turtles, *N. depressus.*

Region	Turtles	Sea snakes
North Atlantic, Caribbean and Mediterranean seas	**Increasing trends (nesting)** CC: Northwest Atlantic RMU (Ceriani and Meylan, 2017; Mazaris and others 2017; Nalovic and others, 2018); Mediterranean RMU (Casale, 2015a; Mazaris and others, 2017; Casale and others, 2018). CM: Northwest Atlantic RMU (Mazaris and others, 2017; Nalovic and others, 2018; Valdivia and others, 2019; NMFS, 2019); South Atlantic DPS (Valdivia and others, 2019); Mediterranean Sea (Casale and others, 2018). EI: West Atlantic RMU (Mazaris and others, 2017; Nalovic and others, 2018; Valdivia and others, 2019). **Stable trends (nesting)** CC: Peninsular Florida recovery unit (Valdivia and others, 2019). LK: After exponential recovery as of WOA I, trends have flattened considerably (Wibbels and Bevan, 2019). **Decreasing trends (nesting)** DC – Northwest Atlantic RMU (Northwest Atlantic Leatherback Working Group, 2019). EI – Mexico (Valdivia and others, 2019).	
South Atlantic	**Increasing trends (nesting)** CC – Southwest Atlantic RMU (Casale and Marcovaldi, 2015). CM – South Atlantic RMU (Mazaris and others, 2017; Broderick and Patricio, 2019). DC – Brazil although variable (Colman and others, 2019). LO – West Atlantic RMU (Mazaris and others, 2017). **Stable trends (nesting)** LO: French Guiana (Nalovic and others, 2018). **Decreasing trends (nesting)** LO – East Atlantic RMU (Mazaris and others, 2017).	Potential expansion of distribution with changing climatic conditions (Lillywhite and others, 2017).
Indian Ocean, Arabian Sea, Persian Gulf	**Increasing trends (nesting)** CC – Southwest Indian RMU (Mazaris and others, 2017). CM – Southwest Indian RMU (Mazaris and others, 2017). LO – Northeast Indian RMU (Mazaris and others, 2017). **Stable trends (nesting)**	

	CM – Egypt, Kuwait (Phillott and Rees, 2018). DC – India (Phillott and Rees, 2018). EI – Kuwait Qatar (Phillott and Rees, 2018). LO – India 2 major and one minor nesting sites either stable or increasing (Phillott and Rees, 2018). **Decreasing trends (nesting)** CC– Northwest Indian RMU (Casale, 2015b). CM– North Indian RMU (Mancini and others, 2019).	
North Pacific	**Increasing trends (nesting)** CC – North Pacific RMU (Casale and Matsuzawa, 2015). CM – North Central Pacific RMU (Mazaris and others, 2017; Chaloupka and Pilcher, 2019); Northern Mariana Islands (Summers and others, 2018) **Decreasing trends (nesting)** CM – Northwest Pacific RMU (Mazaris and others, 2017). DC – West Pacific RMU (Tiwari and others, 2013; Mazaris and others, 2017), East Pacific RMU (Wallace and others, 2013, Mazaris and others, 2017). **No trend (individuals)** CM – Central Western Pacific Ocean count of individuals (Valdivia and others, 2019);	Expanding distribution in the north of their geographic range from new data records (Park and others, 2017). Declining trends in unregulated fishery catches in the Gulf of Thailand (Van Cao and others, 2014).
South Pacific	**Increasing trends (nesting)** CC – Australia (Limpus and others, 2013) **Stable trends (nesting)** ND – Northern Australia (Groom and others, 2017) **Decreasing trends** CM – Raine Island, Australia genetic analysis may indicate dramatic reduction in hatching success (Jensen and others, 2016). EI – Australia – nesting (Bell and others, 2020) ND – Southwest Pacific RMU (Mazaris and others, 2017). **No definable trend (nesting)** ND – Eastern Australia (Limpus and others, 2017).	Expansion of distributional range upon new data (D'anastasi and others, 2016, Udyawer and others, 2020).

4. Threats

Although many marine reptiles are afforded legislative protection and conservation efforts have been undertaken in many regions, globally, threats to marine reptiles remain much the same as those identified in WOA I. Mortality from bycatch in fisheries (both regulated and illegal, unreported and unregulated) remains a significant threat to marine turtle and sea snakes (Lewison and others, 2014; Rees and others, 2016; Riskas and others, 2018). Other key threatening factors that impact marine reptiles include unregulated harvesting, marine pollution, habitat loss, coastal development, disease and climate change. Since WOA I, understanding of the impacts of climate change and marine pollution on marine reptiles has increased, although population-level impacts are still broadly unknown.

4.1. Sea turtles

While bycatch and retention of animals is likely the single most significant threat to turtle populations worldwide, research since WOA I has brought an emerging understanding of the threats from climate change and pollution.

The most significant climate change impacts hypothesized for sea turtles include feminization of the population, as well as increased embryonic mortality from higher nest temperatures (Fuentes and Cinner, 2010). While baseline sex ratios at a number of nesting beaches indicate that the vast majority produce predominantly female hatchlings (e.g. Laloë and others, 2016; Jensen and others, 2018), some models suggest that feminization could actually lead to increased reproductive success in the short term, since males can breed more frequently than females (Hays and others, 2014). Although embryos may be more resilient to high temperatures than previously thought (Howard and others, 2014), rising temperatures do ultimately lead to hatchling mortality (Laloë and others (2017). There are suggestions that climate change could affect population trends at regional scales, with increased reproductive success in temperate areas perhaps balancing decreased hatchling production in tropical areas (Montero and others, 2018). However, climate change impacts from sea level rise (and associated habitat loss), as well as increased incidence of cyclones leading to nest inundation and coastal erosion are also of concern for turtle populations (Fuentes and Cinner, 2010).

In 2010, the Deepwater Horizon oil spill resulted in hundreds of thousands of green, loggerhead and Kemp’s ridley turtles being exposed (at varying levels) to the oil (Deepwater Horizon Natural Resource Damage Assessment Trustees, 2016; Putman and others, 2015). While the long-term population level impacts from this event are yet to be quantified, the numbers of both loggerhead and Kemps ridley nests appear to have decreased as a result of both direct mortality (to adult turtles) as well as deterrence from nesting beaches resulting from beach clean-up activities (Gallaway and others, 2016; Lauritsen and others, 2017). Global risk assessments of interactions between marine turtles and marine debris have estimated that over 50 per cent of marine turtles are likely to have ingested debris (Schuyler and others, 2016), with hawksbill turtles observed to ingest up to 8.8 g of plastic/kg of body weight (Lynch, 2018). Marine debris, like other pollutants has demonstrably detrimental effects on individuals, but the ecosystem and population-level impacts of pollutants on sea turtle populations still require further study (Nelms and others, 2016; Wilcox and others, 2018).

A new potential threat emerging in the Caribbean is the coastal accumulation of an unprecedented proliferation of Sargassum. Though open-ocean Sargassum mats provide important critical nursery grounds for sea turtles, recent studies suggest that Sargassum accumulation on shore may inhibit nesting and impede hatchling dispersal, while decaying mounds may alter oxygen levels and thermal conditions (Maurer et al., 2015). Since this mass seaweed stranding is a new phenomenon, particularly in the eastern Caribbean, its direct impacts on sea turtle nesting remain largely unknown. Nesting beach habitat degradation resulting from coastal development, as identified in WOA1, continues to decrease the quantity and quality of nesting area available to females (Broderick and Patricio, 2019; Casale and Tucker, 2017)

4.2. Sea snakes

In the Gulf of Thailand, high levels of bycatch of sea snakes have been documented in the local squid fishery. Sea snakes are an important commercial bycatch product for Vietnamese fishers that operate in the Gulf of Thailand, the harvest of which is currently unregulated and largely undocumented (Van

Cao and others, 2014). Baseline surveys have detected a decline in sea snake harvests between 2008–2012 (Van Cao and others, 2014). The development of bycatch reduction devices, for example within the Australian trawl fishery industry, may assist in mitigating high incidental bycatch of sea snakes in tropical fisheries that utilize bycatch reduction measures, but may have limited utility in fisheries that rely on commercial bycatch as a source of income (Lobo and others, 2010).

High concentrations of trace heavy metals recorded in sea snakes in close proximity to mineral extraction operations across their range have highlighted marine pollution as an emerging threat to sea snake populations (Rezaie-Atagholipour and others, 2012; Sereshk and Bakhtiari, 2015; Gillett and others, 2017; Goiran and others, 2017).

4.3. Marine iguanas

In WOA I, extreme climatic El Niño events, tourism and introduced species were identified as key threats to marine iguanas, as was pollution (Wikelski and others, 2002). However, no information on the direct impact of any of these stressors on population numbers has been published since WOA I. Population size estimates based on molecular approaches suggest that populations of recently proposed subspecies are generally small and have a reduced evolutionary potential, making them vulnerable to threatening processes (Frankham and others, 2014; MacLeod and Steinfartz, 2016).

Further research on threats to marine iguanas has shown that tourism activities cause physiological stress and suppress the immune system (French and others, 2017). Despite the increasing demand on resources to match the growth of local populations, tourism and the economy (Benitez-Capistros and others, 2014; Walsh and Mena, 2016; Pizzitutti and others, 2017), which may pose potential threats to marine iguanas, no studies have been undertaken to assess the impact from pollution through oil spills, agricultural pesticides and plastics on marine iguana populations since WOA I.

Although control and eradication programmes on introduced species have been ongoing since the 1980s (Barnett and Rudd, 1983; Carrión, 2016) the effectiveness of these programmes in the context of marine iguana populations has not been evaluated.

Overall, the improved management and control of immigration, tourism and the import of goods since WOA I has the potential to reduce cumulative pressures on marine iguana populations from climate change, pollution, tourism and introduced predators but requires continuous attention to reduce ongoing population declines (DPNG, 2014; Asamblea Nacional de la República del Ecuador, 2015; MacLeod and others, 2020).

5. Economic and social consequences of the changes to marine reptile populations

Little has been published on the economic and social consequences of changing marine reptile populations and there is limited information on the economic and/or social role of sea snakes, in particular, in many regions of their global range. Balancing economic growth through tourism and the protection of marine reptile populations, particularly in the case of marine iguanas, remains a major challenge.

Increases in several populations of green turtles has resulted in increasing interest in exploring whether legal harvesting could be conducted (or expanded) in a sustainable manner, particularly for groups that have cultural or subsistence reasons to harvest (Chaloupka and Balazs, 2007; Rees and others, 2016).

The reliance of fishers from developing countries on income derived from sea snakes caught as bycatch (e.g., Van Cao and others, 2014) is poorly understood. However, high bycatch rates of sea snakes may be a source of income in increasingly unprofitable coastal fisheries in southern and south-eastern Asia (Lobo and others, 2010).

The increased exposure of and research into sea snakes since WOA I has led to increased interest from the public in many locations, resulting in the establishment of long-term citizen science-based sea snake data collection programmes (e.g. Goiran and Shine, 2019). The increased reporting by the public of stranded sea snakes has allowed for collection of data on sea snake health which can provide insight into causes of stranding events and changes in distributions (Udyawer and others, 2018).

6. Key knowledge and capacity-building gaps

6.1. Marine turtles

As was highlighted in WOA I, variability in the population demographics for different subpopulations of marine turtles and the threatening processes impacting population highlights the need for ongoing assessments of species and regional subpopulations. A recent review concluded that key knowledge gaps for informing the management of marine turtle populations remain (Rees and others, 2016). The gaps identified broadly comprise those associated with reproductive biology, including nest selection, hatchling fitness and production; foraging habitats, including connectivity between habitats; demographics; disease pathogenesis; and understanding of population level risks associated with threatening processes such as pollution, bycatch, climate change and the potential unintended consequences of associated mitigation measures.

6.2. Sea snakes

There is a lack of fundamental information on and long-term monitoring of sea snakes in most of their global range. A recent survey of experts identified key knowledge gaps for establishing baselines and progressing management of sea snake populations (Udyawer and others, 2018). The gaps identified broadly comprise those associated with defining geographic distributions, including their movements, dispersal and connectivity; identifying key habitats, particularly those in coastal regions; and quantifying resilience to environmental disturbances (e.g. marine heat waves, coral bleaching) and the responses to threatening processes such as bycatch and climate change (Fry and others, 2001; Gillett and others, 2014; Heatwole and others, 2016).

It is also currently unclear how emerging threats such as pollutants might be influencing population health (Rezaie-Atagholipour and others, 2012; Sereshk and Bakhtiari, 2015; Goiran and others, 2017).

Increasing reports of deceased turtleheaded sea snakes (*Emydocephalus annulatus*) within protected lagoons in New Caledonia, with no obvious cause of death, have highlighted the need to understand the prevalence of and susceptibility to disease and potential interaction with climate change (Udyawer and others, 2018).

Given the variety of people likely to have contact with sea snakes (e.g., various industries and recreational beach and ocean users) and potential hazards (e.g., envenomation), potential opportunities for public education and monitoring exist. Collection of data by the public either opportunistically or as part of citizen scientist programmes range from reporting stranded marine snakes (Gillett and others, 2017; Gillett, 2017), through to more involved, structured and repeated surveys (Goiran and Shine, 2019).

6.3. Marine iguanas

A lack of recent data on the abundance of marine iguana subspecies limits any evaluation of population trends in relation to threats and management actions. Recent advances in population genetics and taxonomy of marine iguanas may guide future conservation research and management aims. Further, building local capacity and allocating resources for comprehensive long-term monitoring could facilitate the assessment of population trends and vulnerability of marine iguanas in the future.

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Chapter 6F
Seabirds

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Keynote points

- Since the First World Ocean Assessment (WOA I) (United Nations, 2017), the global conservation status of seabirds has worsened, continuing a long-term trend.
- Thirty-one per cent of species are now threatened with extinction, up from 28 per cent in 2010.
- Pressures related to fishing (by-catch and prey depletion) are now affecting more species, while pollution is affecting fewer species (although marine debris, especially plastics, is an emerging threat with poorly understood consequences).
- Invasive alien species and climate change also remain major causes of seabird decline and affect similar numbers of species as in 2010.
- Current capacity and resources limit the ability to assess population-level consequences and implications for ecosystem services of existing and emerging threats.

1. Introduction

Seabirds (defined as bird species of which a large proportion of the population relies on the marine environment for at least part of the year; Croxall and others, 2012) play an important role in the world's marine ecosystems, being top predators that consume about the same amount of biomass as all fisheries combined (Brooke, 2004). Seabirds occur across all oceans, from coastal areas to the high seas, and many species are highly migratory, connecting different marine systems or ocean basins (Croxall and others, 2005; Shaffer and others, 2006; Egevang and others, 2010; Dias and others, 2011).

Current taxonomy identifies 359 species, representing six orders and 12 families. The worldwide distribution of species (among countries) was summarised by Croxall and others (2012) in terms of species richness, number of endemics, and number of threatened species. Seabirds are relatively well studied (compared with most other marine taxa) and several assessments documenting the status and recent trends of specific taxonomic groups have been conducted since WOA I (Trathan and others, 2015; Phillips and others, 2016; Rodríguez and others, 2019).

WOA I reported that 97 species of seabirds were classified as threatened, to varying degrees (collectively, those species that were classified as Critically Endangered, Endangered, or Vulnerable on the 2010 International Union for the Conservation of Nature (IUCN) Red List of Threatened Species) which represented 28 per cent of the 346 species evaluated at the time. WOA I also highlighted that pelagic seabird species were particularly threatened, and that albatrosses (Family Diomedeidae), gadfly petrels (Family Procellariidae, genus *Pterdroma* and *Pseudobulweria*) and penguins (Family Spheniscidae) were the groups with the highest percentages of species in threatened categories on the IUCN Red List. WOA I concluded that the main causes of population decline of seabirds came from ten primary pressures. At sea, these included: incidental by-catch (in longline, gillnet and trawl fisheries); pollution (oil spills, marine debris, including plastics); depletion of prey species by fishing; and offshore energy production and mining. On land, the main threats were invasive alien species; problematic native species (for example, those that have become super-abundant); human disturbance; industrial and residential development; and hunting and trapping. Climate change and severe weather were identified as affecting seabirds both on land and at sea.

2. Description of the environmental changes (between 2010 and 2020)

The numbers of species in each IUCN Red List category in 2018, by seabird order, are shown in Table 1. Since then, a quantitative review of the threats affecting all seabird species globally using data collected from more than 900 publications and a standardised assessment approach based on the IUCN Red List Threats Classification Scheme has been conducted (Dias and others, 2019).

The review by Dias and others (2019) applied a similar approach to that used by Croxall and others (2012) so the results can be used to evaluate changes in the status of, and threats to, seabirds since WOA I. Since WOA I, 28 species of seabird have been up-listed (that is, the conservation status of those species has worsened) and 11 species have been down-listed (that is, the conservation status of those species has improved; Table 2). Particularly noticeable has been the declining status of species within the orders Anseriformes (sea ducks; five of 18 species up-listed) and Procellariiformes (tubenoses; 11 of 131 species up-listed and four down-listed). Procellariiformes (particularly albatrosses and gadfly petrels) and penguins remain groups with the highest proportions of threatened species (see Table 1). Down-listing of species since WOA I has resulted from improved knowledge (e.g. new colonies discovered, taxonomy revision), rather than a genuine improvement in their status.

Table 1. Number of seabird species (N=346) in each IUCN Red List category in 2018 considered by Croxall and others (2012) and Dias and others (2019) and grouped by taxonomic order. EX = Extinct in the wild; CR = Critically Endangered; EN = Endangered; VU = Vulnerable; NT = Near Threatened; LC = Least Concern; DD = Data Deficient.

Seabird order	EX	CR	EN	VU	NT	LC	DD	Totall
Procellariiformes (Tubenoses)	2	13	20	27	19	47	3	131
Sphenisciformes (Penguins)	0	0	5	5	3	5	0	18
Charadriiformes (Gulls and auks)	1	1	4	10	11	93	0	120
Anseriformes (Sea ducks)	0	0	0	4	2	12	0	18
Suliformes (Gannets and boobies)	0	2	5	8	3	26	0	44
Gaviiformes (Loons)	0	0	0	0	1	4	0	5
Phaethontiformes (Tropicbirds)	0	0	0	0	0	3	0	3
Pelecaniformes (Pelicans)	0	0	0	0	1	2	0	3
Podicipediformes (Grebes)	0	0	0	1	0	3	0	4
All seabirds	3	16	34	55	40	195	3	346

A comparison of the reviews by Dias and others (2019) and Croxall and others (2012) also identifies that threats to seabirds such as invasive alien species and climate change/severe weather, are continuing to affect similar numbers of globally threatened species (Figure 1). Dias and others (2019) identified fisheries by-catch and prey depletion by fishing as impacting more species of seabird in 2018 than in 2010 (respectively, 50 globally threatened species, an increase of 10 from 2010, and 22 globally threatened species, an increase of 12 from 2010). These increases are at least partly due to a better understanding of the impacts of by-catch, particularly in gillnet fisheries, on seabirds (Crawford and others, 2015; see also below) and the effects of competition for prey species between fisheries and seabirds (Crawford and others, 2015; Grémillet and others, 2018; Trathan and others, 2015). Declines in prey species can also be caused by factors other than fishing, including climate change (Mitchell and others, 2020). The major threats affecting threatened species are the same as those affecting all seabird species (Dias and others 2019).

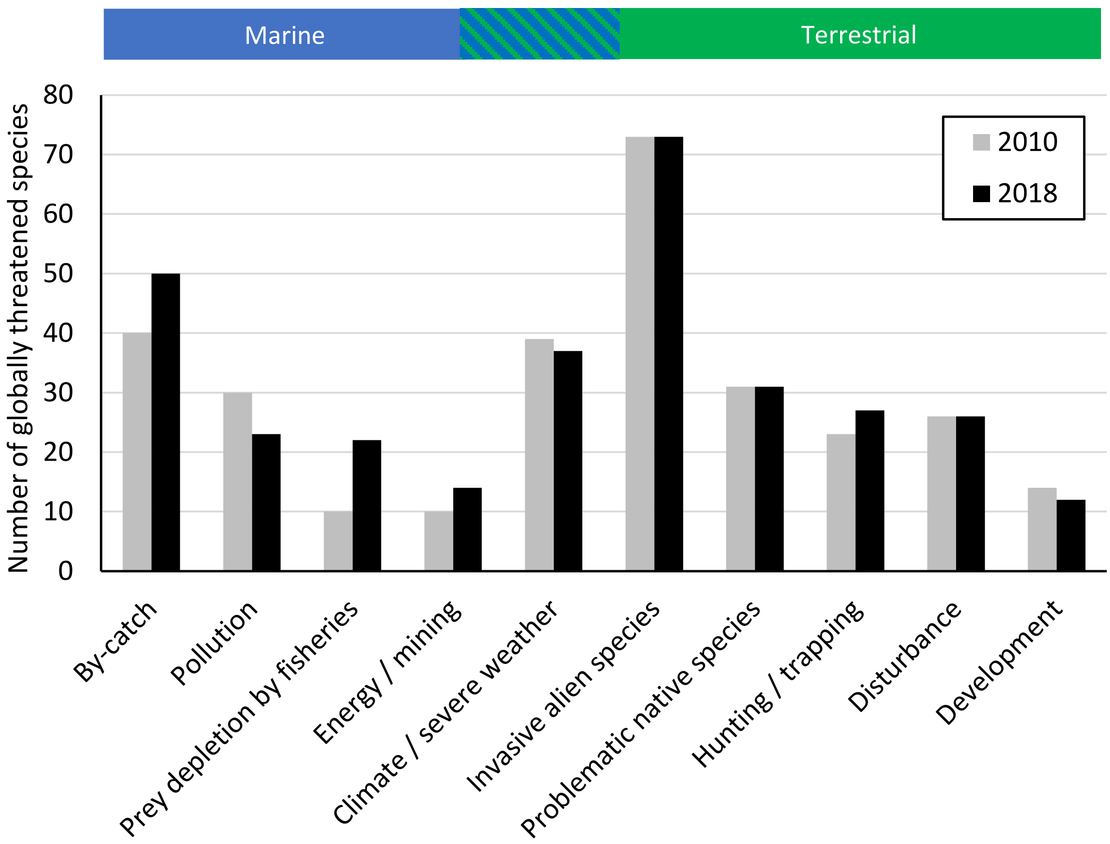

Figure 1. The number of globally threatened seabird species assessed as being affected by marine, terrestrial, and over-arching threatening processes in 2010 (Croxall and others, 2012, grey bars) and in 2018 (Dias and others, 2019, black bars). Only processes considered in both assessments are shown.

Climate change has been reported to have already caused declines in almost 100 seabird species (Dias and others, 2019). For example, changes in sea surface temperature during late winter were associated with declines in the population growth rate of black-browed albatross *Thalassarche melanophris*, primarily through effects on prey availability and subsequent juvenile survival (Jenouvrier and others, 2018). Similarly, Carroll and others (2015) found that the breeding success at 11 colonies of black-legged kittiwake *Rissa tridactyla* in the UK and Ireland was higher when stratification was weaker before the breeding and when sea surface temperatures were lower during the breeding season.

Invasive alien species continue to pose a threat to 73 species, the same number as in 2010, and, of these predators, rats and cats are a particular threat to small petrels such as gadfly petrels and storm-petrels (Rodríguez and others, 2019). In their global review, Jones and others (2016) identified 122 species (202 populations) of seabirds that had benefited (in terms of an increase in population size or colonisation of a location) from the eradication of invasive mammals from islands. Other programmes to restore or improve habitat for seabirds have also been found to be beneficial, including planting and reforestation, weed control, enhancing or providing nesting opportunities, and erosion control (Beck and others, 2015; Bried and Neves, 2015; Buxton and others, 2016).

Table 2. Summary of changes in IUCN Red List status between 2010 (Croxall and others, 2012) and 2018 (Dias and others, 2019), limited to the 346 species of seabirds considered by both authors. Up-list means a worse conservation status (in 2018 compared with 2010), Down-list means a better conservation status in 2018. Species are considered Data deficient here if the IUCN Red List status was Data deficient in either 2010 or 2018 because no meaningful assessment of change in status could be made.

Seabird order	Up-list	Unchanged	Down-list	Data deficient	Total species

Procellariiformes	11	112	4	4	131
Sphenisciformes	1	15	2	0	18
Charadriiformes	8	108	4	0	120
Anseriformes	5	13	0	0	18
Suliformes	2	41	1	0	44
Gaviiformes	0	5	0	0	5
Phaethontiformes	0	3	0	0	3
Pelecaniformes	0	3	0	0	3
Podicipediformes	1	3	0	0	4
All seabirds	28	303	11	4	346

By-catch in fisheries remains the biggest at-sea threat to Procellariiform seabirds, affecting mostly albatrosses, large petrels and shearwaters (Phillips and others, 2016; Rodríguez 2019). SDG Target 14.2 specifies that marine and coastal ecosystems should, by 2020, be managed to avoid significant adverse impacts on those systems, and progress on SDG 12 will need to account for impacts on biodiversity. Efforts to reduce the by-catch of seabirds in fisheries have been increasing, including through the adoption or updating of National Plans of Action by some nations using longline, trawl, or gillnet fishing methods in which by-catch is most commonly an issue. Mandatory mitigation measures have also been introduced within some areas of national jurisdiction and some parts of the high seas, including, for example, line weighting, night setting, bird-scaring lines and area closures (Brothers and others, 1999; Abraham and others, 2017). There is evidence that the number of threatened seabird species affected by depletion of their prey by fisheries has more than doubled in the last decade (Croxall and others, 2012; Dias and others, 2019), although this is at least in part due to increased understanding in this area.

In contrast, the most recent assessment identified that threats associated with marine pollution have decreased, with pollution now affecting 23 globally threatened species (seven fewer than in 2010). This decrease is primarily driven by overall reductions in pollution associated with oil spills, in recent decades (Roser, 2018). Pollution in the form of marine plastics has been documented as affecting seabird species widely (e.g. Wilcox and others, 2015). Despite SDG Target 14.1 specifying the prevention and significant reduction of all kinds of marine pollution by 2025, plastic in the marine environment is expected to continue to affect many seabird species in the coming decades (Kühn and others, 2015; Ryan and others, 2009; Wilcox and others, 2015). Although this form of pollution has not yet been identified as a direct cause of many declines at the population level (but see Auman and others, 1997, Lavers and others, 2014), small, highly pelagic species (such as storm-petrels, prions and auklets; Roman and others, 2019, Wilcox and others, 2015) are thought most likely to be at risk. Light pollution, both at the colonies (Rodríguez and others, 2017; Rodríguez and others, 2019) and from oil platforms, vessels and other artificial structures at-sea, poses a threat to small petrels (Montevecchi., 2006; Rodríguez and others, 2019), although with poorly understood impacts on populations (this threat was not considered in WOA I).

Other emerging threats identified by Dias and others (2019) include energy production particularly offshore wind farms, deep-sea mining (Green and others, 2016), and light pollution including from marine infrastructure such as platforms and vessels (Rodríguez and others, 2017; Rodríguez and others, 2019). Understanding of the consequences of these threats at the population level remains limited but juvenile seabirds and birds near colonies appear to be particularly susceptible to light pollution issues (Rodríguez and others, 2015). Adverse effects such as collision and mortality have been described for at least 21 species of Procellariforms, including as a result of fishing and offshore oil and gas facilities attracting birds with artificial light (Montevecchi, 2006). Development in these areas is relevant to SDG Target 15.9 which specifies that ecosystem and biodiversity values should be integrated into national and local planning and development processes by 2020 (noting also the relevance of SDGs 7, 9, and 11).

Although the population sizes of some penguin species are increasing, climate change has been identified as a major threat to many species in the group, with declines primarily associated with changes in habitat conditions, increased frequency of floods and storms and extreme temperatures (Trathan and others, 2015; Dias and others, 2019). SDG Target 13.2 specifies that climate change measures should be integrated into national policies, strategies and planning, although it does not include a target date. By-catch, competition with fisheries, pollution, invasive alien species and disturbance at the colonies are also now known to be important stressors for penguin species (Trathan and others, 2015; Crawford and others, 2017; Dias and others, 2019).

3. Consequences of the change on human communities, economies and well-being

Changes in seabird populations, particularly substantial declines, impact biodiversity and the associated functioning of marine systems and the ecosystem services they provide (Wenny and others, 2011; Burdon and others, 2017; Tavares and others, 2019). For example, seabirds feeding at sea and nesting ashore can contribute a substantial proportion of nutrients entering the latter systems, enhancing the productivity of local fauna and flora and adjacent coastal systems (Graham and others, 2018). Changes in this nutrient transfer would profoundly affect these systems. The potential consequences of changes in seabird populations for ecosystem services, although poorly understood, are likely to be varied and complex. Thus, the consequential impacts on ecosystem services caused by impacts on seabirds are directly relevant to many of the UN's SDGs, including SDG7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), SDG11 (Sustainable Cities and Communities), SDG12 (Responsible Consumption and Production), SDG13 (Climate Action), SDG14 (Life Below Water), and SDG15 (Life on Land).

4. Outlook

A continuing long-term declining trend in the status of seabird populations, especially for pelagic species in the last 10 years (Figure 2), and the persistence of major threats does not provide a positive outlook for seabirds in the near future.

Current efforts mitigating the impacts of fisheries by-catch and invasive species, particularly in island habitats, will likely continue as the importance for the conservation of biodiversity and seabirds is increasingly recognised and prioritised (Buxton and others, 2016; Jones and others, 2016). However, if fishing pressure on "forage-fish" intensifies, competition between fisheries and seabirds may increase with associated potential detrimental impacts on some seabird populations, although the empirical evidence for a consistent effect is not strong (Hilborn and others, 2017). The impacts of potentially increasing competition may be exacerbated by any decreases in prey abundance related to changes in oceanographic conditions driven by climate change (Grémillet and Boulinier, 2009). In this context, the transition of fisheries to lower trophic levels, in particular those targeting mesopelagic species (St. John and others, 2016), may be problematic because mesopelagic fishes are an important part of the diet of many pelagic seabirds (Watanuki and Thiebot, 2018).

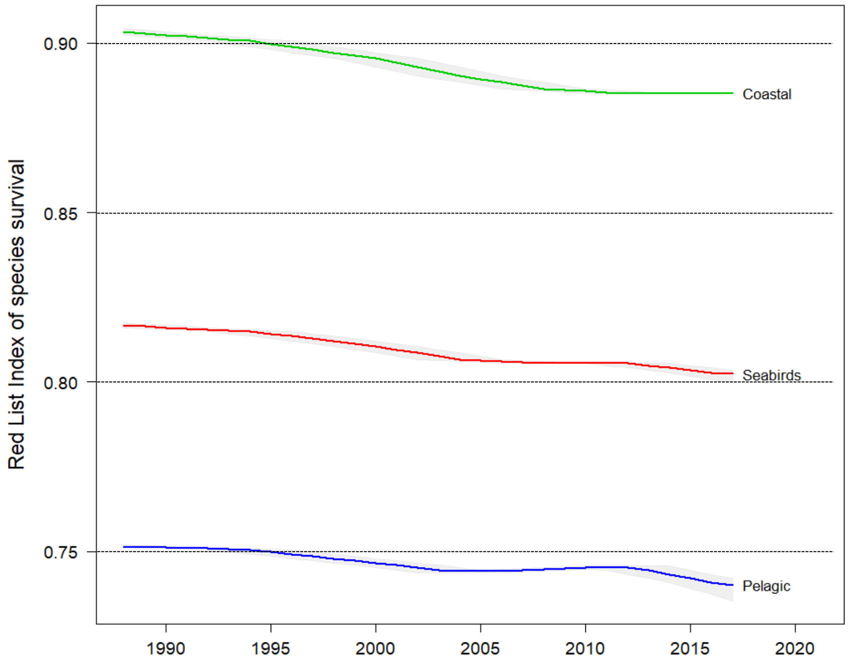

Figure 2. The Red List Index (RLI) of species survival for coastal seabirds (green line), all seabirds as a group (red line), and pelagic seabirds (blue line) for the period 1988–2017. The RLI uses information from the IUCN Red List to measure the projected overall survival rates of species within groups (Butchart and others, 2007). It is based on changes in the proportion of species in each threat classification category resulting from genuine improvement or deterioration in the status of each species. The revised RLI is scaled such that, for any given group, a value of 1 indicates that all species are classified as Least Concern, and an RLI value of 0 indicates that all species have gone extinct.

Climate change is projected to have profound implications for many seabird populations through potential redistribution of prey and changes to the composition of marine communities. Direct climate change effects are likely to: increase heat stress at breeding and roosting colonies; increase disturbance to breeding and roosting colonies via increasing storm frequency and intensity, particularly in low-lying colony regions; and increase inundation of low-lying nesting and feeding areas via sea level rise (Grémillet and Boulinier 2009). Groups such as penguins are particularly vulnerable to the negative consequences of climate change (Dias and others 2019), particularly those species dependent on pack ice or particular habitat conditions that are likely to decline under climate change (Ainley and others, 2010). Although many more species are projected to be impacted negatively by climate change (BirdLife International and National Audubon Society, 2015), some species are projected to be positively impacted through increases in range or population size. For example, the Heard Island-nesting populations of king penguins, *Aptenodytes patagonicus*, and black-browed albatross, *Thalassarche melanophris* are expected to increase (Chambers and others, 2011) via an increase in the extent of breeding grounds as glaciers retreat.

As use of renewable energy (wind, water, waves) technology continues to expand globally, the risk of seabirds interacting with such structures is likely to increase. These interactions are likely to occur predominantly in coastal species such as divers, scooters, terns and shags (Garthe and Hüppop, 2004) and may be more problematic for highly mobile species such as shearwaters (Busch and Garthe, 2018). The potential for increasing impacts could be reduced by locating facilities in areas less-favoured by seabirds, identified through the use of observation and tracking data on habitat use (e.g., Busch and others, 2013; Winship and others, 2018).

Although major oil spills have declined over the past decades, other aspects of pollution, including marine debris, are likely to increase, particularly in light of predicted large increases in the amount of plastic waste in the marine environment (Jambeck and others, 2015). Impacts associated with light pollution are also expected to grow, largely associated with continued growth in maritime traffic which is expanding at a rate of about 4 per cent per year (UNCTAD, 2018). Population effects are thought to be more likely for endangered species or those species with small population sizes (Rodríguez and others, 2019). Increasing maritime traffic may also increase the risk that alien predators or pathogens will be introduced to additional locations, potentially affecting seabird populations (Renner and others, 2018).

New tracking technology for seabirds (for example, Sansom and others, 2018; Zhang and others, 2019) and sophisticated mapping and analytical software will allow us to estimate the exposure of seabird populations to individual threats with increasing precision. This should allow us to identify the species, life-stages, threats, places, and times where mitigation will bring the most benefit for seabird populations, as well as pinpointing critical knowledge gaps. Quantitative spatial overlap approaches have been used most intensely to assess impacts and risks posed by fishing (for example, Tuck and others, 2011; Abraham and others, 2017; Clay and others, 2019), but would be amenable to future assessment of all threats with a spatial component (for example, as reported by Currey and others, 2012; Redfern and others, 2013).

5. Key remaining knowledge gaps

Despite the fact that seabirds are relatively well-studied, several knowledge gaps remain in the demography, status, at-sea distribution and population trends, of small species like storm petrels, gadfly petrels, prions and auklets. In addition, the at-sea distributions of young life-history stages of most seabird species are poorly understood compared with those of adults. Perhaps the biggest gaps, however, are around the likely population-level consequences and resultant changes to ecosystem services (and SDG Targets) of the impacts of emerging threats such as marine debris (especially plastics), coastal and offshore wind and tidal energy facilities, deep-sea mining, and light pollution.

6. Key remaining capacity-building gaps

The key remaining gaps in capacity relate to the knowledge gaps identified above. Current capacity and resources limit our ability to monitor population trends, understand the at-sea distribution of different life stages, and estimate the demographics and productivity of all but the most intensively studied species. These gaps greatly limit our ability to assess population-level consequences and implications for ecosystem services of existing and emerging threats.

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Chapter 6GH
Marine Plants and Macroalgae

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Keynote points

- An extinction risk of about 90 per cent of mangrove, seagrass, and marsh plant species has been determined; 19 per cent of mangroves, 21 per cent of seagrass species and one marsh plant species are on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species.
- Among macroalgae, 1 species of red seaweed from Australia, *Vanvoorstia bennettiana*, is listed as extinct and 21 are listed as threatened, 9 of which are red and 12 of which are brown. The number of macroalgal species assessed and reported on the IUCN Red List is less than 1per cent of the total number of species listed in the Ocean Biogeographic Information System (OBIS). All the threatened species are endemic to the Galapagos Islands, and in the Mediterranean Sea an extinction risk assessment was performed listing more 47 spp. This highlights the knowledge gap with regard to macroalgae.
- In terms of macroalgal endemism, Antarctica ranks highest, with 27 per cent endemics, followed by South America (22 per cent) and the Red Sea Large Marine Ecosystem (LME) (9 per cent).
- New techniques such as genomics have been developed for species identification and for elucidating phylogenetic relationships and, as a result, the number of species is expected to rise, especially for macroalgae but, due to uneven human and infrastructure capacities among regions, some regions will be less studied than others.

1. Introduction

The present Chapter considers the taxonomy, conservation status, and population trends of marine plants and macroalgae. The marine plants covered in the present Chapter include mangroves, marsh plants, seagrasses, and the seaweeds (or macroalgae) section considers red, green, and brown macroalgae. Although mangroves, salt marshes, and seagrass beds were considered in the First World Ocean Assessment (WOA I) (United Nations, 2017), in Chapters 48, 49, and 47, respectively, and are dealt with in the present Assessment in Chapters 7J, 7K, and7I, respectively, their treatment was on the ecosystem scale, not at the species level. Macroalgae were also covered in WOA I but as a source of food, in Chapter 14, and as ecosystems, in Chapter 47 on kelp forests, and Chapter 50 on the Sargasso Sea.

2. Mangroves

Mangroves consist of shrubs and trees that grow in the coastal belt in tropical and subtropical areas worldwide. They have developed characteristic features that allow them to survive in brackish and shallow marine habitats such as: (a) shallow lateral root extensions called pneumatophores that grow upwards from muddy substrates, allowing for the absorption of oxygen in otherwise anoxic (no oxygen) substrates; (b) a branched stem system, known as “aerial roots” or “stilt roots”, and buttress roots for better anchorage in soft substrates and to withstand strong winds or waves; (c) succulent leaves with internal water storage tissues; (d) salt-secreting or exclusion mechanisms such as salt glands in the leaves of some species for osmotic balance; and (e) viviparous reproduction, that is, the seed germinates, with the seedling, called a propagule, still on the parent plant, producing an elongated crude root eventually dropping directly into the substrate, thus, "planting" itself. In undisturbed forests, there is distinct zonation, with each zone dominated by characteristic species.

2.1. Taxonomic treatment

The World Mangrove Database (Dahdouh-Guebas, 2020) lists 65 "valid" or correct names of mangrove taxa in 14 families, inclusive of 5 hybrids and excluding three species of the fern mangrove *Acrostichum* and two species of the leguminous mangrove *Cynometra*. No new species of mangroves has been described since the last decade although new hybrids have been identified using molecular methods bringing the current number to eight (Ragavan and others, 2017; Ono and others, 2016). Relative to other plant groups such as ferns or grasses, the number of species may not be considered high, but mangrove taxa are present in a broad cross section of 16 flowering plant families except three species which belong to the fern family. Of the 16 families, only two (Pellicieracae and Rhizophoraceae) have exclusively marine species

2.2. Current State and Trends

It was reported in the First World Ocean Assessment (WOA I) of mangroves (see Chapter 17, United Nations, 2017) that, depending on the criteria used in defining strict or "true" mangrove species, the number of species runs between 70–73, inclusive of hybrids. It was also emphasized that the groupings of species change as a result of taxonomic studies. For example, the mangrove *Sonneratia* which used to belong to family Sonneratiaceae is now classified in the Family Lythryceae (Little and others, 2004), and Sonneratiaceae is delegated to the sub family level.

Sixty-four species have been assessed for risks of extinction between 1998 and 2018. Of the 64 species assessed and categorized by the IUCN as of 19 November 2019, three are Critically Endangered (*Sonneratia griffithii* (Duke and others, 2010a) *Bruguiera hainesii*[93] (Duke and others, 2010b), and *Sonneratia hainanensis* (WCMC, 1998)), three are Endangered, all belonging to the family Malvaceae (*Camptostemon philippinensis* (Duke and others, 2010c), *Heritiera fomes* (Kathiresan and others, 2010), *H. globosa* (Sukardjo, 2010), five are Near Threatened (*Aegialitis rotundifolia* (Ellison and others, 2010a), *Aegiceras floridum* (Ellison and others, 2010b), *Ceriops decandra* (Duke and others, 2010d), *Sonneratia ovata* (Salmo and others, 2010), *Rhizophora samoensis* (Ellison and Duke, 2010)), five are Vulnerable (*Avicennia lanata* (Chua, 1998), *Avicennia integra* (Duke, 2010a), *Avicennia rumphiana* (Duke and others, 2010e), *Avicennia bicolor* (Duke, 2010b), *Pelliciera rhizophorae* (Ellison and others, 2010c), 47 are of Least Concern and only one, *Excoecaria indica* (Ellison and others, 2010d), is Data Deficient.

The distribution of these species across marine regions as defined by the IUCN is shown in Figure 1. No mangroves are found in the Northern Atlantic Ocean. All the globally Critically Endangered species are found in the eastern Indian Ocean, and the northeastern and eastern central Pacific, while all the globally Endangered species are found in the eastern Indian

[93]In 2016, using molecular markers, Ono and other have identified this species to be a hybrid between *Brugiera. cylindica* x *B. gymnorhiza*.

Ocean and the western central Pacific. Those that are in the Near Threatened category are found in the east Indian Ocean, the western central Pacific. Major threats are residential and commercial development, aquaculture and agriculture, biological resource use such logging for construction materials and fuel, climate change causing habitat shifting and alteration, pollution, sand mining, and replacement by invasive species.

On the regional level, however, some species of Least Concern may be threatened due to various factors. *Avicennia marina* in the Red Sea LME (Sherman and Hempel, 2008), for example, is particularly threatened since it is highly grazed and harvested for forage as it is palatable to livestock such as camels, goats, and cattle (Nawata, 2013) due to its lower content of soluble tannins. Goods and services, and changes in mangrove ecosystems were treated in detail in Chapter 48 of WOA I.

Global distribution, diversity and abundance of mangroves are affected by climate change, such as alterations in temperature and rain fall regimes (Donato and others, 2011; Ward and others, 2016; Friess and Webb, 2013). Warmer winters and sea level rise are expected to allow for expansion poleward at the expense of salt marshes. However, dispersal and habitat availability constraints may hinder expansion near certain range limits. Along arid and semi-arid coasts, decreases or increases in rainfall are expected to lead to mangrove contraction or expansion, respectively.

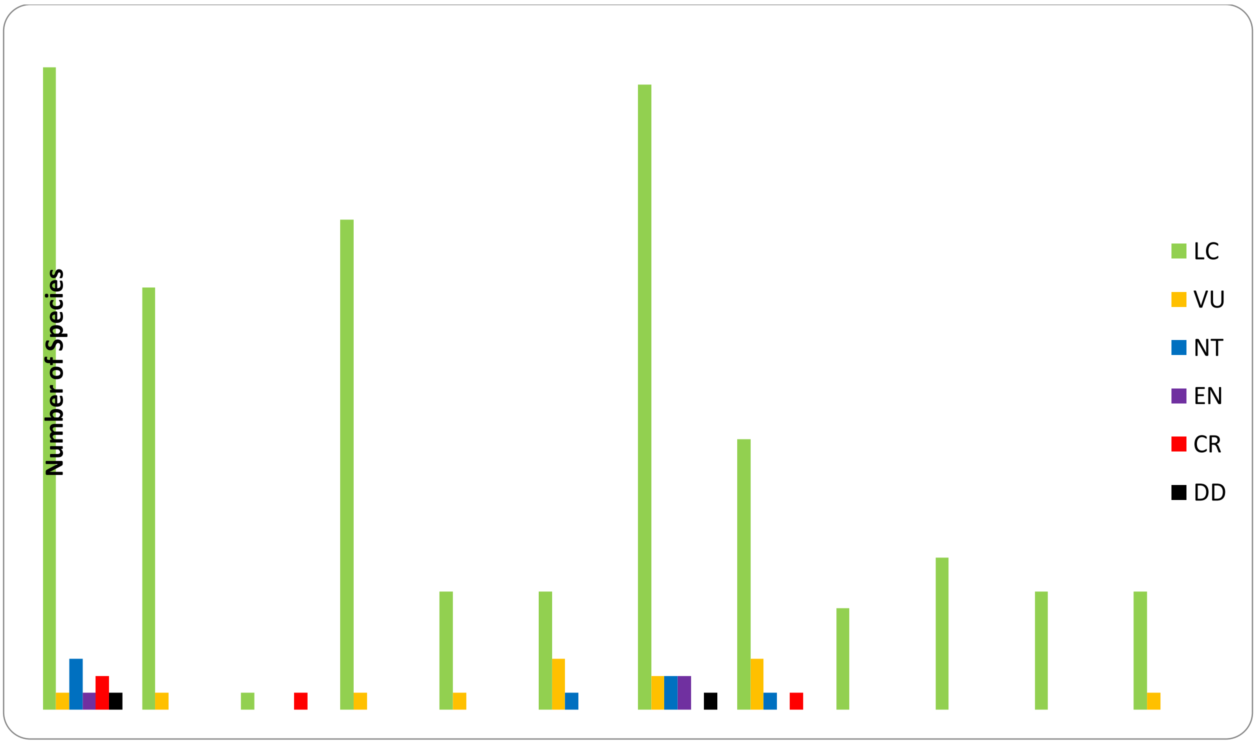

Figure 1. Distribution of species based on IUCN categories and marine regions. Legend: IUCN categories: LC = Least Concern; NT = Near Threatened; VU = Vulnerable = EN = Endangered; CR = Critically Endangered; DD = Data Deficient.
Marine oceanic regions: E-Eastern; W-Western; N-North; S-South; C-Central; Pac-Pacific; Atl-Atlantic

3. Salt marsh plants

Salt marsh plants constitute the major vegetation in the intertidal zones and inland saline areas of the temperate zones. They constitute the lush and highly productive “intertidal grasslands” or salt marshes, with distinct zonation in response to intense physical gradients. Such as salt concentrations exceeding 500mM (Yuan and others 2019). They have a high ability to store carbon, and filter nutrients which increases water quality in nearby coastal systems impacted by urban, aquaculture and agricultural run off. They protect coastal communities from storm, sand erosion, and enhance human well-being by acting as critical nursery habitats for fisheries. These essential ecosystem goods and services are provided to millions of people. Salt marshes store carbon and are valued at 10,000 United States dollars per hectare per year (Barbier and others, 2011; Hopkinson and others, 2012; Möller and others, 2014).

Unlike mangroves, which are dominated by trees, salt marsh plants are usually grasses or shrubs. Just like mangroves, they have developed and adapted to high saline environments, flooding and desiccation, and anoxic conditions.

3.1. Taxonomic treatment

Globally, plant species richness in marshes is surprisingly high, with over 500 marsh plant species known. However, the majority of these are in freshwater lakes and rivers, extending into brackish aquatic environments and occupying an estimated 45,000 km^2 worldwide (Greenberg and others, 2006). The salt-tolerant species inhabiting salt marshes belong to four major families: chenopods (Chenopodiaceae) with two species of chenopods (*Salicornia veneta* and *Salicornia rubra*), Poaceae, with three species of grasses *Spartina* (*S. alterniflora*, *S. gracilis*, *S. maritima*), *Juncus* (many species), and *Phragmites* (many species). However, only two species are reported to be exclusively inhabiting the coastal zone: the chenopod, *Salicornia veneta* and the grass, *Spartina alterniflora*. The rest inhabit freshwater lakes, rivers,, and swamplands and extend into “artificial” brackish and marine habitats such as aquaculture ponds and canals. *Salicornia* and *Spartina* are found throughout temperate North America, with *Salicornia* extending to Mexico. *Salicornia* is also found in some parts of Europe, and northern parts of Asia.

3.2. Current State and Trends

Globally, up to half of global coastal wetlands have been lost due to human conversion for agriculture and aquaculture and to other anthropogenic changes in land use (Pendleton and others, 2012). Climate change, declining water quality and changes in sediment delivery rates associated with human activity continue to affect the world’s remaining wetlands such as salt marshes (Kirwan and Megonigal, 2013).

Salicornia veneta is the only threatened species listed in the IUCN Red List (Foggi and others, 2011) and is categorized as Vulnerable. It is found along the coast of Italy in the Adriatic Sea, and occupies an area of less than 500 km^2. Although common in the distribution area, its population is reported to be decreasing due to coastal development, settlements, and tourism. It is included in national legislation for protection and one site is a protected area. *Spartina alterniflora* is categorized as a species of Least Concern (Maiz-Tome, 2016).

4. Seagrasses

Seagrasses are marine flowering plants that inhabit tidal and subtidal marine environments. They require high levels of light, thus, they are normally abundant in shallow waters where they are productive components of near-shore environments providing food and shelter for many economically important species (Heck and Orth, 1980).

Seagrasses are among some of the oldest plants on Earth, with fossil deposits believed to date back to the Pliocene (Tuya and others, 2017). They have developed adaptations to survive in their particular niche (Papenbrock, 2012). Such adaptations include: mostly thin, flattened, elongated or strap-like leaves that allow for flexibility in waters with strong waves and currents, and diffusion of gases (since they do not have stomata); an extensive system of roots and rhizomes that enable them to anchor in muddy and sandy substrates – for example the temperate species *Phyllospadix* has hooks that allow it to attach to rocks; an adaptability to survive in high and often varying salinities; pollen in gelatinous tubes or floating packets for submarine or air-water surface pollination; and, in some species, viviparous or cryptic viviparous reproduction that enables them to compete with other species (Green and Short, 2003).

The distribution of seagrass depends in part on the dispersal of fruit, seed, seedling, and vegetative propagule by ocean currents. Using a combination of population genetic assignment procedures and dispersal predictions from a hydrodynamic model, it was predicted that 60 per cent of *Posidonia australis* fruits dispersed within 20 km range (Sinclair and others 2018). Their study provided insight into the role of physical transport for long-distance dispersal of fruits and the consequences for the spatial genetic structuring of seagrass meadows.

4.1. Taxonomic treatment

Seagrasses are flowering plants belonging to Class Liliopsida. As of 2011, 72 species in 6 families and 15 genera were recognized (Short and others, 2011). They are distributed throughout the world, except in Antarctica. At least two species have been described so far using molecular characters, the new species *Thalassodendron johnsonii* (Duarte and others, 2012) and one (*Halophila major)* separated from the *Halophila ovalis* complex (Nguyen and others, 2014). Subpopulations have also been identified using barcoding techniques (Nguyen and others, 2015).

4.2. Current state and trends

As of 2011, it was reported (United Nations, 2017, Chapter 47) that 31 per cent (22 of 72 species) of the world’s total number of species have declining populations while 5 per cent have increasing population trends and 22 per cent are unknown. The same report stated that seagrasses have been disappearing at a rate of 110 km^2 yr^{-1} since 1980 and that 29 per cent of the known areal extent has disappeared since seagrass areas were initially recorded in 1879 with rates of decline accelerating from a median of 0.9 per cent yr^{-1} before 1940 to 7 per cent yr^{-1}since 1990.

On a global scale, no further global species extinction risk assessments were done after 2011. Of the 72 species, three, all in the family Zosteraceae, remain in the Endangered IUCN category with decreasing populations (Short and Waycott, 2010a, b, c) *Phyllospadix japonicus*, *Zostera chilensis*, and *Zostera geojeensis*. *Phyllospadix japonicus*, and *Zostera chilensis* are both found in the Pacific Northwest while *Zostera geojeensis* occurs in the Pacific Southeast (see Figure 2).

Five species are listed as Near Threatened, all with decreasing populations (Short and

Waycott, 2010d, e, f). Except for *Posidonia australis* which occurs in both the eastern Indian Ocean and the southwestern Pacific Ocean, all four occur only in one marine region: *Halophila engelmanni* in the western central Atlantic, and *Halophila nipponica*, *Zostera asiatica* and *Zostera caulescens* in the northwestern Atlantic (see Figure 2).

Seven species are listed as Vulnerable with decreasing populations (Short and Waycott, 2010g,h, i, j, k l, m). These belong to three families: Posidoniaceae (*Posidonia sinuosa*), Hydrocharitaceae (*Halophila baillonii*, *Halophila beccarii*, *Halophila hawaiiana*), and Zosteraceae (*Phyllospadix iwatensis*, *Zostera capensis*, *Zostera caespitosa*). Except for *Halophila beccarii* and *Zostera capensis* which are found in two marine regions, the Indian Ocean and the Pacific Ocean, and all the rest are restricted in their distribution: *Posidonia sinuosa* in the eastern Indian Ocean, *Halophila beccarii* in the eastern central Pacific, *Zostera caespitosa*) in the northwestern Pacific Ocean, *Halophila hawaiiana* in the eastern central Pacific Ocean, *Phyllospadix iwatensis* and, *Halophila baillonii* in the northwestern Pacific Ocean and *Halophila baillonii* in the southwest and west central Atlantic Ocean. The seven Vulnerable species belong to three families, i.e. the Posidoniaceae.

Major threats to the seagrasses as stated in the IUCN reports above are residential and commercial development, natural system modification leading to habitat loss, agriculture and aquaculture, pollution, energy production, transportation and service corridors, invasive species and diseases, climate change and severe weather leading to alteration and shifting of habitats. *Posidonia oceanica* which is endemic to the Mediterranean Sea is an example of a species with population that has negatively impacted by threats mentioned above.Population expansion polewards of a tropical species was observed in the South Atlantic with *Halophila decipiens* (Gorman, 2016) and *Halodule wrightii* (Ferreira and others, 2015).

Nine species listed in the IUCN Red list as Data Deficient (Short and Waycott, 2010n, o, p, q, r, s, t, u, v) have remained unstudied up to now: two in the family Zannichelliaceae (*Lepilaena australis*, *Lepilaena marina*), the former found in the eastern Indian while the latter in both and eastern Indian Ocean, and the south-western and western central Pacific Ocean, four in the family Cymodoceae with *Halodule beaudettei*, *Halodule bermudensis*, *Halodule emarginata* occurring in the north-western Atlantic Ocean and *Halodule emarginata* occurring in the north-western Atlantic Ocean, and *Halodule ciliata* in the eastern central Pacific, two in the family Hydrocharitaceae (*Halophia euphlebia*, *Halophia sulawesii*) found in the northwestern and western central Pacific Ocean, and one in the family Ruppiaceae (*Ruppia filifolia*) occurring in the southeastern Pacific and southwestern Atlantic Ocean (see Figure 2).

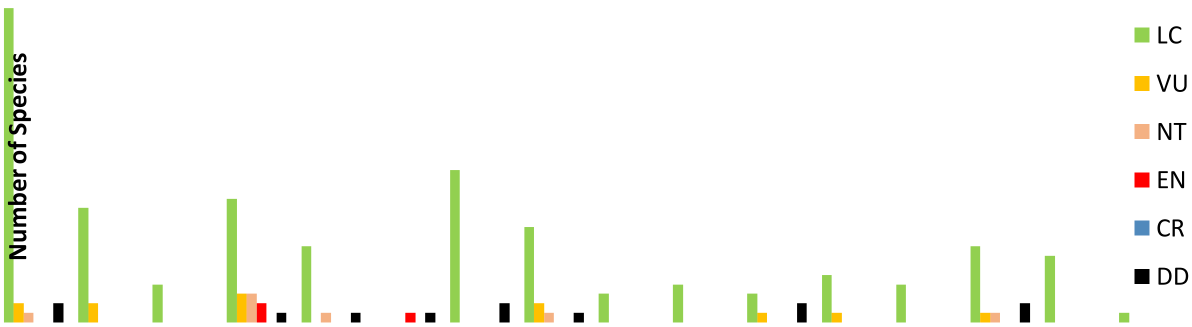

Figure 2. Distribution of species based on IUCN categories and marine regions Legend: IUCN categories: LC = Least Concern; VU = Vulnerable; NT= Near Threatened; EN = Endangered; CR = Critically Endangered; DD = Data Deficient.
Marine oceanic regions: E-Eastern; W-Western; N-North; S-South; C-Central; Pac-Pacific; Atl-Atlantic

On the regional level, however, some species may be threatened due to various factors. For example, *Enhalus acoroides*, has very limited distribution in the Red Sea LME (El-Shaffai, 2016), and may be vulnerable to grazing, especially since the area is home to a significant dugong population (Shawky, 2019; Nasr and others, 2019). Dugongs selectively graze changing not only the community and population structure but also the species composition of seagrass beds. In Atlantic Canada, European green crabs, which are invasive and non-indigenous to the region are having a negative impact on eelgrass (Matheson and others, 2016).
General decreases or increases in seagrass beds in some parts of its distribution have been reported; decreases in *Zostera marina* have been reported in Nova Scotia and in the Gulf of Lawrence, and increases in Newfoundland (Bernier and others, 2018). The non-indigenous *Halophila stipulacea* is reportedly expanding westwards from the eastern Mediterranean (Sghaier et al., 2011), and *Halophila decipiens* was newly recorded in a locality of the Aegean Sea (Gerakaris et al., 2020).

5. Macroalgae

The term "macroalgae" or "seaweeds" refers to non-flowering plant-like organisms which grow anchored in near-shore areas, except for some species of *Sargassum* which grow floating mostly in the Sargasso Sea (see Chapter 7S of the present Assessment). They have developed many adaptations that have enabled them to colonize various habitats, from polar to equatorial regions, and from shallow to very deep areas up to the limit of the euphotic zone. These adaptations include various pigments to trap light, diverse life-history patterns and morphologies to increase survival, and production of anti-herbivory compounds to evade grazing. These adaptations are used to characterize, and identify groups and species.

Seaweeds form the most extensive and productive vegetated coastal habitats, as kelps and other algal beds, in global coastal environments such as rockshores and biogenic reefs, estimated to cover about 3.4 million km^2 and support a global net primary production of about 173 TgC yr^{-1} (Krause-Jennsen and others, 2016), and are harvested and farmed for food and other uses (see Chapter 17 for more details). They are often used as indicators of water quality and reef health. For example, species of the green seaweed *Ulva* are used as indicators of heavy metal pollution and eutrophication (Alp and others 2012).

A group of red algae which contain calcium carbonate in their cell walls (called coralline algae since they resemble hard corals) can cover more sublittoral rocky substrata than any other group of macroorganisms in the photic zone from intertidal habitats to 270 m depth, and are the deepest recorded macroalgae. Most of these heavily calcified red algae encrust rock or other substrata - but some species grow unattached to form important complex habitats that build up over thousands of years known as "maerl beds" or "rhodolith beds" (Riosmena-Rodríguez, 2017). These free-living coralline algae cover extensive areas of coastal seabed and are common in fossil marine carbonate deposits. The largest continuous latitudinal distribution of rhodolith beds occurs off Brazil contributing to the formation of mesophotic reefs on extensive areas of the continental shelf, seamounts tops, and around oceanic islands and atolls (Amado-Filho and others, 2017). Free-living coralline algal thalli grow slowly (a few mm per year) and can be long-lived (>100 years). They provide a three-dimensional calcareous habitat attracting recruits to the benthos and providing refuge for the juveniles of commercially important shellfish.

5.1. Taxonomic treatment

Macroalgae are currently classified as protists (Kingdom Protista). However, recent phylogenetic studies using plastids, suggested that red and green algae share a common ancestor of the Kingdom Plantae, and brown algae share a common ancestor of Kingdom Chromista (Delwiche, 2007). They are a diverse group, consisting of three major divisions based on their dominant pigmentation: red algae (Rhodophyta), brown algae (used to be classified under division Phaeophyta but recently placed in its own class under Division Ochrophyta) and green algae (Chlorophyta). They contain chlorophyll and conduct photosynthesis. Many of them are “plant-like” in appearance but have simple bodies called thalli and lack the water-conducting system observed in terrestrial plants. Unlike seagrasses, they do not bear flowers.

As of 2012, Guiry (2012) listed 12,471 species of algae belonging to the three divisions, of which 6,131 are red, 1,792 are brown and 4,548 are green, but estimated that there about 27,000 species yet undescribed, including macro and microalgae living in habitats other than marine. The Ocean Biogeographic Information System (OBIS, 2020; see also Table 1), which lists only marine species, counts 3,065 reds (Rhodophyta); 879 browns (Phaeophyceae) and 844 greens (Chlorophyta). For taxa (which include subspecies or those of unknown rank), the numbers are higher: 3,406, 1,070 and 1,164 for, respectively, red, brown, and green algae (see Table 1). The species number and records of Chlorophyta are lower than those of red and brown algae since the majority of green algae are found in freshwater environments.

Table 1. Records of red (Rhodophyta), brown (Phaeophyceae) and green algae (Chlorophyta) from the Ocean Biogeographic Information System (OBIS, 2020).

DATA	RHODOPHYTA	PHAEOPHYCEAE	CHLOROPHYTA
Occurrence records	614,096	568,806	392,594
Species level records	449,392	477,331	209,396
Species	3,065	879	844
Taxa	3,406	1,070	1,164
Datasets	266	234	371
Time range	1865 - 2019	1869 - 2019	1778 - 2019

5.2. Current State and Trends

Red algae (Rhodophyta) comprise the highest number of species when compared to brown and green algae (Table 1). They are distributed mainly from tropical to temperate marine waters (Figure 3), with very few species in freshwater ecosystems. They are found in areas with sea-surface temperatures (SST) ranging from 5 to 30^{o}C, salinity of 5–35 PSU (, and mostly at 0–20 m depth (OBIS, 2020) although rhodoliths are recorded at much deeper depths.

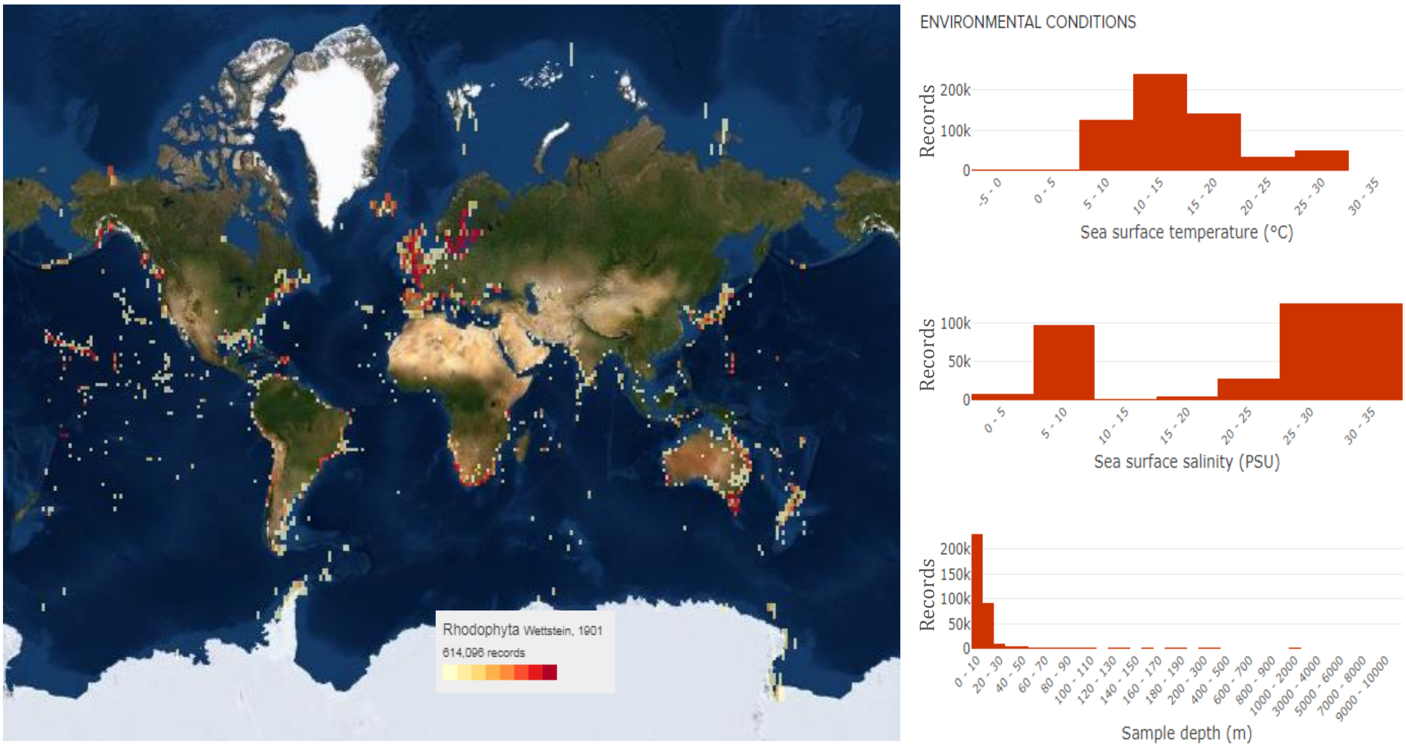

Figure 3. Distribution of red algae (Rhodophyta) and environmental conditions (temperature, sea surface salinity and depths) of occurrence around the world (OBIS 2020, https://mapper.obis.org/?taxonid=852).

Brown algae (Phaeophyceae), which comprise the least species (Table 1), are purely marine and have a wide distribution, mainly in cold waters of temperate and southern Oceans (Figure 4). They grow in areas with SST ranging from 5 to 30^{o}C, but can tolerate low temperatures (from -5 to 5^{o}C), salinity of 5-35 PSU, and mostly at 0–20 m depth (OBIS, 2020).

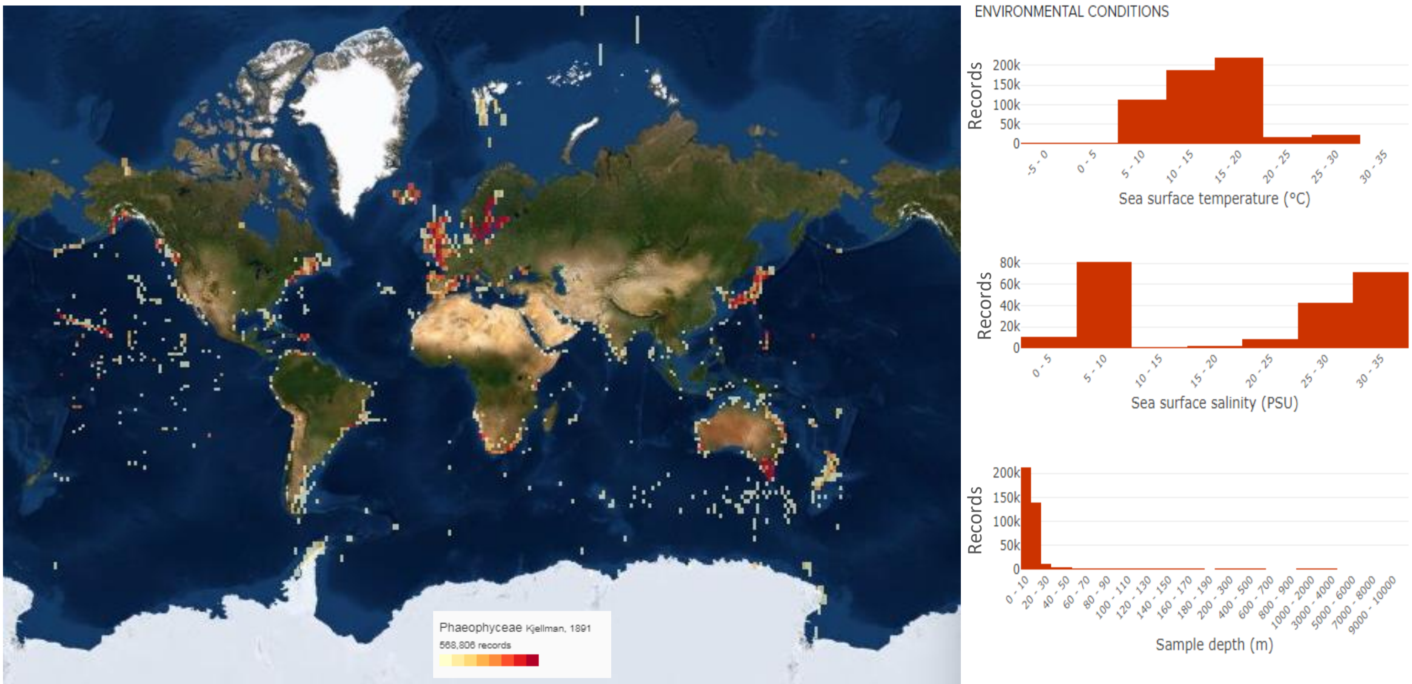

Figure 4. Distribution of brown algae (Phaeophyceae) and environmental conditions (temperature, sea surface salinity and depths) of occurrence around the world (OBIS 2020; https://mapper.obis.org/?taxonid=830).

Green algae (Chlorophyta) have a species number intermediate between red and brown algae (Table 1). They are distributed widely, but mainly in the Northern Hemisphere (Figure 5). They grow in diverse environments, from land to ocean and in seas with SST ranging from 5 to 30ºC, but can tolerate low temperatures (from -5 to 5ºC), salinity of 0-35 PSU, and mostly at 0–20 m depth (OBIS, 2020).

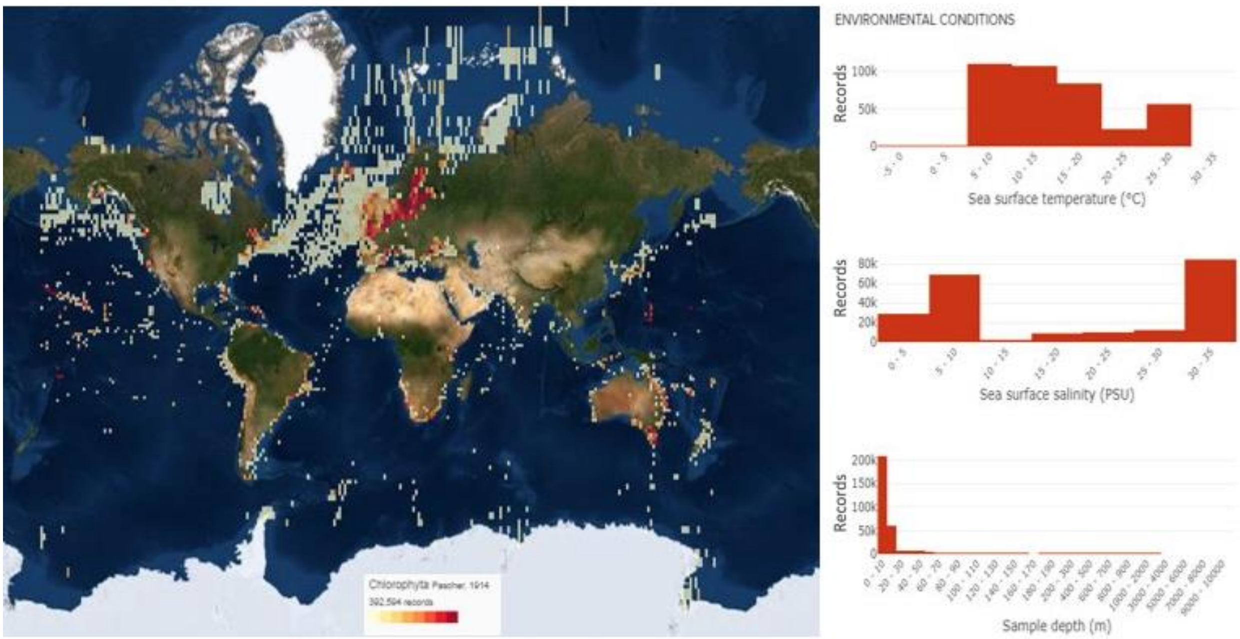

Figure 5. Distribution of green algae (Chlorophyta) and environmental conditions (temperature, sea surface salinity and depths) of occurrence around the world (OBIS 2020; https://mapper.obis.org/?taxonid=801).

Extinction risk assessment of algae was conducted in 2007 (Guiry and Guiry, 2020) and only on a small number of species (125). This does not even cover 1 per cent of the total species inventoried up to now.

One red algal species is listed as Extinct and 15 red and brown algae are in the threatened list, all occurring in the southeastern Pacific Ocean and all are endemic to the Galapagos Islands.

Listed as Extinct is the *Vanvoorstia bennettiana* (Millar, 2003) of the family Delesseriaceae, which was first discovered by William Harvey in 1855 growing in Port Jackson, Sydney Harbour, New South Wales, Australia. It was re-collected in 1886 at about eight kilometres east of the type locality (Millar, 2001). Despite intense searching, no specimens have been seen or collected in over a century, and "habitat loss through human activities caused the extinction of this species" (Guiry and Guiry, 2020). Image and taxonomical information of *V. bennettiana* are available in http://www.algaebase.org/search/species/detail/?species_id=23738.

Ten species were listed as Critically Endangered (Miller and others 2007a,b,c,d,e,f,g,h,i,j,k,l,m,n,o): six species in the Rhodophyta (i.e. *Galaxaura barbata*, *Gracilaria skottsbergii, Laurencia oppositocladia*, *Myriogramme kylinii*, *Phycodrina elegans,* and *Schizymenia ecuadoreana*, and four species in the Phaeophyceae (i.e. *Bifurcaria galapagensis*, *Desmarestia tropica*, *Dictyota galapagensis,* and *Spatoglossum schmittii*). The Critically Endangered red algae belong to families Galaxauraceae, Gracilariaceae, Delesseriaceae, and Schizymeniaceae, respectively, while the brown algae belong to families Sargassaceae, Desmarestiaceae, and Dictyotaceae. Since the year 1970, there have been significant changes in the populations of macroalgae in the Galapagos during El Niño 82-83 and 97-98, affecting *Bifurcaria galapagensis*, an endemic brown macroalga of the Galapagos, which inhabited the shallow intertidal and subtidal habitats (Garske 2002).

One species of brown algae, *Sargassum setifolium* of the family Sargassaceae, was listed as Endangered (IUCN, 2019).

Four species were listed as Vulnerable (IUCN, 2019) – three species of red algae (*Austrofolium equatorianum* (E.Y.Dawson), *Acrosorium papenfussii*, and *Pseudolaingia hancockii*, and one species of brown (*Eisenia galapagensis*).

Four species, all red algae, were listed as Least Concern and 54 species were listed as Data Deficient (IUCN, 2019). None of the green algae assessed were listed as threatened and only *Rhizoclonium robustum* was listed as Data Deficient.

The major threat mentioned in the above reports was climate change, severe weather, followed by invasive and other problematic species, genes, and diseases. Residential and commercial development, transportation and service corridors, biological resources, and pollution were least mentioned.

On a regional scale, different types and levels of seaweed biodiversity assessments have been conducted.

In the Mediterranean, an extinction risk assessment was conducted under the Mediterranean

Action Plan of the Barcelona Convention[94] (wherein 47 species were listed as threatened). Among the threatened species, typical examples are the "habitat-forming" *Cystoseira* species, except *C. compressa*, that are declining and even become locally extinct (Mancuso and others, 2018; Thibaut and others, 2015). However, Verlaque, and others (2019) recommend that this list be reviewed on case by case basis as it includes species that are far from threatened and even considered invasive (e.g. *Caulerpa prolifera*) and a reassessment is suggested. The seaweeds of the Mediterranean, especially the perennial slow growers, are mostly threatened by commercial and industrial development (UNEP, 2015; Mansour and others, 2007; Husain and Khalil, 2013), coastal discharges (Mohorjy and Khan, 2006; Peña-Garcia and others, 2014; Fabbrizzi and others, 2020), climate change (Piñeiro-Corbeira and others, 2018), and introduction of exotic and invasive species through the Suez Canal (Galil and others, 2019). Israel and others (2020) reported that 16 per cent of the marine flora of Israel are regarded as invasive or exotic.

In the Southern Oceans, Miloslavich and others (2011) analysed the marine biodiversity of South America and found that species richness was higher in the tropical East Pacific than the tropical West Atlantic, and that the Humboldt Current system was richer than the Patagonian Shelf. Endemism analyses showed that 22 per cent of species are endemic in South America and 75 per cent of species are reported within only one of the South American subregions. In the South Atlantic, local stressors and coastal urbanization are causing substantial loss of seaweed biodiversity. Seaweed richness is 26 per cent less in urban areas than in areas with higher vegetation cover (Scherner and others, 2013). Among global stressors, heat waves deserve major attention, as it is an important threat to temperature-sensitive species, like the ecologically and biotechnologically important red alga *Laurencia catarinensis*. This species lost around 50 per cent of its total biomass during heat waves from Oct 8 to Nov 13, 2014 when temperatures reached 2.66 degrees above the threshold calculated for the above calendar days, Gouvêa and others, 2017).

In the Red Sea, macroalgal endemism level is around 9 per cent (Persga, 2003) and this is likely to increase with future research. This is because the Red Sea macroalgae are presently one of the least studied despite the long history of scientific exploration dating back to the seventeenth century (Sheppard and others, 1992). Previous records (Walker, 1987) show that the Red Sea contained about 485 macroalgal species which were circumtropical and subtropical in distribution, occurring over extensive parts of the Indo-pacific, Mediterranean and the Caribbean. The composition, distribution, and diversity of the Red Sea macroalgae seems to follow the natural latitudinal gradient in salinity, temperature and nutrient richness (Kurten and others, 2014) where diversity was greater in the northern and southern parts, as compared to the central part (Walker, 1987; Sheppard, 1992).

Antarctic macroalgae are characterized by low species richness when compared to other regions of the world, with a high endemism of approximately 33 per cent (Wiencke and Clayton, 2002; Wiencke and others, 2014), but this level was decreased to 27 percent (Oliveira and others 2020). The highest endemism is found in brown algae (35.3 per cent), followed by red algae (29.4 per cent), and is lowest in green algae (12.5 per cent) (Oliveira and others 2020).

An inverse relationship between species diversity and latitude is observed in Antarctic macroalgae (Wiencke and Clayton, 2002). A total of 104 taxa were identified in the South

[94]Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean; United Nations Treaty Series, vol. 1102, p.27.

Shetland Islands (Pellizzari and others, 2017), which is higher than in Adelaide Island with 41 taxa (Cormaci and others, 1992), and Terra Nova Bay (Ross Sea, above 70°S), with 17 taxa (Mystikou and others, 2014).

The impact of oceanic warming on the distribution of Antarctic seaweeds was evaluated by Müller and others, (2009), who concluded that the temperature increase may not directly affect latitudinal distribution of some Antarctic seaweeds. However, Pellizzari and others (2020) suggested that macroalgal diversity in Antarctica, mainly in the Peninsula surroundings, need to be monitored since the area is susceptible to species introduction and meteorological and oceanographic changes (Hughes and Ashton, 2017).

6. Consequences of the changes on human communities, economies and well-being

The loss of species comprising the major coastal and ocean ecosystems such as mangroves, salt marsh plants, seagrass, and seaweeds or those harvested for use and other applications could cause major health and economic repercussions to society.

A direct impact of loss of species to economies and well-being is demonstrated by the loss of the kelp species, which are brown algae comprising huge kelp forests in the temperate oceans. These species are harvested for food and other industrial, cosmetic, medical, and other applications. Kelps are most affected by rising ocean temperatures as they require cold waters to reproduce and grow. The effect is most apparent at the northernmost and southernmost limits of their distribution (Reed and others, 2016). As ocean temperatures increase, the distribution of some kelp populations have moved south in the southern latitudes, and north in the northern latitudes, and with the associated grazer populations such as urchins have also shifted geographically in recent decades (Wahl and others, 2015). Wernberg and others (2019) and others have shown trajectories of change in kelp abundance based on long-term biomass records (see Figure 6).

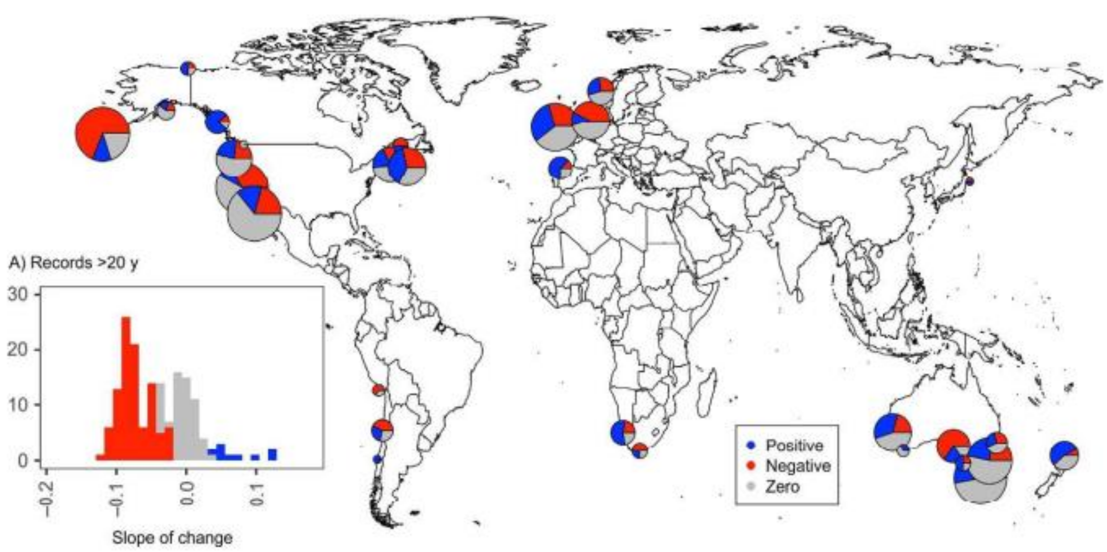

Figure 6. Trajectory of change in records of kelp abundance globally. From Wernberg, and others, 2019, reprinted with permission.

The loss to fisheries as a result of climate change impacts on reef-forming coralline algae and maerl-bed forming rhodoliths is likewise significant. Some publications (Barberá and others, 2003; Riosmena-Rodriguez, R. and others, 2010) on the conservation status of maerl/rhodolith habitats in Atlantic, Mediterranean and Gulf of California waters show that the health of these habitats is decreasing in many parts of the world. Activities such as dredging (e.g. for soil conditioner or shipping channels), destructive fishing (e.g. with dredges or trawls) and fish farming can reduce the complexity and biodiversity of these habitats, as can the spread of invasive species such as the gastropod *Crepidula fornicata* (Pena and others, 2016). As well as these direct impacts, maerl beds have been reported to face pressures from ocean warming and acidification since slow growing coralline algae are highly vulnerable to anthropogenic CO_2 emissions (Martin and Hall-Spencer, 2017; Cornwall and others, 2019). European maerl beds have conservation protection since their three-dimensional carbonate matrix provides a wide range of ecological niches for associated flora and fauna.

Pioneering species such as *Halophila ovalis*, *Halodule uninervis* and *Cymodocea rotundata* are now being used as indicators of seagrass meadow resiliency in vulnerability assessments. Several seagrass species are used as bioindicators for heavy metal pollution, e.g., *Halophila ovalis* and *H. minor* (Ahmad and others, 2015), *Thalassia hemprichii, Enhalusa coroides,* and *Cymodocea rotundata* are potential bio-indicators for cadmium content in sediments, and zinc content in seawater (Li and Xiaoping, 2012).

7. Key remaining knowledge and capacity-building gaps

Although new techniques such as genomics have been developed for species identification and for elucidating phylogenetic relationships, human and infrastructure capacities are still lacking in many regions. Few people study to become systematists, and even fewer to become phycologists (algal taxonomists). Taxonomic and systematic studies are important to enhance the contribution of marine biodiversity to development. This applies particularly to small island states and archipelagic countries. As such, they respond to Sustainable Development Goal 14, specifically Target 14.a. With the development of new techniques in identifying species, the number of species is expected to rise, especially for macroalgae. However, some regions will still be less studied than others depending on the capacities available. In addition, the vulnerability of a majority of plant and macroalgal species to changing climate and ocean conditions has not been assessed. https://www.fisheries.noaa.gov/national/ climate/climate-vulnerability-assessments)

8. Outlook

Climate change is now recognized as a major pressure that affects populations. It could be an opportunity for some species to expand their distribution as in some species mangroves or marsh plants or become more restricted and even go extinct as in some species of kelps. For example, Pergent and others(2014) projected that in the Mediterranean, the endemic seagrass, *Posidonia oceanica,* which has narrow salt and temperature tolerance, will probably decline, mainly in the Levantine Sea, where sea surface temperature and salinity are predicted to increase. *Zostera marina*, which grows in colder temperatures could first be more confined and isolated in the northernmost parts of the Mediterranean, and then become extinct. However, species like *Cymodocea nodosa* and *Halophila stipulacea* which grow well in warmer climates could outcompete *Z. marina* and *P. oceanica* which could lead to a decrease in the structural complexity of the habitats.

Some projections on seaweed species loss in 2100 have been made with habitat modelling in relation to Representative Concentration Pathway (RCP) of greenhouse gas emissions: an average loss of 62 per cent (range = 27 per cent-100 per cent) of their current distribution in Australia of 15 prominent species of kelp and canopy-forming temperate species of seaweeds under the most conservative RCP of 2.6 emission scenario; 50 per cent for North Atlantic for eight kelp species. On the other hand, some species are projected to expand their limits of distribution such as three of the eight species in the North Atlantic into the Arctic or replace another species, or form new forests. The change in populations of herbivores as a result of climate change is also projected to impact on macroalgal populations (see Wernberg and others, 2019).

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Chapter 7 Habitat Diversity
Trends in the state of biodiversity in marine habitats

Introduction

This chapter is composed of 17 subchapters that detail the state of coastal and marine habitats, from the coast to the deepest abyssal plains. Change in state since WOA I is provided on mangrove forests, salt marshes, estuaries and deltas, seagrass meadows, cold water corals, tropical and sub-tropical coral reefs, Sargasso Sea, high latitude ice, hydrothermal vents and cold seeps, and submarine habitats such as seamounts, submarine canyons, and trenches. The subchapter on submarine canyons has been expanded to include continental slopes, the seamounts subchapter includes pinnacles, and the trenches subchapter includes ridges and plateaus. Kelp forests which were included with seagrasses in WOA I are now integrated into a subchapter on marine plants and macroalgae. New assessments are provided on sandy and muddy substrates, intertidal zones, atolls and island lagoons, abyssal plains and the open ocean

Where a baseline of the state of the habitat was available in WOA I, this was used as basis for looking at change over the last decade. Key threats to habitats have been identified and their influence on changes observed discussed. When available, specific regional changes are highlighted, and an outlook for habitats over the near to medium term provided.

Chapter 7AB
Biogenic Reefs, Sandy, Muddy and Rocky Shore Substrates

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Keynote points

- Reefs and sandy, muddy and rocky shores support high biodiversity and a wide range of ecosystem services that benefit human populations.
- They are under pressure from multiple stressors as a result of climate change, urbanization and use of resources; storms, land reclamation, contaminants and pollutants have emerged as the main drivers.
- There is a gap in interdisciplinary research and participative governance to promote resilience and provide for the sustainable development of these habitats.
- Due to their cultural significance and importance for tourism worldwide, they are in a unique position to serve as flagship habitats to promote the role of the ocean in the implementation of the 2030 Agenda for Sustainable Development, including Sustainable Development Goal (SDG) 14.[95]

1. Introduction

Coastal environments are home to a variety of valuable natural resources which include sandy, muddy and rocky shores and reefs. All these habitats present a high biodiversity (see Chapter 6 of the present Assessment), and an increasing number of studies examine patterns, processes and impacts associated with them. Biodiversity and the human impact on rocky shores were recently reviewed at regional scales (Hawkins and others, 2019). However, a gap remains in the understanding of rocky and muddy shores at a global scale. For sandy shores, recent trends show that species richness worldwide is related to ecoregions, where temperature and latitude predict an increase in species richness from temperate to tropical shores (Barboza and Defeo, 2015) (Figure 1). Reefs form biogenic habitats that are ubiquitous in coastal systems worldwide but vary in extent and species composition across biogeographic regions (Firth and others, 2016). While in tropical regions they are typically formed by the calcium carbonate secreted by reef-building corals and calcareous red algae in shallow-water settings (Huang and Roy, 2015), in temperate regions they are formed by invertebrates, including oysters, mussels and annelid worms (Barbier and others, 2008; Dubois and others, 2009; Firth and others, 2016) (Figure 2).

The present Chapter provides an integrated overview of reefs and sandy, muddy and rocky shores, in both intertidal and subtidal zones, which are connected by their locations in the marine and terrestrial interface. These habitats cover all coastlines worldwide (Firth and others, 2016; Luijendijk and others, 2018; Chapter 7C of the present Assessment) and are linked to different ecosystems, including atoll and island lagoons (Chapter 7D), coral reefs (Chapters 7E and 7F), estuaries and deltas (Chapter 7G), kelp forests and algal beds (Chapter 7H), seagrass meadows (Chapter 7I), mangroves (Chapter 7J) and salt marshes (Chapter 7K), and are influenced by many drivers and oceanographic dynamics that emerge from local to global scales (Chapters 4, 5 and 25). To minimize overlap and highlight their interactions, we will focus on reefs and sandy, muddy and rocky shores and note the link with other Chapters where close habitats were detailed (e.g. 7C and 7I), particularly coral reefs in Chapter 7E

[95] See United Nations General Assembly resolution 70/1.

(the tropical and subtropical zone) and cold-water corals in Chapter 7F.

Reefs, sand, muddy and rocky shores are characterized by high biodiversity (Chapter 6) and provision of ecosystem services (Chapters 8, 22 and 24), including water filtration and nutrient cycling (Chapters 10 and 11). There is a strong connection between their ecosystem services and urbanization (Chapter 8), where about 60 per cent of the world's populations live and derive livelihoods along coastal areas (Nicholls and others, 2007). These coastal environments are economically relevant for tourism, recreational, artisanal and commercial fishing and also aesthetic and recreational value (Chapters 8, 15 and 24), where key activities include boating, fishing, surfing, swimming and bird watching (Everard and others 2010; Rodríguez-Revelo and others, 2018). These environments are also interconnected with many aspects of development, including urbanization, aquaculture and infrastructures (Chapters 8, 14 and 16).

As a consequence of the wide range of ecosystem services provided by these habitats and their association with coastal urbanization and coastal protection, they are vulnerable to impacts from multiple stressors (Chapter 28). They continue to be adversely affected by pollutants and contaminants, such as excessive nutrients from fertilisers, toxic chemicals and heavy metals, sewage, waste and plastic (Chapters 10, 11 and 12) and also by mining, oil and gas exploration and exploitation activities (Chapters 11, 19 and 20) and the more recently documented threats of invasive species (Chapter 25). At the same time, sedimentation and changes in coastal erosion (Chapter 13) are long-term processes that are increasing under the pressure of climate change impacts (Chapter 9) that contribute to changes in the formation of coastlines and may also pose a threat to life and property (Rangel-Buitrago and Anfuso, 2009; Le Duff and others, 2017).

The coastal zone is the most urbanized region in the world, hosting 15 of the 20 megacities (with populations of over 10 million people), where there is a diversity of ecosystem services provided by these habitats and a conflict with increasing urbanization, as already stated in the First World Ocean Assessment (WOA I) (United Nations, 2017). The present Chapter will cover the changes recognized since WOA I, including advances in knowledge or policy. It will also highlight the global analysis for sandy shores and the lack of information at the global level on biogenic reefs and muddy and rocky shores needed to support coastal management and marine spatial planning (Chapters 29 and 30). Despite the utility and economic benefits that coasts provide and the advances in global-scale studies on sandy shores, there is no reliable global-scale assessment of historical trends in shoreline changes for rocky and muddy substrates and there are still regions with very little information and data available on their ecosystems.

2. Documented change in state of biogenic reefs, sandy, muddy and rocky shore substrates

Threats to biogenic reefs, sandy, muddy and rocky shores can be from multiple environmental (some extreme, such as storm surges, hurricanes, earthquakes, tsunamis, heatwaves and floods) and anthropogenic drivers, as stated in the introduction. These drivers emerge from local to regional and global scales, while the anthropogenic factors dominate change at multiple scales (Mentaschi and others, 2018).

Changes in biogenic reefs, sandy, muddy and rocky shores are all influenced by different components of the seascape, as mangroves, rhodoliths and algae beds, deep zones, coral reefs and seagrass meadows all respond to stressors differently. There is also atmospheric deposition on coastal zones (Medinets and Medinets, 2010, 2012; Medinets, 2014) and discharge of sediments and nutrients on coastal marine systems by estuaries and freshwater (Teixeira and others, 2018; Oelsner and Stets, 2019). These natural connections (Chapters 7C to 7K) clearly highlight the interconnectivity and complexity of coastal systems (Elliott and others, 2019; Kermagoret and Stets, 2019) since changes in one habitat will influence the dynamic of other habitats, including their associated ecosystem services (Narayan and others, 2016; Osorio-Cano and others, 2019).

The biogenic reefs and sandy, muddy and rocky shores have been increasingly affected by climate change in the last decade, which has influenced environment patterns, biodiversity and ecosystem functioning. It is predicted that the magnitude and frequency of extreme events (wave energy, heatwaves, temperature and rainfall) will continue to intensify (Herring and others, 2018; IPCC, 2018). Changes in the number of days that exceed the temperature thresholds specific to each species, or changes in rain and drought regimes, can lead to sublethal stress, due to physiological and behavioural changes in organisms, particularly those in intertidal and shallow zones (Pinsky and others, 2019; Rilov and others, 2019). The changes in frequency and intensity of the events can lead to physiological lethal levels, increasing mortality and altering the biodiversity, the range of distribution of organisms and the ecosystem services that such habitats provide (Poloczanska and others, 2013).

In the environmental context, high-latitude, intertidal rocky substrates are affected by ice scour (Scrosati and Ellrich, 2018; Chapters 7A and 7M). Sandy, muddy and rocky shores worldwide are also under increasing wave and extreme rainfall disturbances (Mentaschi and others, 2018). This influences sediment dynamics, erosion, boulder movements and landslides that can change biological communities in sandy and rocky shores in wave-exposed areas (Petrovic and Guichard, 2008; Castelle and others, 2018). Changes in wave dynamics and the increasing frequency of extreme weather events also change sediment composition (Masselink and others, 2016) and larval transport to the shore (Mazzuco and others, 2015). In addition, increasing extreme rainfall events in the tropical and subtropical areas influence near-coast salinity and sediment transport as well as the input of nutrients, pollutants and contaminants from terrestrial and freshwater environments (Lana and others, 2018). The cumulative impacts and influence of such stressors can be seen from organisms to communities, leading to the loss of biodiversity and changes in ecosystem functioning in coastal areas (O'Gorman and others, 2012; Ellis and others, 2017), with impacts on ecosystem services, as well as commercial, recreational and aesthetic values.

In addition to the changes in coastal oceanographic dynamics and increase in the frequency of extreme events due to the effects of climate change (Chapter 9), other drivers such as seabed exploration (Chapters 19 to 23), urbanization (Chapters 8 and 14) and artificial coastal infrastructures (Chapter 7C and 14) are influencing reefs and sandy, muddy and rocky shores due to contamination (Chapters 10, 11 and 12) and changes in the processes of erosion and sedimentation (Chapter 13). Sandy beaches are present in the coastline worldwide, varying from 22 per cent in Europe to 66 per cent in Africa, with their relative occurrence increasing in the subtropics and lower mid-latitudes (20°–40°) but decreasing (<20 per cent) in the humid tropics, where mud and mangroves are most abundant as a result of high temperatures and rainfall (Figure 3) (Luijendijk and others, 2018). The erosion of sandy beaches has been increasing over time and with the intensity of greenhouse gas emissions (Vousdoukas and others, 2020). Erosive and accretive tendencies have been interchanging across regions and along nearby coastal segments (Vousdoukas and others, 2020), with more than 50 per cent of the world's sandy shores suffering chronic and severe rates of change over the period 1984–2016, and with 24 per cent of shores eroding at a rate exceeding 0.5 m/yr, while 27 per cent are accreting (Luijendijk and others, 2018) (Figure 4). From a continental perspective, Oceania and Africa present net erosion, while all other continents show net accretion, with the highest accretion rate (1.27 m/yr) in Asia (Luijendijk and others, 2018), likely due to land reclamation and artificial structures (Luijendijk and others, 2018; Chapter 14). On a global scale, a relatively high percentage of sandy shorelines recorded in the World Database on Protected Areas are experiencing erosion, bearing in mind that 32 per cent of all marine protected shorelines are sandy, and 37 per cent of these protected sandy shorelines are eroding at a rate above 0.5 m/yr, while 32 per cent are accreting (Luijendijk and others, 2018).

Changes in erosion and sedimentation and the presence of artificial structures can directly influence biodiversity and ecosystem services at different scales. The increase in coastal infrastructure to avoid erosion requires the strengthening of blue engineering approaches for sustainable development (Firth and others 2016; Strain and others, 2018). Although coral concrete has been suggested for the development of marine infrastructure and land reclamation (Wang and others, 2018; Liu and others, 2018), to achieve sustainable development, it is critical to understand the source, the amount of the coral material needed and the impact of its extraction from the environment, as coral reefs have biological, chemical and physical importance in the dynamics of coastal areas and in the climate change scenario (Chapters 7E and 7F).

The impacts of urbanization on coastal zones warrant consideration of several key stressors, including anthropogenic drivers, that exist in the coastal zone. Invasive species (Chapter 25) have increased worldwide (Seebens and others, 2017), thus affecting all types of substrates. Biological invasions are expected to increase as a result of maritime transport and also the increase in coastal infrastructure in coastal areas as a new substrate to rocky and reef species (Ivkić and others, 2019; Sardain and others, 2019). Furthermore, recent data sets worldwide show land-based pollution (nutrient pollution, agrochemicals, sewage discharge, chemical contamination by persistent organic pollutants (POPs) in the form of pharmaceuticals, pesticides and heavy metals), coastal urbanization, land reclamation and oil spills that change habitats, increase contamination and cause sublethal to lethal processes that affect muddy, sandy and rocky shore biodiversity and ecosystem health (Kovalova and others, 2010; Snigirov and others, 2012; EMBLAS, 2019; Martinez and others, 2019; Zhai and others, 2020). Many impacts on these shores have their origin offshore, such as oil spills (Escobar, 2019; Soares and others, 2020), or inland, as mine tailings, with accidental discharge in the coastal zone, through riverine inputs, reaching and impacting the biodiversity and ecosystem services of sandy, muddy and rocky shores on large spatial and temporal scales on the coast (Queiroz and others, 2018), and affecting local and indigenous communities that depend on those ecosystem services for their survival (Dadalto and others, 2019).

Finally, another consequence of coastal urbanization relates to the negative impacts of tourism and human exploitation on biogenic reefs, sandy, muddy and rocky shores at local scales (Mendez and others, 2017). Artificial light at night has been shown to change macroinvertebrate community structure on sandy shores (Garratt and others, 2019) and influence trophic interactions on rocky shores (Underwood and others, 2017; Maggi and Benedetti-Cecchi, 2018). Similarly, shading by artificial infrastructure can influence biodiversity and ecosystem functioning on rocky shores (Pardal-Souza and others, 2017). Trampling has been shown to negatively impact biodiversity on sandy, muddy and rocky shores (Leite and others, 2012; Schlacher and Thompson, 2012; Kim and others, 2018), in addition to other factors such as littering, noise and extraction (EMBLAS, 2019). Plastic and chemical pollution has become a global threat to the marine environment, especially to sandy shores, where plastic input has increased as a result of transport during oceanographic and meteorological events (Krelling and Turra, 2019) and direct contamination by locals and tourists (EMBLAS, 2019).

3. Consequences of the changes on human communities, economies and well-being

Coastal habitats are the first point of contact between human society and the ocean. They provide many direct and indirect services, including space for leisure and sports, environmental chemical-physical processes, biological and fisheries resources and coastline protection. From intertidal to subtidal areas, reefs and sandy, muddy and rocky shores are explored in many ways by human populations, thus creating a relationship that has been impacted by changes over centuries, but at an accelerating pace in recent decades (Biedenweg and others, 2016; Zhai and others, 2020).

Sandy and rocky shores provide space and natural resources for leisure, sports, educational and scientific studies, traditional, religious and cultural practices for indigenous peoples and traditional communities, and a place to visit for residents from urban areas and tourists (Everard and others, 2010). There are many physical, mental and spiritual health benefits related to time spent in coastal environments and to the health of that environment (Gascon and others, 2017; Marselle and others, 2019). The human-environment link develops psychologically through a sense of place and identity, a connection with nature and belonging, with feelings of pride in one's environment, and the revitalizing properties of aesthetic landscapes, while the environment also physically influences us by providing tangible services such as food (Biedenweg and others, 2016). Finally, muddy, sandy and rocky shores also benefit society as a result of economic aspects related to business and industrial links in urbanized coastlines, by providing jobs and by promoting involvement with governance, and thus access to communications, community participation and trust in management (Biedenweg and others, 2016).

The importance of reefs and sandy, muddy and rocky shores for human communities is similar worldwide. They are indirectly relevant to the well-being of human communities through many ecosystem services, such as water filtration, biodiversity, biotechnology, nutrient cycling, carbon sinking, coastal protection and impacts on pelagic primary production (Hoerterer and others, 2020). Many species of biotechnological interest have been studied recently, thus indicating a potential for scientific and economic development (Park and others, 2019; Girão and others, 2019). Biogenic reefs and sandy, muddy and rocky shores present species of economic interest, mainly molluscs, crustaceans and fishes, that are particularly important for traditional communities as sources of proteins and income, based on traditional fisheries (e.g. Gelcich and others, 2019).

The importance of services from sandy, muddy and rocky shores to human well-being and economy explain the high urbanization and tourism at coastal regions, which has an important economic contribution (Nitivattananon and Srinonil, 2019). However, the higher the population at the coast, the bigger the coastal impacts are. The contrast between more pristine to more polluted areas changes tourism and recreational and artisanal fishing values (Qiang and others, 2019). Low impact, natural sandy and rocky shores are an important tourist attraction, both for leisure and snorkelling (Drius and others, 2019). Clean and healthy shores attract many tourists, thus triggering development of a region's tourist sector. Meanwhile, sandy and rocky shores become very vulnerable under the pressure of recreational and touristic activities, as a result of contamination and the alteration of the natural habitats of many organisms due to the introduction of artificial infrastructures (Strain and others, 2018; Drius and others, 2019). The contrasts between more pristine to more polluted shores lead to variable seascapes and tourist destinations along the coastline. Increasing changes in the coastline due to climate change, other anthropogenic impacts and erosion can alter tourism dynamics by decreasing tourism in impacted areas and increasing it in low impact areas. Such changes will influence coastal communities, and local people working in the tourist and support sectors, socially, culturally and psychologically, as well as economically (Jarrat and Davies, 2019; You and others, 2018).

Investment in the sustainable development plans of coastal areas brings multiple economic, social and environmental benefits. Urbanization pressure is increasing as people look to improve their well-being and take advantage of the benefits of coastal environments. Rocky shores tend not to be heavily exploited directly but, as one of the most conspicuous and favoured landscapes, local communities grow up, with houses often within 100 metres of the shore. Muddy shores are challenging but lucrative areas for real estate developers, investors and private builders. Because of this, there is often excessive construction in such areas, and many existing building codes and standards are ignored. These natural shores are then damaged, including as a result of huge landslides which negatively affect the marine ecosystem. Sandy shores are adversely affected by urbanization due to the removal of coastal vegetation, land cleaning and increased instability during extreme events and erosion, leading to weaker coastline protection (Defeo and others, 2009). The construction of artificial islands has been driven by demand for coastal housing. Yet the development of these sites in many regions has accelerated without any detailed consideration of the ecological impacts, both on the source areas, where sand is extracted on a large scale as construction material, and on the local ecosystems that are disturbed or displaced by construction activities (Rahman, 2017a, 2017b).

Changes in coastlines, sea level rise, extreme events and tourism activities lead to a change in environmental perception by human populations and increase social conflicts in the coastal zone (Robinson and others, 2019; Whitney and Ban, 2019). Wave height is arguably beneficial for wave-power electricity, as it provides increasing power, but ongoing increases in average wave height present a threat to the physical generator infrastructure that is already pushing the limits of engineering endurance (Penalba and others, 2018).

The complexity of ecosystem services from sandy, muddy and rocky shores, the drivers influencing these environments, the conflict between use and conservation with the benefits for and impacts from human population highlight the importance of sustainable development. The complex system that integrates these habitats and the potential and challenges for its governance show the importance of marine spatial planning to support and regulate the use of these environments, and of the 2030 Agenda for Sustainable Development and its SDGs,[95] including SDG 14, and the inclusion of goals to decrease impacts on sandy, muddy and rocky shores (Kidd and others, 2020; Borja and others, 2020).

4. Key region-specific changes and consequences

There is limited information from the Arctic and Southern regions of the Ocean, but other regions have recorded changes. Along the shores of the North-West Atlantic, North-East Pacific, North Sea and Black Sea, oceanographic drivers are an important issue due to wave disturbance (Voorhies and others, 2018), ice scour (Scrosati and Ellrich 2018) and the increasing frequency of extreme weather events (Smale and Wernberg, 2013) that impact intertidal rocky shores, thus changing sediment transportation, which affects muddy and sandy shores (Masselink and others, 2016) and increasing erosion and boulder movements that can change biological communities in wave-exposed areas (Petrovic and Guichard, 2008; Castelle and others, 2018). Changes in wave dynamics in these regions also influence benthic-pelagic coupling and ecosystem functioning (Griffiths and others, 2017) by influencing larval supply (Mazzuco and others, 2018), organic matter (Massé Jodoin and Guichard, 2019), temperature and hypoxic events (Vaquer-Sunyer and Duarte, 2011).

In the north-west part of the Black Sea, sandy shores have become narrower in recent years in most parts of the coastline (Allenbach and others, 2015), where vegetation has expanded (Allenbach and others, 2015). Meanwhile the depth of shelf waters near the mouth of the Danube and Dniester rivers has decreased because of riverine sediment input (Anton and others, 2017), which has also led to the formation of shore dunes in some areas. However, in the eastern part of the Black Sea, coastline erosion is associated with sediment starvation in riverine water discharge as a result of dams and engineering works (Kosyan and Velikova, 2016). There has been significant erosion of muddy and rocky shores as a result of landslides caused both by climatic and anthropogenic factors over the last decades (Freiberg and others, 2010, 2011; Goryachkin, 2013; Tătui and others, 2019). Increased erosion rates have been registered in coastlines, adjacent to rural areas, where there are no wave breakers, and also around Serpent’s Island (Cherkez and others, 2006, 2020; Goryachkin, 2013). The impacts of all this, together with socioeconomic drivers due to the over-exploitation of shores for construction, and recreational and touristic activities for higher revenues, have affected the coastline in many ways (Goryachkin, 2013; Stanchev and others, 2013, 2018; Kucuksezgin and others, 2019).

Oceanographic drivers also cause coastal erosion and a reduction of the surface of sandy shores on the coasts of Argentina and Brazil in the South-West Atlantic, thus also influencing wave energy and larval supply as a result of the increasing frequency of extreme events and cold fronts (Mazzuco and others, 2015, 2018). Changes in erosion and coastline impacts affect the economy of local communities and change the way they perceive natural coastal ecosystems on the Atlantic coast of South America as a whole (Bunicontro and others, 2015). In addition to a constant driver such as changes in the oceanographic dynamics and its influence on coastal habitats, environmental disasters have been a key issue in the South-West Atlantic (Gil and others 2019; Marcovecchio and others, 2019). In the last five years, there have been two inland mine tailing disasters where discharge reached the coastal zone, thus impacting different habitats, including reefs, sandy, muddy and rocky shores and communities in Brazil, and one oil spill that affected more than 3,000 km of coastline (Escobar, 2019; Soares and others, 2020). These disasters have a high temporal and spatial impact on the environment, ecosystem services and human communities, particularly in view of the cumulative effects with oceanic-climatic drivers that might resuspend the chemicals in the sediments from sandy and muddy shores (Queiroz and others, 2018; Dadalto and others, 2019).

In the Indian Ocean region, the construction of artificial islands has created new local navigational hazards from unsecured installations intended to prevent erosion, and also illegal dumping of waste material (Rahman, 2017a), with new structures that have changed the routes to fishing grounds (Rahman, 2017b). The results of the initial detailed environmental impact assessment of a project in Malaysia led to a revision of the planned layout of new islands to prevent destruction by smothering of a diverse seagrass meadow (Williams, 2016; Chapter 7I). However, further and long-term environmental impacts require ongoing review.

A global survey shows the coasts of the Western Pacific and the Eastern Atlantic as hotspots of concentrations of several pollutants, and mostly affected by a warming climate (Lu and others, 2018). Although many of the drivers from other regions also influence the Pacific coast, climate change and oceanic-climatic events emerge as a key issue in the Eastern Pacific (Xiu and others, 2018). The Eastern Pacific coast is one of the most productive marine ecosystems due to the presence of upwelling systems, which are considered to be the most important driving factor for changes in sandy, muddy and rocky shores (Randall and others, 2020). In the North Pacific, it is expected that increased upwelling intensity associated with stronger alongshore winds in the coastal region (Xiu and others 2018) will change the ecosystem functioning on sandy, muddy and rocky shores due to changes in nutrient input and oceanographic conditions. In the South Pacific, changes in the Humboldt Current System are influencing different countries in different manners (e.g. an increase in upwelling-favourable winds off Chile and a decrease off Peru) (Bertrand and others, 2019). The Pacific coast is strongly affected by El Niño and extreme events that may become more frequent and influence the coastline and coastal ecosystem services from sandy, muddy and rocky shores (Bertrand and others, 2019). Climate change and associated impacts affect the natural coastal dynamics of sandy and rocky shores and their services, including fisheries, aquaculture, erosion and tourism due to the increased frequency of extreme events that lie outside the realm of present-day experience (Aguilera and others, 2019).

5. Outlook

When considering a business-as-usual scenario, reefs and sandy, muddy and rocky shores worldwide will be impacted, with a serious loss of ecosystem services. It is expected that in the medium term (approximately 20 years) all issues will be aggravated significantly, and we may lose substantial parts of natural shores, with negative socioeconomic and cultural consequences. There is an increase in human population on the coasts and, as a consequence, an increase in the pollutants, waste and other factors influencing the sandy, muddy and rocky shores. The increase in coastal infrastructures and land reclamation will accelerate this process, and, to date, little is known of the long-term impacts on coastlines from changes in hydrodynamics, biodiversity and the source of materials to build those infrastructures. On the other hand, if coastal urbanization develops based on blue engineering, this will be an opportunity to increase sustainable initiatives (Chapter 7C; Strain and others, 2018) and increase public awareness of the value of coastal ecosystems and socio-ecological coastal systems based on ocean literacy (Santoro and others, 2017; Fleming and others, 2019).

There is a direct connection between coastal populations and ecosystem services from biogenic reefs and sandy, muddy and rocky shores, where the increase in the population and use of environmental resources might be higher than the shore resilience. At the same time, climate change will increase the frequency and intensity of storms reaching the coast (IPCC, 2018). From an ocean perspective, there are expected changes in oceanic-climatic drivers impacting the coastline by increasing wave energy, erosion, sediment transport and sea level rise, including reduction in the intertidal range of some shores (Herring and others, 2018). From an inland perspective, increasing rainfall will disturb sediment transport and increase the input of nutrients, contaminants and pollutants from terrestrial and freshwater environments to coastal habitats (Lana and others, 2018).It is expected that 13.6–15.2 per cent (36,097–40,511 km) of the world's sandy beaches could face severe erosion by 2050, and 35.7–49.5 per cent (95,061–131,745 km) by the end of the century. So a number of countries could face extensive sandy beach erosion issues by the end of the century (Vousdoukas and others, 2020).

The cumulative effects of climate change and other anthropogenic influences will continue to impact biodiversity, ecosystem services and environmental health. These continuous multiple stressors, according to the One Health concept of the World Health Organization, will influence human well-being and health (Fleming and others, 2019). By increasing coastal populations and infrastructures, we also can expect an increase in cultural conflict between traditional and indigenous communities with the advent of larger cities and industrial activities. In different areas, the increase in contamination of resources, the loss of biodiversity, changes of coastline and a increase in conflicts, with the loss of indigenous and local knowledge and traditions, will have a negative economic impact as a result of a decrease in tourism and an increase in investments needed in the health, economic and infrastructure sectors for the citizens of the region. On the other hand, studies in some regions have shown the potential of including traditional ecological knowledge in the governance processes for decreasing conflicts and strengthening a positive sustainable development (Stori and others, 2019; Van Assche and others, 2019). Also, there is a potential use of integrated catchment management as a key tool in helping to manage coastal marine systems (Henderson and others, 2020).

6. Key remaining knowledge and capacity-building gaps

There have been advances in recent decades in knowledge relating to biogenic reefs and sandy, muddy and rocky shores, which allows us better to understand their importance and critical impacts. New satellite imaging and modelling also provide important data to visualize change and identify areas at high risk, involving multiple scientific areas (Sagar and others, 2017; Mentaschi and others, 2018). However, there remain some gaps in knowledge. Despite recent scientific advances, we have too little information available to anticipate mid- or long-term scenarios with accuracy. Also, regional knowledge and the volume of data available are unbalanced across many regions of the world, such as the South Atlantic, Wider Caribbean and western Pacific. Most of the data available worldwide are from local and regional analyses and very few global results allow for a critical review of the situation of coastal habitats. In this context, however, there is a clearer global assessment of sandy shores, so plans of action can be established to mitigate impacts (Luijendijk and others, 2018; Vousdoukas and others, 2020). A global analysis of biodiversity and impacts relating to biogenic reefs and muddy and rocky shores remains outstanding. Considering the increasing impacts on these shores and the lack of data sets, it is important to improve scientific protocols, capacity-building and databases for the standardized monitoring of indicators for biodiversity, ecosystem functioning and environmental drivers to be applied with regard to biogenic reefs and sandy, muddy and rocky shores worldwide. At the moment, many scientific data are collected at local levels using different protocols, which precludes any integrative regional or global analysis.

We need to promote interdisciplinary science in order to strength natural and social sciences working together so that they can provide scientific data on the human dimension in the environment (McKinley and others, 2020), particularly with regard to biogenic reefs, sandy, muddy and rocky shores. Considering the range and interlinkages of disciplines related to biogenic reefs, sandy, muddy and rocky shores, due to their high biodiversity and ecosystem services, including the human presence on intertidal shores and use, and all the related economic and health services, it is necessary to integrate natural and social science to promote nature-based solutions, blue engineering, ecosystem resilience and human well-being (McKinley and others, 2020; Stepanova and others, 2020). It is necessary to increase the knowledge on multiple stressors in these habitats in order to support a better understand on the impact of these threats on those habitats, both as individual drivers and the synergy among multiple stressors. The increasing knowledge on multiple-stressors effect will support a better science based decision making.

It is important to build capacity in the development of science through multisectoral cooperation, where scientific questions are looked at not just on the basis of where there are scientific gaps but also where there are social, management and economic gaps (Lubchenco and others 2019; Urban and others, 2020). Decision makers and policymakers need sound research to solve practical problems when managing resources and biodiversity. Marine spatial planning is a key issue and a great example of how conflicts in the coastal zone and impacts on biogenic reefs and sandy, muddy and rocky shores can be managed on the basis of a multi-stakeholder and interdisciplinary approach for the benefit of sustainable development (Kidd and others, 2020). Also, we need to try to understand and include the human dimension in research on biogenic reefs, sandy, muddy and rocky shores, and increase communication and awareness through ocean literacy (Santoro and others, 2017). These habitats can be used as flagship to promote the role of science in the implementation of the 2030 Agenda for Sustainable Development, including SDG 14. By increasing scientific knowledge of how to integrate human and natural dimensions in studies on impacts and the conservation of biogenic reefs, sandy, muddy and rocky shores, we will thus enhance science that can support the best coastal management practices based on a multiple-stakeholder partnership and understanding of the importance of the ocean, the coastal habitats and the multiple stressors they are enduring.

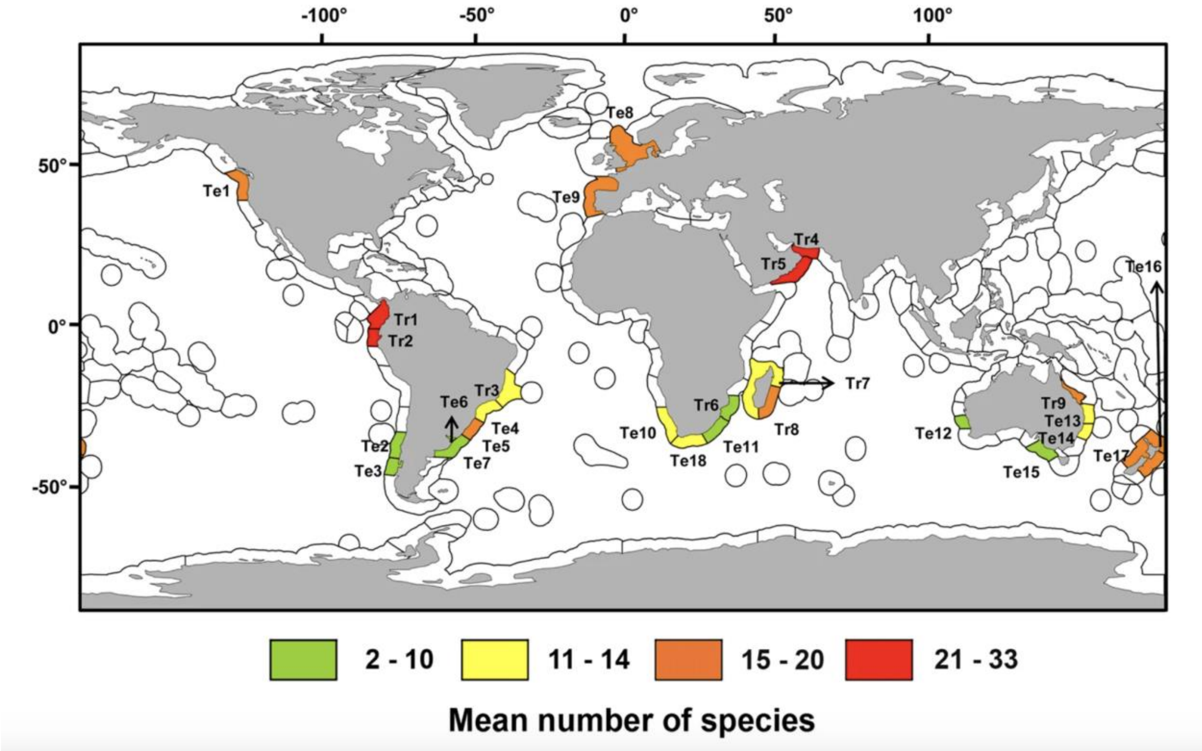

Figure 1. Sandy beach species richness in temperate (Te) and tropical (Tr) ecoregions defined in the MEOW system developed by Spalding and others (Reprinted from Barbosa and Defeo, 2015); Spalding, M. D. and others Marine ecoregions of the world: A bioregionalization of coastal and shelf areas. Bioscience 57, 573–583 (2007)). Te1: Oregon, Washington, Vancouver Coast and Shelf; Te2: Araucanian, Te3. Chiloense; Te4: Southeastern Brazil; Te5: Rio Grande; Te6: Rio de la Plata; Te7: Uruguay-Buenos Aires Shelf; Te8: North Sea; Te9: South European Atlantic Shelf; Te10: Namaqua; Te11: Natal; Te12: Houtman; Te13: Tweed-Moreton; Te14: Manning-Hawkesbury; Te15: Western Bassian; Te16: Northeastern New Zealand; Te17: Central New Zealand; Te18: Agulhas Bank; Tr1: Panama Bight; Tr2: Guayaquil; Tr3: Eastern Brazil; Tr4: Gulf of Oman; Tr5: Western Arabian Sea; Tr6: Delagoa; Tr7: Western and Northern Madagascar; Tr8: Southeast Madagascar; Tr9: Central and Southern Great Barrier Reef. The map containing ecoregions was downloaded from http://maps.tnc.org/gis_data.html. The final map was generated using gvSIG 1.12 (http://www.gvsig.org).

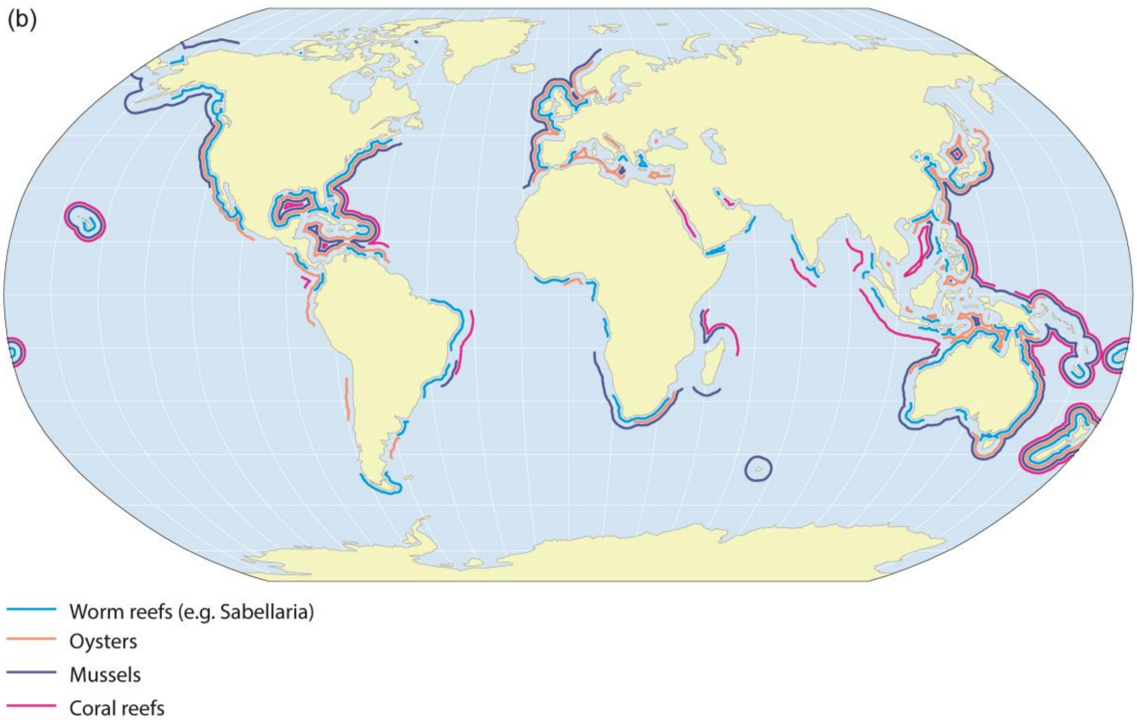

Figure 2. Global distribution of coastal biogenic reefs (coral, mussels, oysters, worms). (Data extracted from the Global Biodiversity Information Facility, http://www.gbif.org/, and United Nations Environment Programme Ocean Viewer, http://data.unepwcmc.org/datasets/6. Maps created by Shaun Lewin, Plymouth University.) (Reprinted from Firth and others, 2016).

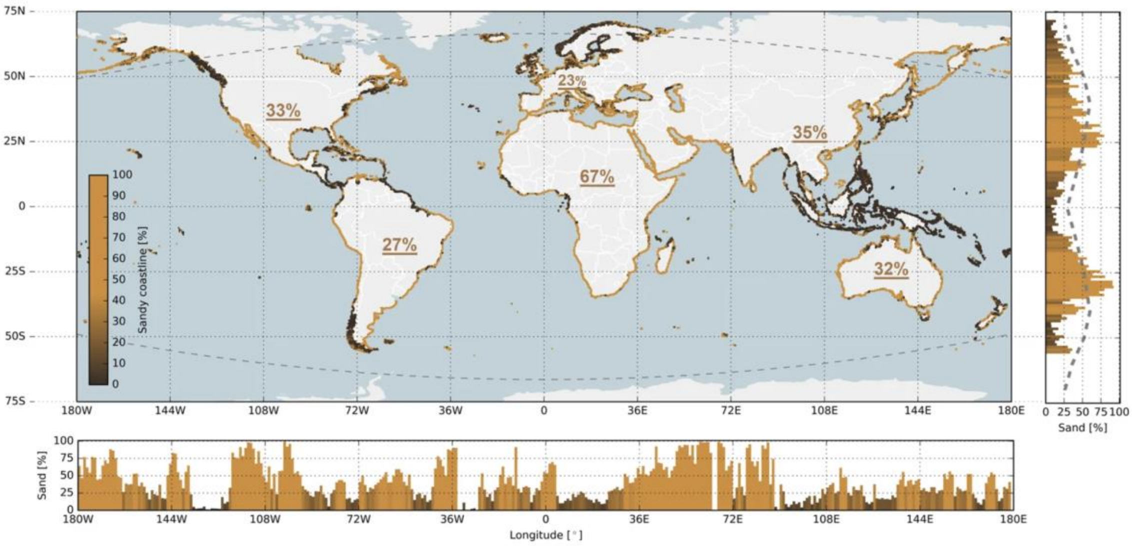

Figure 3. Global distribution of sandy shorelines; the coloured dots along the world's shoreline represent the local percentage of sandy shorelines (yellow is sand, dark brown is non-sand). The subplot to the right presents the relative occurrence of sandy shorelines per degree latitude, where the dashed line shows the latitudinal distribution of sandy shorelines reported by Hayes (Hayes, M. O. Relationship between coastal climate and bottom sediment type on the inner continental shelf. Jour. Mar. Geol. 5, 111–132 (1967)). The lower subplot presents the relative occurrence of sandy shorelines per degree longitude. The curved, dashed grey lines in the main plot represent the boundaries of the ice-free shorelines considered in our analysis. The underlined percentages indicate the percentages of sandy shorelines averaged per continent. Map is created with Python 2.7.12 (https://www.python.org) using Cartopy (v0.15.1. Met Office UK.

https://pypi.python.org/pypi/Cartopy/0.15.1) and Matplotlib (Hunter, J. D. Matplotlib: A 2D graphics environment. Computing in Science & Engineering 9(3), (2007)) (Reprinted from Luijendijk and others, 2018).

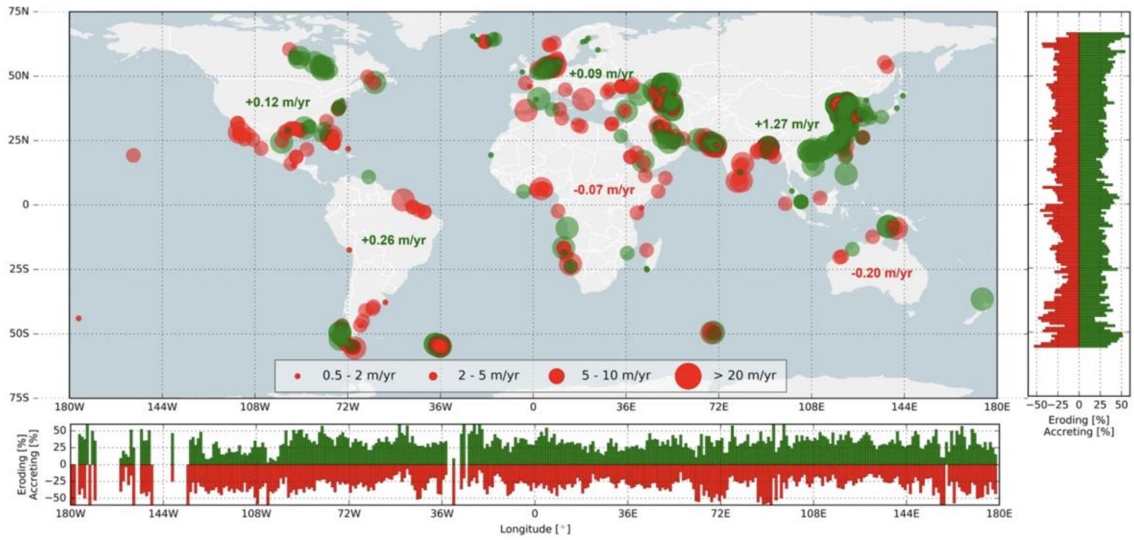

Figure 4. Global hotspots of beach erosion and accretion; the red (green) circles indicate erosion (accretion) for the four relevant shoreline dynamic classifications (see legend). The bar plots to the right and at the bottom present the relative occurrence of eroding (accreting) sandy shorelines per degree latitude and longitude, respectively. The numbers presented in the main plot represent the average change rate for all sandy shorelines per continent. Map is created with Python 2.7.12 (https://www.python.org) using Cartopy (v0.15.1. Met Office UK. https://pypi.python.org/pypi/Cartopy/0.15.1) and Matplotlib (Hunter, J. D. Matplotlib: A 2D graphics environment. Computing in Science & Engineering 9(3), (2007)). (Reprinted from Luijendijk and others, 2018).

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Chapter 7C
Intertidal Zone

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Keynote points

- The intertidal zone encompasses many different habitats on the world's coasts.
- A large proportion of humans live in proximity to the intertidal zone.
- Human activities impact the intertidal zone directly, through coastal modification, and indirectly, through climate change.
- Despite our close relationship with intertidal habitats, key knowledge gaps remain and taxonomic infrastructure is needed in developing countries to resolve baseline data.

1. Introduction

The intertidal zone stands at the vanguard of human influence on the oceans - where the seas meet the land. The intertidal region worldwide encompasses the diverse habitats that occur at the shore, and these environments are unified by special properties in that they are not continuously covered by water but regularly exposed by the waning tide. The interface between terrestrial and marine factors create a spectrum of increasing saltwater influence, with species and habitats occupying different points along a gradient. This is clearly seen in the stacked bands or zones on rocky intertidal shores (Figure 1A), or in the succession from dunes to salt marsh to tidal flats (Figure 1B). The intertidal zone further encompasses sandy beaches, mangroves, coral rubble and shallow reefs (Figures 1C and 1D), and intertidal areas provide the primary habitats for macrofauna considered to have special significance, such as marine reptiles (see Chapter 6D). Species that inhabit intertidal zones are characterized by special adaptations that enable them to tolerate the periodic transitions between air and water. The intertidal zone is the most accessible part of the oceans, and therefore of particular importance for subsistence and small-scale fisheries, and harvesting. Because of this accessibility, the intertidal zone is the marine realm most closely connected to human activities and interactions.

Figure 1A. Exposed intertidal area on a rocky outcrop showing horizontal bands formed by mussels (black band, closest to sand), barnacles, and lichen. Ucluelet, British Columbia, Canada, photo J. Sigwart.

Figure 1B. Exposed intertidal area of mudflats fringed by rural development and rock armour. Newtownards, N. Ireland, photo J. Sigwart.

Figure 1C. Vegetative intertidal in the form of mangroves, adjacent to rocky substrata. Phuket, Thailand, photo J. Sigwart.

Figure 1D. Intertidal live coral, shown below the water surface, in an area of shallow coral reef and coral rubble infrequently exposed on extreme natural tides. Port Dickson, Malaysia, photo J. Sigwart.

In the period since the First World Ocean Assessment (WOA I) (United Nations, 2017), the most important changes to intertidal habitats have been those resulting from climate change and human alteration to coastlines. In the context of the present Assessment, the "intertidal" or "coastal zone" is not a single habitat and includes aspects of many other habitats covered in other subsections of the present Chapter (see table 1), including sandy beaches, rock, high latitude ice, mangroves, coral rubble and shallow reefs. Similarly, it is important to clarify that coastal habitats and communities are primarily benthic, but the benthos is a broader category of sea bottom, from the intertidal to the deep sea.

Table 1. Source table for information on habitats with an intertidal aspect.

Habitat type	Intertidal aspects	Major changes and threats	Source
Sand and mud substrates (soft bottom)	Sand beaches and mudflats	Sand extraction for building artificial islands; erosion and redistribution of sediment from increased wave action	Chapter 7A
Rocky substrates and reefs	Rocky shores	Increased thermal range and wave impacts from storms, and invasive species, all decrease local biodiversity.	Chapter 7B
Atoll and island lagoons	Shallow fringing reefs, coral rubble	Rising sea levels, ocean warming, increased wave heights and coastal erosion	Chapter 7D
Tropical and subtropical coral reefs	Coral rubble and intertidal hard and soft corals	Coral bleaching and physiological responses to ocean warming; coastal erosion and nutrient runoff	Chapter 7E
Estuaries and deltas	Tidal estuaries	Rising sea levels, terrestrial pollutants and run-off	Chapter 7G
Kelp forests and algal beds	Intertidal algae	Increased thermal range and wave impacts from storms, and invasive species, all decrease local biodiversity.	Chapter 7H
Seagrass meadows	Intertidal seagrass	Physical disturbance from anchoring or development; warming sea temperatures	Chapter 7I
Mangroves	Coastal mangroves	Logging and clearance	Chapter 7J
Salt marshes	Tidal marshes	Rising sea levels, terrestrial pollutants and run-off	Chapter 7K
High latitude ice	Polar coastal environments	Climate related loss of winter ice cover increases disturbance from temperature fluctuations and physical impact of broken sea ice and iceberg scouring; loss of ice also opens pathways for species to invade new areas.	Chapter 7M
Artificial substrates and built environment		Invasive species, pollutants	herein

The action of tides differs considerably across the regions of the world and these dynamics influence the flora and fauna, as well as human activities in the oceans. In many enclosed water bodies such as the Mediterranean Sea, the flux of the tides is almost negligible. Areas of very high tidal flux are target sites for tidal energy extraction, such as in Northern Ireland's Strangford Lough in the United Kingdom of Great Britain and Northern Ireland and Sihwa Lake in the Republic of Korea (Leary and Esteban, 2009). Areas with lower tidal currents, including protected estuaries, are often sites of port development linked to the world's major cities and global shipping centres. The introduction of artificial substrates and built marine structures is increasing with development of coastal regions worldwide. Artificial substrates occur on all coasts and broadly incorporate reclaimed land and built islands, as well as maritime infrastructure, and human-created habitats such as artificial reefs. All of these coastal habitats are dealt with in this section.

2. Description of the environmental changes (between 2010 and 2020)

Coastal and near-coastal marine environments are the marine habitats most impacted by climate change (Hoegh-Guldberg and Bruno, 2010). Many intertidal species are harvested or cultivated worldwide, which depends on access to coastal habitats, and the condition of those habitats in context of species distributions, physical disturbance, development, traffic, and pollution. The impacts of degradation of intertidal environments are worst for island and coastal countries, where the intertidal zone represents a larger proportion of their territorial area, but all nations are affected, directly or indirectly (Curran and others, 2002). Vegetated intertidal areas, including saltmarshes and mangroves, have been removed or severely degraded by coastal development, with over 50 per cent of wetlands and mangroves removed during the last century (Burke and others, 2001). Coastal environments are also affected by pollution run-off from terrestrial sources. The combined impacts can alter freshwater as well as marine resources. Human activities continue to modify the physical shape of coasts both directly and indirectly, through construction that alters or creates shorelines, and consequent modifications to hydrodynamics and sediment transportation all change habitat conditions.

The overall effect of changes to coastal environments is to reduce available intertidal habitats, and to reduce the quality of remaining habitat. Intertidal organisms and ecosystems are typically at the edge of tolerance for one stressor, and may have unexpected reactions to additional stresses from environmental change, meaning that local responses are often unpredictable (Hewitt and others, 2016). This limits the distribution and sustainability of fished species. The impacts of climate change include temperature change, but also sea level rise and changes of wave heights and increasing storm events. Sea level rise reduces availability of intertidal habitats as the natural environment is confronted by mitigation efforts such as construction of sea walls and coastal defences. This is a type of "coastal squeeze", whereby, when sea level rises, marine influences move inland, to space already occupied by human activities (Pontee, 2013).

Human alteration of coastlines also includes urbanization and development, and the construction of urban and maritime infrastructure and development of recreational activities. Physical infrastructure includes bridges, roads, seawalls, dams and flood gates, and also energy infrastructure such as wind and tidal energy converters. Such structures create substrata, a potential reef-like hard bottom that can be occupied by rocky intertidal species. However, while this may create a local-scale increase in species diversity, the overall effect is habitat loss. In recent years, the scale of human alteration to the coasts has accelerated dramatically, with major projects to build artificial islands and peninsular structures to increase coastal housing. These impact intertidal communities in as yet unknown ways as the physical material, rock and sand, imported from outside the local region, will bring additional alien biological material. Construction of new islands smothers the habitat that previously occupied the same space, and changes local hydrodynamic conditions and sedimentation that will smother further adjacent habitats. New structures are also inhabited by high-density human populations that introduce additional environmental impacts.

3. Economic and social consequences

The ocean, and particularly coastal areas, impact on all United Nations Sustainable Development Goals (SDGs).[96] Intertidal habitats provide the most common examples of marine ecosystem goods and services, and coastal habitats have value for biodiversity as well as in service to humanity. There is also a strong gender element to the exploitation of marine resources, but some fisherwomen's organisations have been developed in Europe starting during the 1990s (Frangoudes and others, 2014).

Local species appropriate to a local context may not be the most efficient example of a particular service but, more importantly, contribute to regional biodiversity. For example, mussels and oysters provide water filtration and food, but there are over 300 species in those taxonomic families of bivalves (WoRMS Editorial Board, 2017), many of which fill discrete niches or ecosystem functions. Many of these species are widely cultivated and consumed. It is not sustainable in the long term to select a single species for large-scale aquaculture on all global coasts. Additional species in their local native habitats support biodiversity and diversification of human resources.

The current consequences of human alterations to coastlines have both positive and negative impacts on intertidal biodiversity. The relative impacts of the various anthropogenic pressures mentioned in section 2, differ between developed and developing economies. Rock armour, or riprap, are hard structures built to control erosion of coastlines. These materials include structures designed to support habitat space for intertidal organisms which can provide important local-scale mitigation to habitat loss and improve delivery of additional benefits to humans (Chapman and Underwood, 2011). Structures engineered to increase habitat space are sometimes called "living seawalls" and can reduce some impacts of coastal hardening. Artificial substrates also, apparently, favour non-native and invasive marine species that out-compete native fauna in rocky substrata (Tyrrell and Byers, 2007). These eco-engineering approaches can limit, if not mitigate, habitat loss through coastal sprawl. Another form of coastal modification is land construction ("reclaimed" land) which, although beneficial to humans in the short term, reduces the ability of natural systems to deliver other benefits, including natural wave and storm defences. Coastal communities are at risk from changes to physical safety and access to food, with implications for profoundly important issues related to the SDGs such as poverty, education and availability of food.

4. Key region-specific changes and consequences

Specific habitat types have greater prevalence in some regions, depending on local coastal morphology. For example, rocky intertidal habitats have very high biodiversity in temperate latitudes in the North Atlantic and the North Pacific, while the Brazilian coast in the South Atlantic is considered a hotspot for macroalgae (Miloslavich and others, 2016). Mangroves and corals (extending to subtidal depths) are characteristic habitats in tropical and subtropical coastlines where the threat from sea level rise is the greatest.

We know more about intertidal than subtidal habitats almost everywhere in the world - except where coasts are inhospitable or pose significant dangers (e.g. areas dominated by saltwater crocodiles) and in high latitudes where human population density is sparse to non-existent. The Antarctic and Arctic regions contain areas that remain completely unsampled for coastal flora and fauna. Tropical regions in the Global South,

[96] See United Nations General Assembly resolution 70/1.

particularly in South-east Asia, contain disproportionate numbers of new species that have not been described, but are increasingly being recognised, in particular, through molecular genetic analysis. Species under pressure in areas that have been less studied are at higher risk from potential extinction as appropriate conservation measures cannot be assessed.

Artificial habitats also vary in their distributions according to local conditions. Built islands are features that are found mainly in the shallow, sheltered seas of the Arabian Gulf and southeast Asia. Rock armour is found worldwide, but in terms of its contribution to habitat space has been most studied in Australia, North America and Europe. Energy converters such as offshore wind turbines (artificial structures not covered elsewhere in this Assessment) are found especially in Europe and increasingly in North America. There is a growing demand for coastal development, both for housing and urban development, but also for coastal resources such as aquaculture and energy converters, with increasing detrimental effects on vegetated habitats. In regions with intensive coastal urbanization, such as Australia, the Middle East, Asia, Europe and the United States of America, more than half of available shoreline in some regions has been modified through engineering and built coastal structures (Dafforn and others, 2015). Climate change is increasing coastal erosion, which prompts construction of additional hard engineering defences such as sea walls and accelerates coastal modification (Asif and Muneer, 2007).

5. Outlook

The outlook for the knowledge base on intertidal habitats is good in many respects, and marine research has a natural emphasis on intertidal and coastal regions, because of their accessibility in most regions and importance to human activities. Intertidal areas have been included in some Marine Protected Areas.

The socioeconomic consequences of continued change in intertidal habitats are potentially severe. In countries where extensive tidal flats well developed and local populations are highly dependent on marine ecosystem services, such as in many Asian coastal areas, reduction of intertidal space through coastal squeeze will have severe impacts reducing both area and provisioning resources. Physical degradation of coastlines through climate change will decimate local economies. Biotic degradation through altered hydrodynamics, invasive species and over-exploitation have dramatic and complex impacts. The removal of mangroves and biotic reefs eliminates natural coastal defences that protect human settlements. Invasive species reduce local biodiversity. Overfishing or over dependency on monoculture aquaculture species, mainly cultivated in intertidal regions, lowers nutritional quality and puts human prosperity at risk. Coastal areas house key public infrastructure such as power, wastewater treatment, and transportation facilities (e.g. airports), which are also at risk from sea level rise. Protection of natural, local, coastal areas and intertidal biodiversity is crucial for human sustainability.

6. Key remaining knowledge gaps

Several topics require critical attention to ensure sustainability of intertidal habitats. Slow, cumulative systemic shifts are often not recognized until the change becomes catastrophic. Assessments of damaged environments set the targets for conservation, meaning that the environment will never recover to a truly robust and sustainable condition (Plumeridge and Roberts, 2017). Even in European seas, where there is perhaps the longest continuous history of recorded observations, pre-industrial "baseline" data are already influenced by human impacts, and this problem is far worse in under-studied systems and in many developing nations.

The physical parameters and coastline alterations associated with anthropogenic impacts and sea level rise require additional studies, to enable predictive models for hydrodynamic impacts and small, local-scale models using analogous systems, where the behaviour of one well-studied physical system can be applied to predict impacts in another place. WOA I highlighted a need for more information on succession of habitat types and species ranges with alterations in coastlines, but this remains a key knowledge gap. Finally, underpinning all of these issues is an urgent need for more detailed studies of biodiversity in under-studied areas, especially in regions where significant knowledge gaps exist and scientific infrastructure is less developed, but where there is great species diversity (Lira-Noriega and Soberón, 2015). Many species, even in the well-studied intertidal zones, remain unnamed and undescribed by science. Without species identification, the biodiversity of these habitats cannot be accurately quantified or monitored.

7. Key remaining capacity-building gaps

"Coastal squeeze" reduces intertidal environments with sea-level rise on one side, and human urbanisation on the other side. Human development should include future planning to provide coastal and intertidal habitats space for retreat from increasingly frequent storm events and climate disruption, to maintain these important protective buffers.

The countries that are the most extremely diverse in terms of important areas of biodiversity and species richness are, for the most part, developing economies (Lira-Noriega and Soberón, 2015). There is an urgent need to support baseline studies and monitoring to develop and sustain the same kind of long-term data sets in developing countries that are available in developed nations, especially in Europe and North America. In developed countries, citizen science approaches can be effective tools to expand monitoring; with further capacity development for taxonomy this could be applied to more widely.

There is an urgent need also to build taxonomic infrastructures, which support emerging technologies such as environmental DNA (eDNA), through specimen collections and barcode catalogues, as well as to develop human capacity through training and technology transfer and access to the latest scientific resources and to data and scientific literature in the country of origin. It is not possible to use emerging technologies, such as eDNA barcoding, where there is no taxonomic infrastructure in place. Barcodes can recognize only what is already in a database. Taxonomic infrastructure must also include specialist skills, literature and the resources to support fundamental science. These are essential to enable robust environmental impact assessment processes, especially in developing countries. Further, these types of fundamental science underpin the ability to further develop capacity to conduct climate vulnerability assessments with respect to key marine species and habitats.

Although the intertidal zone includes the most accessible (and most vulnerable) habitats, a high proportion of undescribed invertebrate and algal species occur in tropical shallow marine ecosystems. The lack of taxonomic ability to identify local species obscures potential loss, encroachment of species with shifting ranges and indicators of disturbance and makes it difficult correctly to recognize invasive species and take appropriate measures to protect local resources (Sigwart, 2018). Scientific infrastructure underpins downstream economic growth and protection of environmental resources.

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Chapter 7D
Atoll and Island Lagoons

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Keynote points

- The health of atolls and island lagoons, and sustainability of communities that depend on them for their livelihoods are challenged by many environmental limitations and stressors, often exacerbated by human actions.
- Islands on atolls and other coral reefs are low-lying and very vulnerable to impacts of climate change, particularly sea level rise; individual islands are likely to respond in different ways.
- Climate change threatens coral reef ecosystems with implications for habitability of islands. Of particular significance are: coral bleaching; erosion and inundation of islands; carbonate dissolution; and the effects of extreme events, such as tropical storms.
- Developed urban atoll islands are increasingly dependent on engineering solutions, which need to integrate “hard” and “green/blue” options to avoid unintended impacts, whereas less populated rural island communities rely on the health, productivity and function of surrounding marine and coastal ecosystems.

1. Introduction

Low-lying tropical coral reef and atoll islands, with their associated lagoon systems, are geologically young features formed over the past few millennia. Their formation and maintenance is constrained by sea level, biological production of calcium carbonate sediments, and ocean/atmosphere conditions which re-work, transport and re-deposit those sediments. Islands are scattered, and often very isolated, across reef-forming seas. Common attributes are that they are low-lying, small in extent and exposed to surrounding marine conditions. They offer marginal agronomic potential and limited fresh groundwater resources to subsistence communities which live on them, and who have an inextricable dependence on surrounding reefs for daily food security. Associated marine and coastal ecosystems, including seagrasses, mangroves and terrestrial vegetation, are also important to the agroecological stability and services on which local communities depend.

Atoll islands and lagoons were not evaluated specifically in the First World Ocean Assessment (WOA I) (United Nations, 2017b), although its Chapter 7 (United Nations, 2017a) described carbonate production and contribution to coastal sediments, and atolls were mentioned in other Chapters. In the present Assessment, Chapter 7E, on tropical and sub-tropical coral reefs, is particularly relevant and there is complementary material in Chapter 7I, on seagrass meadows.

A recent review concluded that 439 features could be classified as atolls worldwide (Goldberg, 2016). There are 268 atolls with associated reef islands, but the present Chapter includes consideration of sand cays and shingle motu on other coral reefs which behave similarly to islands that form on atoll rims. Atolls are most numerous in the Pacific Ocean (84 per cent of atolls occur in the Pacific, including the South China Sea, the Philippines and Indonesian archipelagos); approximately 13 per cent occur in the Indian Ocean and less than 3 per cent occur in the Caribbean (Goldberg, 2016). French Polynesia contains 83 atolls (nearly 20 per cent of the global total). Tabiteuea, a single atoll system, has some 50 named islands along its eastern rim. Rocas Atoll is the only atoll in the South Atlantic and it is a fully protected Brazilian conservation unit (Pereira and others, 2010; Soares and others, 2011). The Maldives and Lakshadweep archipelagos contain most of the atoll formations in the Indian Ocean, with only isolated atolls elsewhere (e.g. Aldabra and Glorieuses).

Atoll and associated island formation was first explained by Charles Darwin (Darwin, 1874). An emergent volcanic island that subsequently subsides, eventually below sea level, grows a carbonate reef rim constructed by corals and associated organisms, eventually leaving behind just an atoll reef rim and a central lagoon. Reef islands can form where atoll rims are emergent above highest tides and conditions are conducive. They are entirely composed of calcareous skeletal remains of reef organisms, including coral broken down into boulders, cobbles, shingle and sand, and other organisms, such as foraminifera, molluscs and coralline algae. Island expansion and persistence depends on ongoing reef sediment production, to counterbalance continual erosion by waves, currents and wind.

Reef islands appear to have formed on many atolls as a consequence of a slight fall in sea level from a mid-Holocene highstand enabling accumulation of reef sediments. Inhabited reef islands tend to be those that are larger, have interior areas where more complex soils and vegetation have developed, and have more reliable fresh groundwater resources. Colonization by people may have occurred soon after islands formed (Nunn, 2016; Allen and others, 2016); intensive human use of these complex ecosystems leads to degradation. Atolls with no islands or uninhabitable islands have considerable ecological value and represent the healthiest, least disturbed and most resilient coral reef habitats (Riegl and others, 2012; Donner and Carilli, 2019). A decline in reef health or productivity threatens persistence of these ecosystems and the communities that depend on them.

2. Documented changes in state of atolls and island lagoons

2.1. Description of the environmental changes (between 2010 and 2020)

Erosion of islands. Erosion of island shorelines has often been attributed to rising sea level, although proving a link between erosion and sea level rise is challenging. Studies demonstrate variability of response around individual islands and across entire atolls (Ford and Kench, 2015), and short-term fluctuations often mask any genuine long-term signals (Mann and others, 2016; Ryan and others, 2016; Nunn and others, 2017, 2019). In Solomon Islands, several islands have disappeared, but displacement of others in response to wave activity indicates that this is not simply drowning by sea level rise (Albert and others, 2016, 2017). Variations in shoreline position have been recorded on many islands in the Indian Ocean (Hamylton and East, 2012; Purkis and others, 2016; Testut and others, 2016) and many have grown, and seem likely to continue to grow in the future (Beetham and others, 2017). In the Pacific Ocean, relatively insignificant changes were observed on Tuamotu atolls where the role of sea level seems to have been relatively minor, compared with that of climate regime, sediment supply, and anthropogenic impacts on shoreline stability (Le Cozannet and others, 2013; Duvat and Pillet, 2017). In Tuvalu, reef islands on Funafuti Atoll have increased in area, in part as a consequence of tropical cyclones (Kench and others, 2015; McLean and Kench, 2015), and shoreline change for all 101 islands in Tuvalu indicated land area increase in eight of the nine atolls over the past four decades (Kench and others, 2018). However, recent shoreline impacts following tropical cyclone Pam in March 2015 have caused significant shoreline recession in some islands in Tuvalu, highlighting the significant variability in the effects of tropical disturbances on these islands. An analysis of available data, covering 30 Pacific and Indian Ocean atolls, including 709 islands, revealed that no atoll lost overall land area and that 88.6 per cent of islands within them were either stable or increased in area, while only 11.4 per cent contracted (Duvat, 2018).

Inundation of reef islands. There has been disproportionately less focus on inundation and increased recurrence of nuisance flooding (Ford and others, 2018). A detailed digital elevation model of atoll topography developed for Majuro Atoll, using drone-derived photography, enabled comprehensive consideration of potential errors when mapping atoll vulnerability to future flooding (Gesch and others, 2020).

Altered wave climate. Wave conditions may change as sea level rises (Esteban and others 2018; Costa and others, 2019). Increased overwash is foreshadowed for many reef islands (Storlazzi and others, 2015), and recent analysis has inferred that most atolls may be uninhabitable by the 2050s (Storlazzi and others, 2018). Reef islands are likely to become thinner and longer, with increased run-up and inland flooding (Shope and others, 2016, 2017). Impacts can be affected by dimensions of adjacent reefs and patterns of longshore sediment transport (Quataert and others, 2015; Shope and Storlazzi, 2019), with salinization of groundwater (Oberle and others, 2017).

Reef degradation. It is estimated that coral reefs cover 0.5 per cent of the oceans, equivalent to ~1,500,000 km^2 (Leão and others, 2008). It is also estimated that more than 30 per cent of reefs are already severely damaged, and that approximately 60 per cent of reef areas will be totally degraded in coming decades, as a result of human actions, especially overfishing, marine pollution and global climate change (Gherardi and Bosence, 2005; Pereira and others, 2010). Warming of tropical surface waters is causing widespread and more frequent coral bleaching globally (**Eakin and others, 2019),** and is discussed in Chapter 7E of the present Assessment. Recurrent bleaching devastated large areas of the Great Barrier Reef in 2016 and 2017 (Hughes and others, 2017, 2018). The period 2014–2017 was marked by an unprecedented succession of record-breaking hot years, coinciding with the most severe, widespread and longest-lasting global-scale coral bleaching event ever recorded (Eakin and others, 2019). **Bleaching of atoll reefs has been recorded across the tropics (**Marshall and others, 2017; **Head and others, 2019).**

Lagoon pollution. Intensive use of lagoon ecosystems leads to water pollution and ecosystem degradation. Studies in Tuvalu have identified domestic wastewater as the primary pollution source and recorded heavy metal contamination of sediments (Fujita and others, 2013, 2014).

Ecological Implications. Remote uninhabited or sparsely inhabited atolls can be locations of unique ecological value. Climate change and sea level rise pressures threaten the persistence and unique ecology of these islands as well as potentially threatened and endangered species. (Gillespie and others, 2008). For example, in the remote and mostly uninhabited Phoenix Islands cycles of coral mortality and recovery to increasingly strong heatwaves may eventually fail, in spite of active management (Rotjan and others, 2014). Cyclones may have devastating effects on critical habitats on small islands, posing a critical challenge to vulnerable species over the long term (Huang and others, 2017). Climate threats may also intensify local pressures on islands more exposed to human pressures, such as of invasive species facing reduced resistance in climate-impacted island systems (Russell and others,

2017) and spread of diseases, such as the stony coral tissue loss (SCTLD) disease in the Caribbean (Aeby and others, 2019).

2.2. Factors associated with the changes: drivers, pressures, impacts and response

Interactions between islands and the dominant currents and wave regimes affecting them, together with geomorphological characteristics of subsidence and/or uplift, impose overarching controls on island morphology and change. Modelling studies of Rocas Atoll imply that increased wave action due to refraction following slight sea level rise may explain planimetric and volumetric changes to reef islands (Costa and others, 2017, 2019).

Coral reefs in warm shallow seas accrete vertically and, under some circumstances, accretion rates can exceed current rates of sea level rise (Perry and others, 2015a, 2015b). However, a gradual fall of sea level over the past 2,000 years has caused coral growth on Indo-Pacific reef flats to turn off (Harris and others, 2015). Individual islands will be subject to the pattern of relative sea level change at that location, with subtle variations due to oceanographic and geophysical drivers (Pfeffer and others, 2017). Insights into marine climatic and environmental reconstructions over different timescales, interpreted from massive, long-lived corals which contain retrospective geochemical archives, are becoming possible (Dassié and Linsley, 2015; Evangelista and others, 2018).

Quantification of rates of carbonate production, together with estimates of erosion and sediment removal, provide insights into the budget of reef sediments (Perry and others, 2016, 2017a; Hamylton and others, 2016; Morgan and Kench, 2017). Sediment production contributes to gradual lagoon infilling. For example, the grazing of reefs by parrot fish produces fine sediment (Perry and others, 2015b; Yarlett and others, 2018), augmented close to continental shores by terrigenous sediment (Perry and others, 2017b). Sediment budgets have rarely been calculated for reef islands; they are dependent on biogenic production by a range of reef organisms (Morgan and Kench, 2016). Different reef islands can be in one of several stages of development, namely nucleation, growth, stable, decay, relict or endangered (Garcin and others, 2016). Small sand islands composed of freshly deposited coral fragments lack soil and are less able to support human livelihoods than older more established islands (Connell, 2015).

Reef islands are fragile systems prone to devastation by extreme climatic events, particularly tropical storms. In 2017, hurricanes Maria and Irma caused major damage and casualties across numerous Caribbean islands and, in 2018, tropical cyclone Gita struck the Pacific islands of Eua and Tongatapu, affecting 80 per cent of the population of Tonga and causing destruction of buildings, crops and infrastructure (Magnan and others, 2019). Cyclone Idai in the western Indian Ocean was one of the strongest cyclones ever recorded in the region, resulting in the second highest death toll. Such high-energy events leave lasting morphological impacts for several years on reef islands (Jeanson and others, 2014; Kayanne and others 2016). The proportion of very intense cyclones has increased since 1975, Thi is attributed to warming (Holland and Bruyere, 2014), and is expected to continue into the future (Walsh and others 2016). Add to this, the growing populations and increased infrastructure on islands, thus higher exposure, and severe impacts to islands from cyclones are bound to increase. Islands are also vulnerable to unusually high tides and water levels attributed to distant-source wind waves, as occurred in 1987 in the Maldives (Wadey and others, 2017), and in several Pacific islands in December 2008 (Hoeke and others, 2013, Smithers and

Hoeke, 2014).

Geochemical changes in the ocean, particularly ocean acidification, may lead to dissolution of lagoonal sediments and decreased availability of sand to replenish reef islands and reduced potential for reefs to keep up with future sea level rise (Perry and others, 2018). Recent studies have shown that dissolution of reef sediments is negatively correlated with the aragonite saturation state of seawater and is ten times more sensitive to ocean acidification than coral calcification (Cyronak and Eyre, 2016; Eyre and others, 2018).

3. Consequences of the changes on human communities, economies and well-being

Communities that live on reef islands contend with many pressures, and the outcomes of these multiple stressors remain highly uncertain. Despite widespread perception of susceptibility to various impacts of climate change, there is little evidence that can be directly attributed to it. Many problems facing small reef islands result from other pre-existing pressures (Birk, 2014; Duvat and others, 2017), particularly anthropogenic causes that have exacerbated their vulnerability (Connell, 2015; McCubbin and others, 2015).

The recent Intergovernmental Panel on Climate Change Special Report on the Ocean and Cryosphere in a Changing Climate considers consequences of climate change for low-lying islands (Oppenheimer and others, 2019). It distinguishes urban atoll islands from the many outlying smaller islands, which include capital islands (or groups of islands) such as Fongafale (Tuvalu), South Tarawa (Kiribati) and Malé (Maldives). The future of urban atoll islands is important because they concentrate human populations (~3,200 people per km^2 in South Tarawa; ~65,700 people per km^2 in Malé), economic activities and critical infrastructure (airports, harbourfronts) in low-lying areas exposed to marine flooding and coastal erosion. These populous islands are more dependent on imported food than local cultivation (McCubbin and others, 2017). There is also heavy dependence on hard engineering protection. In some cases, relocation of people and critical infrastructure to another island is being considered (Oppenheimer and others, 2019). However, there are many barriers to migration (Birk and Rasmussen, 2014), including a lack of will to move (Jamero and others, 2017, 2019).

A range of hard and soft engineering options can be used to protect vulnerable island shorelines (Wong, 2018), many of which can be considered adaptive responses. Hard defences protecting Malé have proven successful in preventing further damage. However, the impacts of hard engineering coastal defences on natural shoreline and ecosystem processes can be severe and maladaptive, with long-term negative impacts that may overshadow earlier benefits (Donner and Webber, 2014; David and others, 2019). The expense of hard engineering options has led to greater interest in “soft” ecosystem-based resilience measures (Naylor, 2015). With greater experience of coastal erosion and extreme events since 2004 and the Indian Ocean tsunami, the values of natural reef and coastal vegetation ecosystems are becoming clearer and leading to design principles that harness natural as well as artificial structures to reduce coastal vulnerability.

Inhabitants of atolls do not identify climate change as their prime concern. For example, more than 50 per cent of Maldivians questioned perceive future sea level rise to be a serious national challenge, but many other cultural, religious, economic and social factors also play an important role in making decisions about migrating or not (Stojanov and others, 2017).

Similarly, most Tuvalu residents are not anticipating out-migration (Mortreux and Barnett, 2009). In Kiribati, a “sinking nation paradigm” has politicized decision-making, with “adaptation” becoming a metaphor for economic development (Mallin, 2018), and social science counter-narratives are challenging notions of islander out-migration (Barnett, 2017; Kelman, 2018; Yamamoto and Esteban, 2017). Coarse-scale assessments downplay variations in community experiences and local knowledge of environmental change (Leon and others, 2015; Owen and others, 2016). There may be reluctance to move from low-lying islands, based on strong cultural traditions and in some low-lying islands, inhabitants have opted for in-situ adaptation strategies such as raised houses on stilts in response to flooding rather than migration to the mainland (Jamero and others 2017). These options are seen as preferable even if it seems likely that livelihoods in such circumstance might not be sustainable in the long term (Duce and others, 2010; McNamara and others, 2017).

Sea level rise is often inferred as the primary explanation for harmful, unusual or unprecedented environmental changes on small islands, when other factors are actually driving that change. Contemporary environmental changes on most Pacific islands are more likely to be responses to local stresses, including cyclones, seawall construction, pollution, overfishing, habitat degradation and sand mining. It has been suggested that small islands offer sites where global climate change narratives can be made tangible and visible, and attributed to distant sources (Connell, 2015).

4. Key region-specific changes and consequences

Although most atolls are in the Pacific Ocean, with several archipelagos in the Indian Ocean, and very few in the Atlantic Ocean (IPBES, 2018), no gross differences were apparent on the basis of ocean basin in a recent study of atoll island changes in size (Duvat, 2018). The study indicated that Maldivian islands appeared more affected by erosion than Pacific islands, with 23.3 per cent decreasing in the former, compared to 7.5 per cent in the latter. Most notably, the study found high variability within and across atolls and archipelagos. Differences have been noted between urban and outlying rural atoll islands, both in demographic trends and in their response to climate change, sea level rise and other threats. Variability between islands suggests that attention should be paid to the specific context of individual archipelagos, atolls and islands in understanding change and its consequences which appear to mask regional patterns.

5. Outlook

Atolls and island lagoons remain vulnerable to varied environmental hazards but it is the synergies and interactions between these hazards, the specificity of how they play out in a local geographic and geomorphological setting, and interactions with social and economic factors that may determine the outlook for islands (Duvat and Magnan, 2019). Because of their small size and vulnerability, climate change may impact islands through increased magnitude of oscillations in major climatic systems, such as of the El Niño Southern Oscillation, as seen in stronger and longer thermal stress and coral bleaching events throughout coral reef island systems globally (Eakin and others, 2017; Hughes and others, 2018).

Key local and climate change pressures include:

- Warming of ocean temperatures that increases coral bleaching.

- Sea level rise, which threatens to drown islands and perhaps increase erosion, and may increase wave processes across reefs.
- Ocean acidification, which may lead to weaker calcareous skeletons and appears likely to reduce lagoon and reef island sediments due to alkalinity changes.
- Storms and rare wave events, which play an important role in transporting sediment, as any increase in storm frequency or intensity may have consequences for reefs and reef islands.
- Overfishing and mismanagement of natural resources, particularly those with a key role in island and habitat structure, such as coral reefs and mangroves.
- Demographics and human population density, and their influence on pollution and impacts on local island systems, and on exposure and vulnerability of people and infrastructure to environmental and climate threats.

Duvat and Magnan (2019) identify five key adaptation pathways for addressing these interacting challenges on atoll islands, which are: to focus on ecosystem resilience; to minimize the risk of maladaptation; to facilitate internal relocation; to ensure appropriate shoreline protection with respect to ground elevation; and to consider and support permanent international migration.

The outlook for islands depends heavily on policy dimensions, both at the national level between individual island States and other countries, and at global levels through the United Nations and other forums. The former is key in identifying island-specific future options, whether these involve investment in adaptive infrastructure (e.g. to build resilience to sea level rise) or relocation.

6. Key remaining knowledge gaps

The response of reefs, lagoon habitats and reef islands to the combination of local and global threats they now face is inadequately understood. There is little information on how reef processes will respond to changes in individual, and compounded, climate drivers as these change. Geographical variability in shoreline erosion and inundation is observed but the causes of these spatial patterns are poorly understood, which largely precludes any forecasting of how particular locations will behave. Observational analyses of shoreline changes over past decades are being augmented by attempts to model how reef islands may respond. Recent attempts at modelling include large wave tank experiments (Tuck and others, 2018, 2019; Masselink and others, 2019, 2020), as well as hydrodynamic and shoreline response models (Costa and others, 2019; Ortiz and Ashton, 2019; Shope and Storlazzi, 2019). The vulnerability of small islands composed of calcareous bioclastic sand and shingle that occur on atoll rims or in other reef and lagoon environments can be examined in greater detail using more recent sophisticated remote-sensing technologies to monitor reef island shorelines, including high-resolution satellite imagery, airborne LiDAR, and drone-acquired imagery (Casella and others, 2016; Lowe and others, 2019; Gesch and others, 2020).

Whereas most atolls are not experiencing net overall erosion, their physical viability is under increased pressure. Atolls, the reef islands around them and lagoons within them, are the product of calcifying organisms that contribute to sediment budgets which determine the trajectory of individual islands. There is insufficient knowledge about the productivity of major organisms contributing bioclastic sediments, the breakdown and transport of derived sand and gravel, and the dissolution and removal of this material.

A further aspect that requires more detailed investigation is the fate of the groundwater lens beneath small islands upon which populations depend, as this seems likely to contract if shorelines erode or waves overtop islands (Terry and Chui, 2012; Gulley and others, 2016; Bailey and others, 2016; Deng and Bailey, 2017; Ford and others, 2018). Resilience of the fresh groundwater lens to changing natural and demographic factors, particularly during drought conditions, has only recently emerged as an area of active research (Werner and others, 2017; Oberle and others, 2019), and requires further examination, particularly as it appears dependent on morphological adjustments of islands, which are incompletely understood.

From a social-ecological perspective, how island communities and nations will adapt to, and influence, the responses of island systems to the aforementioned threats, is important (Duvat and Magnan, 2019). Government, citizens and community institutions, foreign aid and investment partners and non-governmental actors all play a role in determining how islands will respond to future challenges, and in anticipating and diminishing crises. The Sustainable Development Goals[97] provide a framework, both for national/international policy, but also for the integrated planning and action that will be needed at multiple levels (Obura, 2020).

7. Key remaining capacity-building gaps

There is clearly a lack of adequately trained and resourced personnel within small island communities to monitor changes at the local level, to undertake site-specific research and assessment, and to implement adaptation and other programmes, despite the efforts of international agencies to build capacity within small island nations. Skills addressing the multiple threats and emerging issues mentioned above will be needed. The adaptive capacity of small island communities appears limited and many are overly dependent on international aid for sponsorship of major projects. Global frameworks, such as the Sustainable Development Goals, the SIDS Accelerated Modalities of Action (SAMOA) Pathway[98] and the United Nations Decade of Ocean Science for Sustainable Development (2021–2030),[99] provide multiple opportunities for identifying critical needs and channelling resources for capacity-building to meet these needs.

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[97] See United Nations General Assembly resolution 70/1.
[98] See United Nations General Assembly resolution 69/15, annex.
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Chapter 7E
Tropical and Sub-Tropical Coral Reefs

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Keynote points

- Global declines in coral cover continue, primarily due to increasing ocean temperatures associated with climate change, as well as extractive activities, pollution and sedimentation, novel coral diseases and physical destruction of coral reefs.
- The frequency of disturbances caused by heatwaves, storms, flooding and crown-of-thorns starfish outbreaks has increased, resulting in a decrease in recovery time between disturbances.
- Understanding of the value of ecosystem services provided by coral reefs is improving, not only in terms of direct economic benefits (market use value) but also through less tangible use, such as aesthetic value.
- Substantial knowledge gaps remain, particularly on responses of coral reef communities to climate change and how these responses might influence human use of coral reefs.
- Projections of future states suggest continued decreases in coral abundance, reef-associated fishes and the architectural complexity of reef frameworks.

1. Introduction

The present Chapter provides an update to findings in Chapter 43 of the First World Ocean Assessment (WOA I) (United Nations, 2017b) on tropical and sub-tropical coral reefs. In providing such an update, there may be overlaps or interactions with the content of other Chapters herein (e.g. Chapters 4–10, 13–15, 24 and 28–30). Therefore, they will need to be read in conjunction with this Chapter.

Chapter 43 comprehensively covered many aspects of the state of global coral reefs up to 2010, when coral reefs were estimated to cover 249,713 to 284,300 km^2 but were determined to have continually declined over the last 100 years (United Nations, 2017a). Tropical and sub-tropical coral reefs were identified as one of the most vulnerable ecosystems and, under a business-as-usual carbon emission scenario, were projected to be potentially functionally extinct by 2050 (IPCC, 2014). Anthropogenic-driven impacts exacerbated by population pressures were identified as the major threat to reefs, and include climate change (e.g. ocean warming, ocean acidification and sea level rise); extractive activities (e.g. overfishing); pollution and sedimentation; and physical destruction. Other stressors identified and linked to the above stressors (particularly climate change) included coral diseases and crown-of-thorns starfish (COTS) predation. The degree to which each stressor was impacting coral reefs was identified as varying considerably among different species and geographical regions.[100]

2. Description of the environmental changes (between 2010 and 2020)

[100] See report of the Secretary-General on protection of coral reefs for sustainable livelihoods and development (A/66/298 and A/66/298/Corr.1).

The status of global coral reefs has not improved since described in WOA I. Recent global marine heatwave events (e.g. 2014-17; Eakin and others, 2019) have caused widespread mortality of corals through heat stress and associated bleaching, with recovery from such events uncertain (Leggat and others, 2019; Hughes and others, 2017a). Continued global declines in coral reef biodiversity (e.g. fish) (Johnson and others, 2017), as well as regional changes in reef composition of coral species (e.g. to *Porites* dominance) (Moritz and others, 2018) have been reported since WOA I (see also section 5 below). There has been a 50–75 per cent decrease in coral cover globally over the last 30–40 years (Bruno and others, 2019). Few coral reef areas have not been impacted (i.e. areas largely unaffected by direct human activities), with most occurring in areas afforded high protection status (Jones and others, 2018).

The steady degradation of coral reefs around the world continues to be closely linked to population growth and increased anthropogenic pressures, with an overlaid impact of climate change affecting even remote areas (e.g. Jarvis Island; Vargas-Ángel and others, 2019). The major threats include extractive activities, pollution (including runoff, chemicals), sedimentation, physical destruction and anthropogenic climate change. Although regional or local efforts will assist with mitigating decreases in coral cover, they are unlikely to offset the loss of coral caused by climate change (Bruno and others, 2019).

Globally, greenhouse gas levels have steadily increased (IPCC, 2018; see also Chapter 5 of the present Assessment). Ocean warming hotspots (e.g. Australia, South Africa, Brazil, Madagascar and India) are appearing (Fordyce and others, 2019; Kerr and others, 2018; Popova and others, 2016) resulting in substantially altered ecosystems, for example in Australia where coral has replaced kelp (Wernberg and others, 2016). Coral community changes are being seen globally (Hughes and others, 2018b), including delayed/reduced spawning (Birkeland, 2019) and coral reef areas now dominated by macroalgae (Johns and others, 2018) or cyanobacteria (de Bakker and others, 2017). In association with increased incidence of marine heatwaves (Smale and others, 2019), rates of thermal stress to corals have been steadily increasing (Lough and others, 2018). A 36-month global heatwave from 2014-2017 resulted in 75 per cent of the world's coral reefs experiencing bleaching and 30 per cent of coral reefs experiencing mortality as a result of bleaching (Babcock and others, 2019; Eakin and others, 2019). For some reefs, this was the first recorded bleaching event (e.g. southern offshore Great Barrier Reef; Hughes and others, 2017). Globally, the frequency of bleaching events has increased such that recovery is uncertain (Hughes and others, 2018a).

There are many other factors which cumulatively affect the quality and quantity of coral reefs globally. Ocean pH has decreased steadily, with net carbonate loss occurring in coral reef frameworks (Albright and others, 2016; Kuffner and others, 2019; Steiner and others, 2018). Physical destruction of coral reefs is increasing as a result of major Category 4 and 5 storms (e.g. Atlantic Ocean; Murakami and others, 2014). Flooding impacts associated with storm events have been severe and repetitive (Butler and others, 2015) and recovery is regionally variable (Adjeroud and others, 2018; Holbrook and others, 2018). There has been an increase in coral diseases globally (Ruiz-Moreno and others, 2012), which has been linked to thermal stress (Anyamba and others, 2019; Randall and van Woesik, 2015).

There are some areas where coral reefs are thriving (e.g. "bright spots"; Cinner and others, 2016a; Flower Garden Reefs; NOAA, 2020) and replacing other habitats (e.g. kelp forests). With increased warming and strengthened currents, coral reefs have expanded into higher latitudes, for example, in Japan over the last ~80 years (Yamano and others, 2011; Kumagai and others, 2018) and eastern Australia over the last ~20 years (Baird and others, 2012; Booth and Sear, 2018).

3. Description of the economic and social consequences and/or the other economic or social changes

Around 79 Member States of the United Nations have coral reefs in their maritime areas. Coral reefs are important as a source of income and protein to millions of people through fisheries; a major source of income through tourism; and a basis for sociocultural identity (Cinner and others, 2016b; Kittinger and others, 2012). The value of goods and services derived from coral reefs was estimated at 9.9 trillion United States dollars in 2012 (Costanza and others, 2014). It is now estimated that globally up to 500 million people benefit from coral reef services (Bruno and others, 2019), including six million fishers who depend directly on coral reefs (Teh and others, 2013). The economic value from tourism, fisheries and coastal development, for example, across countries in Mesoamerica and the Coral Reef Triangle, are valued at 20.1 billion US dollars per year (UNEP and others, 2018). Globally, the value from tourism per hectare of coral reef is estimated to be above 400,000 US dollars, with some reefs valued up to 7 million US dollars per hectare (Spalding and others, 2017).

Coral reefs are important for coastal protection (value 170,205 US dollars per hectare per year) and exploitable for rock and sand (value 22,000 US dollars per hectare per year) (Costanza and others, 2014). The annual value of flood risk reduction provided by coral reefs in the United States is estimated at above 18,000 lives and 1.805 billion US dollars (Storlazzi and others, 2019). Globally, the extra costs associated with coral reef loss associated with increased flooding from a major storm is estimated at 272 billion US dollars (Beck and others, 2018). In the United States of America, coral reefs annually prevent indirect damages worth over 699 million US dollars in the economic activity of individuals and over 272 million US dollars in avoided business interruption (Storlazzi and others, 2019).

The value of coral reefs for health and well-being far exceeds traditional economic valuations (UNEP and others, 2018). However, coral reefs have a complicated interaction with society (Cinner and others, 2016b), which makes it difficult to assign a dollar value to health and well-being benefits. There has been progress in understanding effective governance arrangements for coral reef conservation and the importance of sustainable use (Aswani and others, 2015; Turner and others, 2018), particularly where exploitation expands faster than governance arrangements (Eriksson and others, 2015). Conflicts occur between community-based management of coral reefs and that of national or international management frameworks. Increased local knowledge has supported community-level ownership and control of coral reefs and their management (e.g. Hawaii: Schemmel and others, 2016; Solomon Islands: Shaver and others, 2018).

Coral reefs contribute to the lives of millions of humans globally, and coral reef health impacts the ability to achieve the Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development.[101] The attainment of any, or all, SDGs may be compromised through loss of healthy coral reefs. In particular, they contribute to SDGs 1, 2, 3 and 12 through income and nutrition, as well as SDGs 3, 6, 11, 12, 13 and 14 through their aesthetic/natural values, healthy environmental conditions and the development of medical products. Healthy reefs maintain the integrity of island and coastal land and water resources

[101] See United Nations General Assembly resolution 70/1.

and infrastructure, thereby contributing to SDGs 6, 9, 11 and 13 and are linked to the ability of countries to attract and maintain skilled communities (SDGs 3, 4 and 10).

4. Key region-specific changes and consequences

4.1. Mediterranean Sea

Coral reef areas of the Mediterranean are sub-tropical and temperate in nature and limited in scale, with temperate reefs considered in Chapter 7 of the present Assessment. Some corals, e.g. *Oculina patagonica*, are expanding in range/abundance with increased temperature and light availability (Serrano and others, 2018). Other corals are decreasing in coverage (e.g. *Cladocora caespitose*: Chefaoui and others, 2017), through changes from coralligenous to algae dominated reefs (e.g. *Womersleyella setacea* and *Caulerpa cylindracea)*(Gatti and others, 2015).

4.2. Atlantic Ocean, particularly Wider Caribbean

Overall, 43 per cent of reefs in the Caribbean are under high/very high threat from human activities (ICRI 2018a). Primary threats to Caribbean reefs are the same as those impacting global reefs (Mumby and others, 2014), including rapid expansion of coral diseases (van Woesik and Randall, 2017) such as the novel “stony coral tissue loss disease” (Alvarez-Filip and others, 2019). Invasive lionfish (*Pterois volitans)* are now considered a threat to native reef fish populations and overall reef biodiversity (Chagaris and others, 2017).

Marine heatwaves occurring across the Caribbean region since the 1970s, and in particular during 2015 and 2016 (Banon and others, 2018), have reduced live coral cover from over 70 per cent to approximately 14 per cent (ICRI, 2018a), although there is substantial regional variation (Jackson and others, 2014, Cortés and others, 2018, Muniz-Castillo and others, 2019). Van Hooidonk and others (2014) predict that most coral reefs in the Caribbean will suffer annual bleaching by 2045-50 and ocean acidification could result in carbonate saturation levels dropping below those required to sustain coral reef accretion by 2050. Perry and others (2013) report that 37 per cent of Wider Caribbean reefs are eroding and only 26 per cent are accreting. Significant reductions in calcification rates and the density of structure have been reported for species such as *Orbicella faveolata* in the Seaflower Biosphere Reserve (Lizcano-Sandoval and others, 2019) with strong indications that reefs in general in Florida are eroding (Kuffner and others, 2019). Major tropical storms in the Western Central Atlantic (five Category 5 and three Category 4 hurricanes in 2017, 2018 and 2019) are believed to have caused massive damage to coral reefs across the region, although official data have not yet been published.

There has been progress with regard to standardized monitoring and reporting of coral reef health across the Caribbean (e.g. GCRMN-Caribbean 2016). Reef report cards indicate improvement in reef health across the Mesoamerican Barrier Reef system over the last ten years (McField and others, 2018). There have been enhanced efforts to improve conservation and sustainable use of coral reefs and coastal environments across the region (CCI 2019) and efforts to restore herbivores (ICRI 2013; Vallès and Oxenford, 2018). Reef restoration/rehabilitation have expanded in the Wider Caribbean and are benefiting from new research and improved nursery and outplanting technologies (Lirman and Schopmeyer 2016, Baums and others 2019).

4.3. Indian Ocean

Coral reef abundance has been stable across the Indian Ocean since 2010, except reefs near Mozambique that have decreased substantially (Obura and others, 2017). Global marine heatwaves have caused widespread bleaching (e.g. Maldives; Cowburn and others, 2019; north-western Australia; Keesing and others 2019) across the region. Over 65 per cent of reefs across the region have been identified as at risk as a result of local threats, with 33 per cent considered to be at high or very high risk (ICRI, 2018b). Nineteen per cent of coral reefs are contained within marine protected areas (MPAs). However, only 25 per cent of the total number of MPAs are considered effective (ICRI, 2018c), and many lack management plans (Obura and others, 2017).

Coral reefs in the Red Sea and Persian Gulf show resilience to high temperatures and mortality from bleaching (Howells and others, 2016), though calcification rates appear to be declining (Steiner and others, 2018). Harmful fishing practices, including poisoning and dynamite, are decreasing in occurrence in the Indian Ocean (Obura and others, 2017), with notable exceptions, such as Tanzania (Chevallier, 2017). Other direct impacts to coral reefs are increasing, such as anchoring by fishers and tour boats (Obura and others, 2017), as well as outbreaks of COTS (Saponari and others, 2018; Keesing and others 2019).

4.4. Pacific Ocean

Threats to coral reefs in the Pacific Ocean, including the biodiverse Coral Triangle Region, are similar to those globally (ICRI, 2018c). A three per cent decrease in coral cover was reported from 1999 to 2016 (ICRI, 2018c) and widespread bleaching events have occurred throughout the region since 2015 (Moritz and others, 2018; Hughes and others, 2019), the impacts of which are only now being reported (Gorospe and others, 2018). Outbreaks of COTS continue to occur across the Pacific Ocean causing coral decline, including, for example, in French Polynesia (Kayal and others, 2012), Mexico (Rodríguez-Vilalobos and Ayala-Bocos, 2018), Japan (Yasuda, 2018), Australia (MacNeil and others, 2017) and other Pacific Islands (Moritz and others, 2018).

Biodiversity of coral species across the Pacific is changing as a result of disturbance, with certain coral species, such as *Porites* spp., becoming increasingly dominant, while *Pocillopora* spp. showed significant decline (Moritz and others, 2018). A poleward range expansion of corals to former seaweed habitats has been reported from Japan (Yamano and others, 2011; Kumagai and others, 2018). Coral reef cover around the north-western side of the island of Hawaii decreased from around 44 per cent to 31 per cent between 2002–2014, mainly due to human use-related activities (e.g. animal production, land development/deforestation and urban sprawl, fishing and recreation) and climate-related heatwaves (Gove and others, 2016).

Around 88 per cent of reefs are under threat from human activities, especially localized threats (ICRI, 2018c). Around 13 per cent (8,960km^2) of coral reef areas across the Pacific Ocean are contained in protected areas, of which 20 per cent have formal management plans implemented (Moritz and others, 2018). Of those reefs contained in MPAs in the South-East Asian region, only 30 per cent are identified as having effective management and compliance measures in place (ICRI, 2018c).

5. Outlook

Coral abundance and cover have decreased from 2010 to 2019 and are expected to continue in the coming decades (Graham and others, 2017). Bleaching events since 2015 have led to reduced production of larvae and reduced recruitment which will lead to reduced/delayed recovery (Hughes and others, 2018b). Climate projections (see also Chapters 5 and 9 of the present Assessment) suggest that many of the world's coral reefs will experience annual bleaching by mid-century associated with warming temperatures (Hughes and others, 2018b). Greater erosion, sedimentation and nutrient flow associated with increasing storm intensity (Walsh and others, 2016; Vitousek and others, 2017); increased mortality associated with a reduction in oxygen (Nelson and Altieri, 2019; Altieri and others, 2017) and drowning of coral reefs as sea levels increase (Perry and others, 2018; Storlazzi and others, 2019) have all been projected to occur. Deepwater areas appear a less likely option for thermal refuge for corals because the thermal relief provided by the deeper waters only occurs at certain times of the year and only certain species are tolerant of the deeper water environment (Frade and others, 2018). Future coral communities are likely to be dominated by fewer species resistant to high temperatures and bleaching (Moritz and others, 2018; Birkeland, 2019). The effects of ocean acidification should become more apparent in the coming decades, with continued dissolution of reefs (Eyre and others, 2018; Birkeland, 2019).

Coral reefs are expected to expand into higher latitudes as a result of warming oceans and warm currents (Wilson and others, 2016, 2018). Coral habitats or species' ranges are, however, expected to be bound between higher latitudes, where the saturation state of aragonite decreases, and lower latitudes, where warmer water temperatures result in thermal stress (Matz and others, 2018; Yara and others, 2012).

Greenhouse gases and climate change are considered by many reef scientists to be the key risk to future coral reefs (e.g. Beyer and others 2018; Rinkevich 2019). To combat losses of coral reefs, coral reef restoration techniques are being improved (van Oppen and others, 2017), widely used and demonstrating some success (Bayraktarov and others, 2019; Rinkevich, 2019). Further investigations are taking place to understand the response of corals to climate change and develop methods which help corals to adapt to future conditions (e.g. alterations to symbiotic microalgae diversity; Rinkevich, 2019). Modelling approaches that identify risk envelopes for coral reefs may assist in prioritising efforts so that they are focused on reefs that have the greatest resilience and likelihood of survival (Beyer and others 2018). Innovative sustainable funding mechanisms for supporting marine resource conservation and sustainable use, especially of coral reefs, are finding traction under the blue economy (e.g. Deutz and others, 2018).

Overall, the continued loss of coral reefs expected for the coming decades will also result in erosion of the many socioeconomic benefits of healthy coral reefs.

6. Key remaining knowledge gaps

The key knowledge gaps reported in WOA I included understanding of the responses of corals and coral dependent species (such as fish) to climate change and the spatial extent of mesophotic coral reefs (reefs found in lower light conditions and depths of 30–150m). Progress has been made in addressing them, however, the specific knowledge gaps today are somewhat different, but remain in the same broad areas. These gaps are: (i) the responses of reef communities to climate change; (ii) the socioeconomic value of coral reefs; and (iii) the distribution and ecology of mesophotic coral reefs.

Greater understanding is still required on the responses of reef communities to climate change, though progress is occurring with regard to coral adaptation to change (e.g. Dziedzic and others, 2019). There is still limited understanding of coral reef responses to ocean acidification (Morais and others, 2018) and current understanding is confounded by inaccuracy in measurements of net reef growth/erosion. In particular, there is a lack of understanding of the impacts of increasing ocean temperatures on the life cycles of reef taxa, changes to neurosensory function and metabolism in a variety of key reef-associated taxa and the cumulative effects of climate change and other stressors, such as nutrient enrichment, increased sediment load and overfishing on coral reef systems. There is currently limited understanding of the role of coralline algae and microbial communities to reef ecology and health (Cornwall and others, 2019; Ricci and others, 2019), though there are clear seasonal links between microbiome and macroalgae abundance (Glasl and others, 2020). There are also significant geographic gaps in our understanding of coral reefs and their responses to climate change and other stressors, such as reduced oceanic oxygen and emerging pollutants. Western south Atlantic coral reef communities and deeper water coral reef communities are poorly described (Loya and others, 2016; Morais and others, 2018). Further information is needed to identify the mechanisms of coral diseases and how they are transmitted, particularly their relationship with coral bleaching events and poor water quality.

For the socioeconomic value of coral reefs, robust evaluations of the economic value of the ecosystem services that reefs provide at local and national scales are lacking, so their value is not properly accounted for in cost-benefit analyses of development projects. There are further knowledge gaps regarding effectiveness of management tools and efforts to improve reef resilience, including coral restoration (Boström-Einarsson and others, 2020).

Finally, there is emerging evidence that mesophotic coral reefs occur widely (e.g. Baker and others, 2016), beyond the Atlantic (Loya and others, 2016) and further information is required regarding their biodiversity and ecological function.

7. Key remaining capacity-building gaps

WOA I identified capacity-building gaps at the local, national and regional levels. These remain within most developing countries and, in particular, a lack of qualified technicians and researchers limits the monitoring and management of coral reefs and therefore capacity to identify change over time and respond to changes. There have been substantial improvements to the development of new technologies to monitor coral reef systems (Bayley and Mogg, 2019; Hedley and others, 2016), but there is limited local capability for utilization/application of such technology (e.g. Díaz and others, 2015; Timpte and others, 2018). Greater capability for implementing adaptation strategies in response to climate changes (Cinner and others, 2018) and building adaptive management capabilities (Hoegh-Guldberg, 2018), both locally and globally, is needed. Public awareness and capacity-building for management and sustainable use of expanding corals is an emerging issue at higher latitudes. The capabilities for coral reef rehabilitation are currently limited, and capabilities for transplanting and farming corals (Kittinger and others, 2016, van Oppen and others, 2017) and maintaining them need to be developed.

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Chapter 7F
Cold-Water Corals

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Keynote points

- Cold-water coral and sponge ecosystems are common features along continental margins, mid-ocean ridges, and on seamounts worldwide, providing habitats for numerous species and contributing to carbon sequestration.
- The basic knowledge of cold-water coral biology and distribution is still limited to the few areas of the deep ocean that have been explored.
- Threats from fishing, offshore oil drilling, deep-sea mining, waste deposition and climate change continue. Some efforts to curb demersal trawling and establish marine protected areas have been effective. However, because of their slow-growing and long-lived nature, recovery from anthropogenic impacts can take decades to centuries.
- Cold-water corals are highly sensitive to elevated temperatures and deoxygenation, but recent work suggests they are relatively resilient to ocean acidification, particularly when nutritional resources are plentiful.
- Future projected declines in cold-water coral abundance will reduce habitat available to commercially significant species, reduce carbon sequestration in deep waters, eliminate potential genetic resources and have an effect on numerous Sustainable Development Goals (SDGs), particularly SDG 14, but also SDGs 2, 10, and 12.[102]

1. Introduction and summary of the First World Ocean Assessment (WOA I)

Cold-water corals (CWC) occur globally (Figure 1), forming important habitats that support a high diversity and biomass of associated organisms. Following the framework established in the First World Ocean Assessment (WOA I) (United Nations, 2017), the present Chapter focuses on corals found below 200 m. Cold-water corals are found where hard substrata are available on continental margins, mid-ocean ridges (Chapter 7Q) and seamounts (Chapter 7N) worldwide. These habitats are components of the slopes of volcanic islands (included in Chapter 7D), submarine canyons (Chapter 7L) and fjords, as well as seamounts and pinnacles (Chapter 7N), and ridges and plateaus (Chapter 7Q). Coral habitats may be found on the periphery of cold seeps and extinct hydrothermal vents (Chapter 7R). Cold water corals, sponges, and associated species also interact directly with the overlying open ocean (Chapter 7P) through benthic-pelagic coupling. Surface-derived productivity forms the energetic basis of the vast majority of the deep-sea food web and CWC systems recycle nutrients that can fuel surface productivity via upwelling and transport of nutrients by diel vertical migrators.

[102] See United Nations General Assembly resolution 70/1.

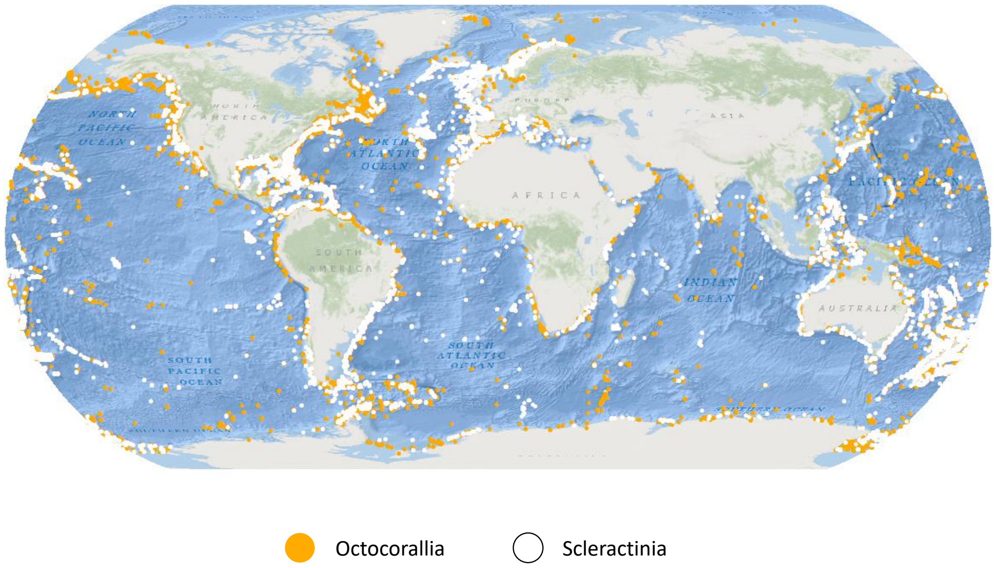

Figure 1. Map of global distribution of deep-sea corals including Subclass Octocorallia (gorgonian sea fans, soft corals) and Order Scleractinia (stony corals). Coral occurrence records from the UN Environment World Conservation Monitoring Centre (https://data.unep-wcmc.org/datasets/3), the Ocean Biodiversity Information System (https://obis.org/), and the NOAA Deep-Sea Coral & Sponge database (https://www.ncei.noaa.gov/maps/deep-sea-corals/mapSites.htm). The underlying basemap created in ArcGIS Pro v. 2.3, using data compiled from multiple sources and data providers, including General Bathymetric Chart of the Oceans GEBCO_08 Grid, National Oceanic and Atmospheric Administration (NOAA), National Geographic, Garmin, HERE, Geonames.org, and Esri, and several additional contributors. Map courtesy of Dr. Jay Lunden.

Modelling of global habitats predicts that major cold-water framework-building scleractinian corals (Figure 2) are likely most abundant in (i) hard substrate areas necessary for settlement of coral larvae, (ii) waters supersaturated with aragonite, (iii) depths shallower than 1500 m, (iv) water masses containing dissolved oxygen concentrations of >4 ml L^{-1}, (v) waters that have a salinity range between 34 and 37 PSU[103] and (vi) temperatures between 5 and 10°C (Davies and Guinotte, 2011). However, CWC of a variety of taxa occupy wider niches in the deep ocean (Quattrini and others, 2013, 2017). Food is supplied to CWC through rapid downwelling (Davies and others, 2009), geostrophic currents, internal waves, tides, Taylor columns (eddies causing upwelling and enhancing food concentration; White and others, 2005), intermediate and bottom nepheloid layers (Mienis and others, 2007), and via diel vertical migrators (Maier and others, 2019).

Cold-water coral ecosystems provide essential services for human communities and well-being (see also Section 3). Demonstrated services include the discovery of novel marine genetic resources (Chapter 26 of the present Assessment), carbon sequestration, and significant aesthetic value (see Thurber and others, 2014, for a review). Most directly, CWC provide a habitat that acts as shelter and/or nursery grounds for commercially exploited or exploitable fish stocks (Baillon and others, 2012; Quattrini and others, 2012; Roberts and others, 2009). The Food and Agriculture Organization of the United Nations (FAO 2009) recognizes taxa of CWC as indicators of vulnerable marine ecosystems (VME) and the United Nations General Assembly (2005, 2007) has called for conservation measures to protect

[103] Practical salinity unit.

VMEs from anthropogenic impacts. The wealth of niches combined with high food availability make some CWC reefs “hotspots” of biodiversity and biomass, including hundreds of other sessile and mobile species (Cordes and others 2008; Henry and Roberts, 2007), as well as carbon and nutrient cycling (Cathalot and others, 2015; van Oevelen and others, 2009).

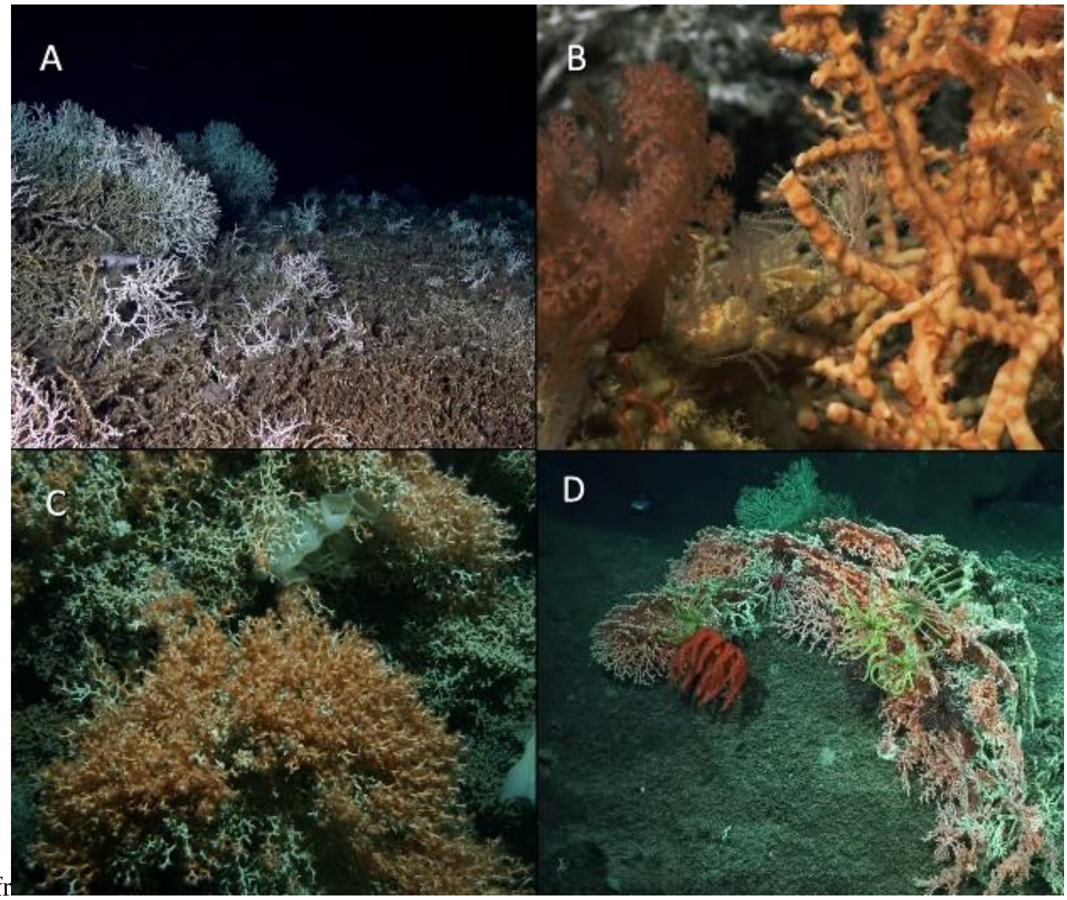

Figure 2. Common cold-water scleractinian corals. A. *Lophelia pertusa* and B. *Madrepora oculata* and a neptheid octocoral from the Atlantic coast of the United States. Images courtesy of the Deep Search program, US BOEM, USGS, NOAA, copyright WHOI. C. *Solenosmilia variabilis* from the Pacific off New Zealand. Image courtesy of Malcolm Clark, NIWA. D. *Enallopsamia profunda* om the Phoenix Islands in the Central Pacific. Image courtesy of Erik Cordes and the Schmidt Ocean Institute.

2. Description of the environmental changes (between 2010 and 2020)

As sessile organisms with very slow growth rates, CWC and the frameworks they create (both living and dead) are extremely vulnerable to direct and indirect impacts from bottom trawling, oil and gas exploration, and deep-sea mining. While the current stressors on CWC are not significantly different to those identified in WOA I, the distribution of pressures and their magnitude has changed. As fisheries activities (Chapter 15) continue to operate in deeper waters and the search for oil and gas reserves (Chapter 20) moves further offshore, these activities impact CWC gardens and reefs more frequently. Further, the accidental release of hydrocarbons (Chapter 11) associated with oil and gas extraction can have drastic effects on these habitats as highlighted by the 2010 *Deepwater Horizon* oil spill in the Gulf of Mexico (Fisher and others, 2014; White and others, 2012). In the vicinity of the oil spill, where octocorals were over 50 per cent impacted by the spill, their health and colony size has continued to decline (Hsing and others, 2013). Some recovery has been observed in coral colonies with less than 50 per cent coverage by oil and dispersant, although some branch loss has been observed (Hsing and others, 2013).

The impacts of fisheries activities on CWC is well recognized with bottom trawling, in particular, having strong direct physical (e.g. breaking or dislodging colonies) as well as secondary sedimentation effects (e.g. smothering individuals or colonies) (see review by Clark and others, 2016). Surveys of coral populations on seamount features off New Zealand and Australia show little sign of recovery 15 years after trawling was stopped, but where other unfished seamounts have been protected, they have dense coral populations (Clark and others, 2019; Williams and others, 2010). Recent work on the Hawaiian Seamount chain suggests there may be some regrowth of CWC between 300-600 m depth 30-40 years after fishing (Baco and others, 2019). In general, the estimated extent of deep-sea trawling has decreased in recent decades (e.g. Victorero and others, 2018).

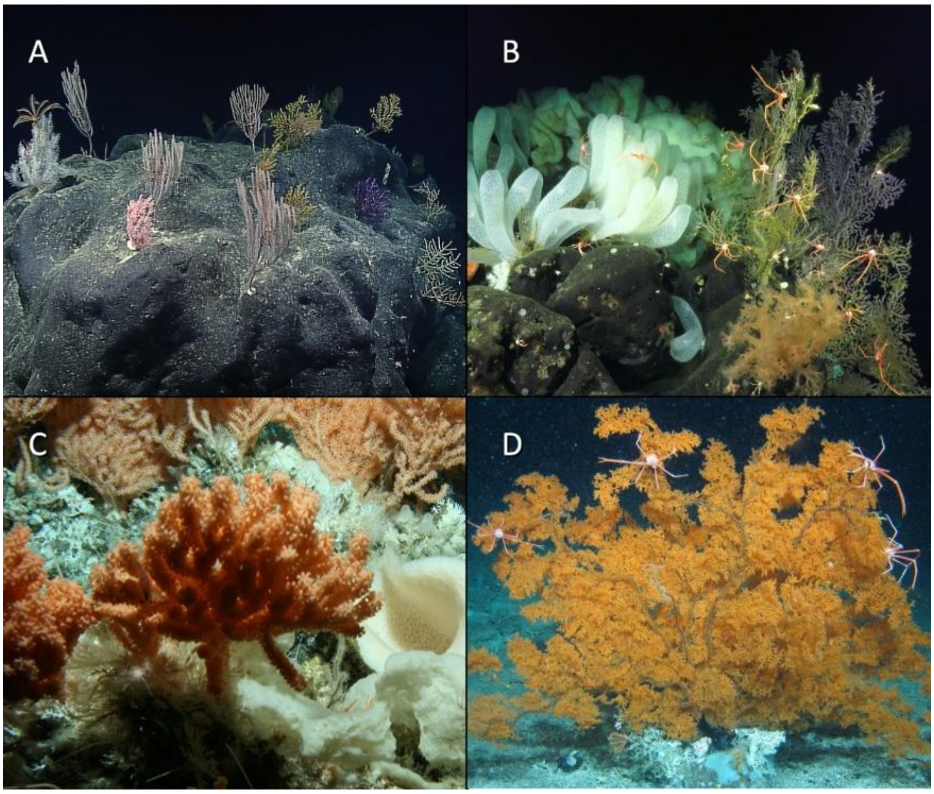

Figure 3. Representative cold water octocoral gardens. A. High diversity of octocorals (primarily primnoids and plexaurids) and antipatharian corals from the Phoenix Islands in the Central Pacific. Image courtesy of Erik Cordes and the Schmidt Ocean Institute. B. Yellow and purple *Paramuricea* sp. octocoral sea fan colonies with orange chirostylid crab associates and *Euplectella* sp. hexactinellid (glass) sponges to the left of the image. Image courtesy of Erik Cordes and the ROC HITS program, NSF, and the Schmidt Ocean Institute. C. *Paragorgia* sp. octocorals, stylasterid hydrocorals, and hexactinellid sponges from the Macquarie Ridge, New Zealand. Image courtesy of Malcolm Clark, NIWA. D. A large *Leiopathes glaberimma* colony in the North-East Atlantic. Image courtesy of J. Murray Roberts and the Changing Ocean Expedition, 2012.

Predicting the response of CWC populations to anthropogenic disturbance requires knowledge of their current distribution and resilience. Recent predictive habitat models have led to new CWC discoveries in a productive, iterative process (i.e. Georgian and others, 2020) and also to the development of new modelling techniques (Robert and others, 2016; Diesing and Thorsnes, 2018). Recent discoveries include populations of habitat forming octocorals

(Figure 3) on the Antarctic continental shelf (Ambroso and others, 2017), scleractinian coral reefs in low pH waters in the North Pacific (Baco and others, 2017; Gómez and others, 2018) and thousands of CWC mounds surviving under low dissolved oxygen (DO) along the Moroccan Atlantic continental margin (Wienberg and others, 2018).

An understanding of the reproductive factors influencing CWC distribution is also required to determine their recolonization potential. Recent studies indicate that *Lophelia pertusa* larvae are planktotrophic and reside in the upper water column for up to five weeks before settlement (Larsson and others, 2014; Strömberg and Larsson, 2017). Similarities in the genetic structure of the cup coral *Desmophyllum dianthus* (Miller and Gunasekera, 2017) over large areas suggest wide connectivity (Holland and others, 2019). Conversely, variable genetic structure in the reef-building stony coral *Solenosmilia variabilis* suggests that asexual reproduction and localized recruitment may be prevalent (Miller and Gunasekera, 2017). Zeng and others (2017) report genetic differentiation among three CWC species off New Zealand, primarily determined by regional and local currents (Dueñas and others, 2016; Holland and others, 2019). The limited number of population genetic studies of deep-water octocorals indicate that gene flow among populations is restricted to those residing at similar depths, with water masses creating barriers to larval dispersal and genetic exchange (Baco & Shank 2005, Quattrini and others, 2015).

The increased use of long-term observatories, identified as a major capacity-building gap in WOA I, has highlighted the influence of seabed heterogeneity (Pierdomenico and others, 2017), hydrodynamics (Mienis and others, 2019) and *in situ* growth dynamics (Lartaud and others, 2017) on the spatial extent and morphology of CWC habitats at local scales (De Clippele and others, 2018), and CWC and sponge fauna composition at regional scales (van Soest and de Voogd, 2015; Radice and others, 2016). Modelling of interactions between tidal currents and CWC mounds suggests an enhanced downwelling of surface food particles that promotes the proliferation of benthic communities (Cyr and others, 2016; Soetaert and others, 2016). Data from the LoVe (Lofoten-Vesterålen) cabled ocean observatory[104] have led to the identification of turbulent mixing in winter and spring along with vertically migrating zooplankton in the stratified waters of warmer months as the food supply mechanisms to CWC on the Norwegian continental shelf and emphasized the benefits of sustained ocean observatories (Van Engeland and others, 2019).

Climate change remains a persistent and pervasive threat to CWC through global ocean warming, ocean acidification, deoxygenation, reduced food supply (Figure 4) and the cumulative effects of these stressors (Hebbeln and others, 2019; Sweetman and others, 2017; Wienberg and Titschack, 2017). Currently, many CWC that occur at shallower depths appear to be near the limits of their temperature tolerance (Georgian and others, 2016b; Morato and others, 2020). This may be particularly significant in regions where ocean temperature is most rapidly changing (Levin and Le Bris, 2015; see also Chapter 5 of the present Assessment). Expanding oxygen minimum zones are perhaps more immediate threats to living corals (Fink and others, 2012; Lunden and others, 2014, Tamborrino and others, 2019).

At the deeper ends of their distribution, corals appear to be limited by aragonite and calcite saturation states. However, there are now several reports of scleractinian corals surviving and growing below the aragonite saturation horizon (Baco and others, 2017; Gómez and others, 2018), and octocorals persisting at depths near or below the calcite saturation horizon (Quattrini and others, 2017). In undersaturated waters, coral colonies can continue to calcify

[104] Available at http://love.statoil.com.

in laboratory experiments, although variable responses have been noted from different species and populations (i.e. Gammon and others, 2018; Georgian and others, 2016a). The differences in the response to ocean acidification by CWC suggest distinct interspecific sensitivity to environmental changes and the importance of food supply and energy allocation in the nature of the response (Kurmann and others, 2017; Glazier and others, 2020). Reduced tissue coverage of coral skeletons may make corals more vulnerable to acidification, since reduced pH can elevate the chemical dissolution (Hennige and others, 2015) and even bioerosion rate (Schönberg and others, 2017) of dead coral skeleton, which makes up much of the standing coral reef structure.

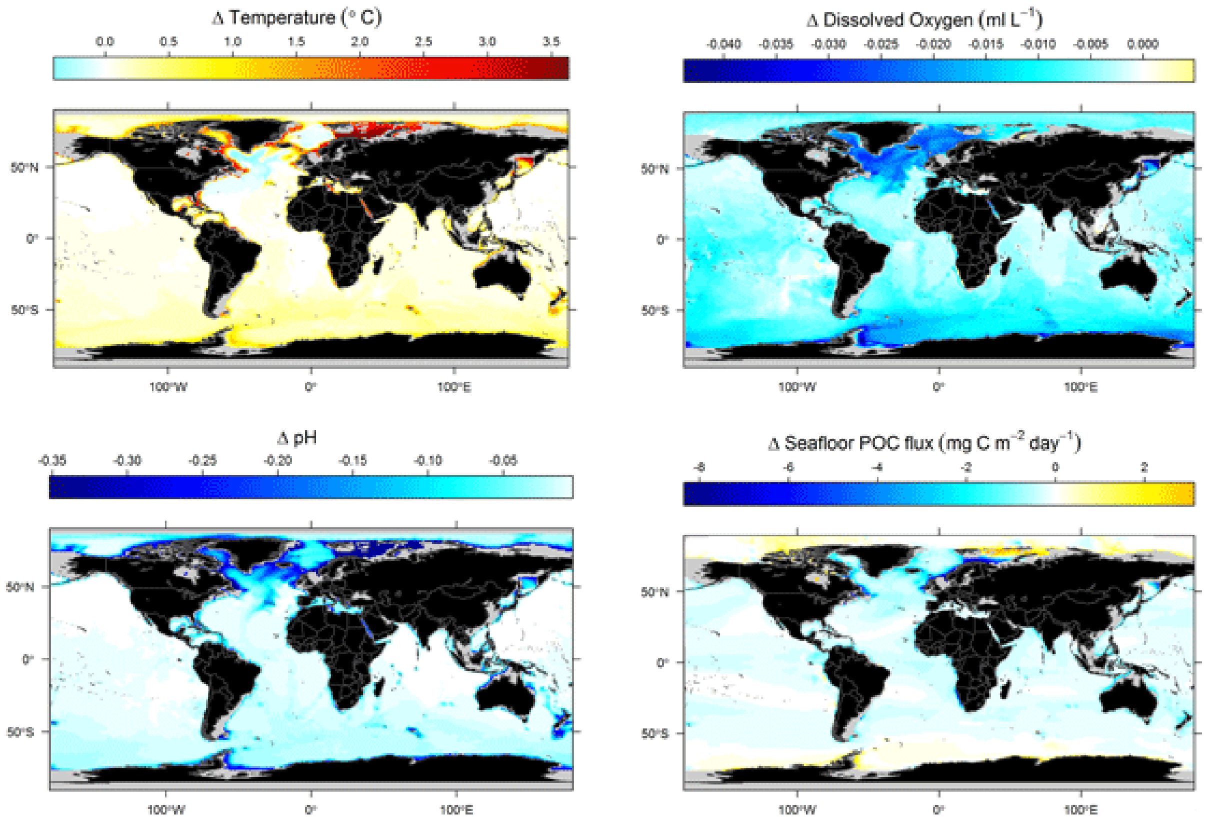

Figure 4. Modelled environmental changes at the deep seafloor in the year 2100. Modelled changes in A. temperature (°C), B. dissolved oxygen (mL L–1), C. pH, and D. sea floor POC flux (mg C m–2 d–1) that could be seen at the at the deep (> 200 m) seafloor by 2100 relative to present-day conditions. Source: Sweetman and others, (2017).

Laboratory experiments have demonstrated that CWC tolerance to high temperature, low pH, and low DO improves when there is an abundance of nutritional resources. For example, regular food pulses to the hermatypic (reef-building) scleractinian *Lophelia pertusa* was highlighted as important for maintaining its metabolic rate (Georgian and others, 2016a; Maier and others, 2019). Recent studies have revealed that *L. pertusa* hosts a versatile microbiome, likely shaped by nutritional status or environmental conditions, while *Madrepora oculata*, another reef-forming CWC, has a more stable and consistent microbiome regardless of the underlying conditions (Meistertzheim and others, 2016). However, the degree to which this variability in the microbial community confers metabolic plasticity in coral species in their natural environment has not been determined. Experimental work has unravelled how sponges, key contributors to CWC ecosystems, can proliferate under food-limited conditions (Kazanidis and Witte, 2016; Kazanidis and others, 2018).

Emerging threats include marine debris, with microplastics (see also Chapter 12) observed in corals at all depths in the ocean (Taylor and others, 2016), and physical disturbance associated with deep-sea mining (see also Chapter 19), particularly on seamounts and in the vicinity of active and extinct hydrothermal deposits. There is the potential for direct restoration efforts in deep-sea coral communities to accelerate recovery from disturbance, although there have only been a limited number of pilot studies to examine these techniques (e.g. Boch and others, 2019).

3. Economic and social consequences

Cold-water corals overlap with human economic and social interests increasingly as the range of human activities in the deep sea expands. Changes in CWC distribution through removal or differential survivorship along with changes in health and metabolism will impact numerous SDGs. Beyond the obvious and direct changes of relevance to SDG 14, CWC and sponges are of increasing interest as genetic resources for the development of pharmaceutical products (Molinski and others, 2009; Rocha and others, 2011), which would be impacted by the loss of species and habitat. CWC and sponge habitats actively sequester carbon through both feeding and carbonate precipitation in the deep ocean (Kahn and others, 2015; Soetaert and others, 2016). While there are few empirical rate estimates of these processes, carbon sequestration by CWC could contribute to mitigating global climate change (SDG 13), including ocean acidification (target 14.3).

CWC also provide habitat for numerous fishes, including many significant fisheries species such as swordfish, roughy, and fishes of the snapper-grouper complex (Ross and Quattrini, 2009; Morato and others, 2020). CWC ecosystems also recycle nutrients at depth that are brought back to the surface through upwelling to fuel shallow-water productivity (White and others, 2012; Soetaert and others, 2016). Therefore, changes in their distribution and ecosystem function will impact SDG 2 and associated sustained food security and use of marine resources (SDG 12). Changes in the availability of nutritional or genetic resources derived from CWC would disproportionately impact the economic benefits to small island developing states and least developed countries, thereby affecting the achievement of SDG 10.

Recent conservation efforts have resulted in the protection of CWC and sponge ecosystems including bans on fishing activities by the European Union and around many seamounts in the North and South Pacific as well as the establishment of protected areas such as the Northeast Canyons and Seamounts Marine National Monument, the Phoenix Islands Protected Area, and Pacific Remote Islands National Marine Monument.

4. Key region-specific changes and consequences

While human activities are impacting CWCs globally, there is regional heterogeneity to the degree of those impacts. For example, deep-sea oil and gas activities are more widespread in the Gulf of Mexico (Cordes and others, 2016), leading to greater potential issues in that region. Deep-water oil and gas exploration is expanding in the Caribbean, in the South Atlantic (off the coasts of Brazil, Namibia, and South Africa), and in the Indian Ocean (off South Africa and Mozambique). These expansions and potential associated impacts are occurring in regions where the capacity to conduct and review deep-sea environmental assessments is lower, and future efforts should be focused on augmenting this capacity (see also section 8). Deep-sea bottom trawling tends to be focused in only some regions of the world (e.g., Southwest Pacific, Indian Ocean). Although the amount of seafloor impacted and overall effort have declined in recent decades, the limited distribution of these fisheries concentrates associated impacts to individual CWC reefs and gardens on pinnacles and seamounts targeted.

Regional variability in the impacts of climate change will result in region-specific effects on CWC. For example, areas of upwelling (e.g. the North Pacific) have an aragonite and calcite saturation depth that is relatively shallow. In these regions, where scleractinian corals are living close to saturation horizons, species are thus at greater potential risk to ocean acidification over relatively short timescales (i.e. Gómez and others, 2018). Projected changes to ocean circulation under climate change scenarios include a slowing down of the Atlantic Meridional Overturning Circulation (Bryden and others, 2005; Thornalley and others, 2018), which is expected to have an impact on temperature, salinity and food supply to corals in the North Atlantic Ocean.

Emerging impacts associated with microplastics and deep-sea mining also vary regionally. The impacts associated with microplastics are expected to be higher in regions with marine canyons as these structures facilitate the trapping and “channelling” of submerged matter (Fabri and others, 2019; Pham and others, 2014). Cobalt-rich ferromanganese crusts, the mining of which is driven by developing battery technologies, occur on seamounts and guyots. In recent years, exploration licences have been issued by the International Seabed Authority for areas in the Northwest Pacific Ocean and South Atlantic Ocean that host seamounts with stony corals and octocorals. Leases for mining of polymetallic nodules in the Clarion-Clipperton fracture zone have been issued and mining of seafloor massive sulphides may soon begin off Papua New Guinea. Both regions contain CWC, including long-lived species of antipatharian black corals (Boschen and others, 2013; Molodtsova and Opresko, 2017), making recovery times from these types of removal activities extensive.

5. Outlook

Current trends suggest that human activities and the effects of global ocean change will continue to increase in deep waters. The responses of CWC could be through range shifts, alterations of metabolism and physiology or local and potentially widespread reductions in genetic diversity and even extinctions of species. Any and all of these responses would have an effect on the distribution and magnitude of the ecosystem services provided by CWC. Achievement of the SDG target 14.5, the conservation of 10 per cent of coastal and marine areas, would significantly improve the outlook for CWC.

6. Key remaining knowledge gaps

At the most basic level, much of the ocean floor remains unmapped, although the Seabed 2030 project has made great advances and modern multibeam bathymetric surveys now cover approximately 20% of the seafloor (GEBCO 2020). Due to the remoteness of the deep sea, current knowledge regarding CWC and the structures they form, as well as the variability in key environmental drivers, is still very limited. There is a clear need to monitor environmental variables (e.g. temperature, DO and pH), particularly in areas near the edge of coral species niches such as the periphery of large oxygen minimum zones, near the aragonite saturation horizon, or in basins where temperature is already high (i.e. the deep Mediterranean Sea), as well as where CWC ecosystems are threatened by the cumulative stressors of human activities.

The resilience of CWC to changes in oceanographic conditions remains a major information gap. In particular, research on the impacts of deoxygenation is lacking compared to studies of ocean acidification (Levin and Le Bris, 2015). The long-term energetic costs associated with coral acclimation, or the potential for adaptation to any and all ocean change stressors, and combinations thereof, remains to be determined for most species. The dead coral framework, has been largely understudied and understanding of bioerosion processes and impacts of ocean acidification is limited.

Basic biological information is still lacking for many coral species and, similarly, the applicability of using other species as "proxies" is uncertain. The majority of experimental studies conducted to date are on the "model organism" *Lophelia pertusa*. Application of experimental studies to other CWC species of a variety of taxonomic groups (i.e., octocorals, antipatharians) and to other deep-water groups, such as sponges, is necessary to test for the universality of the conclusions based on this model organism. Reproductive and age-and-growth studies are receiving more attention amongst researchers (e.g. Larcom and others, 2014) and increasing use of "seascape genetics" (e.g. Miller and Gunasekera, 2017) can help managers to adopt more integrated broad-scale management options. Nevertheless, improved marker development is required for genetics to support future coral connectivity research and/or molecular-based taxonomy (Quattrini and others, 2017).

Advances in modelling approaches, such as species distribution and habitat suitability modelling (Robert and others, 2016); use of emerging technologies, such as machine learning (Osterloff and others, 2016); cross-sectoral collaboration (Murray and others, 2018); and appropriate data archiving in online databases, will improve data availability and reduce processing time, which can improve assessments of the status of CWC and associated structures. Overcoming challenges associated with limited standardisation of studies through the development and use of standardized protocols for video acquisition and analysis will improve the comparability of data and thus upscaling from local to regional spatial scales (Davies and others, 2017; Girard and Fisher, 2018).

Although baseline surveys are often required prior to human industrial activity (Cordes and others, 2016), the *Deepwater Horizon* oil spill highlighted a lack of local information on CWC and the deep sea in general. Baseline assessments of the status of these ecosystems have only recently been established, with the earliest baselines from the 1980s, and many CWC habitats continue to be discovered even in relatively well-explored regions. Further, when surveys are conducted, the information generated is often proprietary and not made available publicly, which then limits transfer of baseline information and incorporation into further investigations and broader modelling efforts. In addition, surveys may be designed simply to look for hazards and not characterize the environment or document the fauna, and therefore lack the potential to improve understanding of CWC habitats. However, the requirement for documentation of habitats associated with industrial activities is increasing. For example, detailed baseline data collection is a requirement for contractors undertaking exploration for deep-sea minerals in the Area[105] under the auspices of the International Seabed Authority. This may provide the means to address some of the current knowledge gaps associated with this deep-water habitat.

[105] The Area is the seabed and ocean floor and subsoil thereof, beyond the limits of national jurisdiction (United Nations Convention on the Law of the Sea, article 1).

7. Key remaining capacity-building gaps

Gathering the data necessary to evaluate the status and trends of deep-sea ecosystems is difficult, time-consuming, and expensive. There is an urgent need to develop the capacity to carry out these surveys, particularly in developing countries. Fundamental to these studies is the proper taxonomy of the species investigated, which is required to correctly assess population sizes and distributions as well as properly attribute impacts. For example, the iconic deep-sea coral species, *Lophelia pertusa*, is currently listed as *Desmophyllum pertusum* in the World Register of Marine Species (WoRMS) database based on evidence presented in Addamo and others (2016). However, this renaming remains controversial as there are a large number of populations around the world for which there are few genetic or genomic data, and the genus *Desmophyllum* otherwise consists of only solitary species. Proper identification of CWC is itself a capacity gap, with a decline in the numbers of properly trained taxonomists in recent years, particularly for octocorals.

Access and the proper expertise to use the tools required for studying CWC habitats (e.g. multibeam echosounders, manned and unmanned deep-water vehicles) is a major gap for many of the areas where CWC are abundant and their distribution overlaps with proposed industrial activities. The necessary tools and training to collect the appropriate baseline data allowing for an evaluation of the impacts of industrial activity on CWC need to be made available to, and ideally be located in, those countries in which the activities are taking place. Furthermore, where impacts have already occurred, there is little capacity anywhere in the world for deep-sea coral restoration. The development of effective techniques is a critical capacity gap that should be a large focus of future work and will become increasingly important in the future. Although the capacity-building gap is most obvious in developing States, the deep sea is so remote and unexplored that numerous capacity and information gaps remain within developed States.

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Chapter 7G
Estuaries and Deltas

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Keynote points

- Human populations, fisheries, shipping, engineering activities, including river upstream dams and recreation/tourism exert pressures on the resources and health of estuaries and deltas.
- Interactions between multiple stressors on estuary and delta habitats are not fully understood.
- A key gap remains in identifying measurable indices of ecosystem health and human well-being across diverse estuarine and deltaic systems.

1. Introduction

Estuaries and deltas, where major rivers meet the sea, are highly productive systems supporting diverse biota that are structured by temporally variable gradients in salinity, nutrients and other factors. This variability reflects both natural (e.g. precipitation, tides) and anthropogenic (e.g. development, contaminant loading) drivers. While they are often heavily populated and perturbed systems in their natural state, estuaries and deltas typically maintain biodiversity within a variety of ecosystems, many of which are the subject of other Chapters in the present Assessment, such as mangroves (Chapter 7J), salt marshes (Chapter 7K), seagrass meadows (Chapter 7I), sand and mud substrates (Chapter 7A), and an often extensive intertidal zone (Chapter 7C). The mouths of rivers are locations where freshwater mixes with the ocean, thus are the receiving bodies for land-derived nutrients, sediments and pollutants (Chapters 10–13), and often host invasive species, particularly from ballast water (Chapter 25). Estuaries and deltas are valuable for their intrinsic biota and the commercial and subsistence fisheries they support (Chapter 15), and the tourism and recreation activities they attract (Chapter 24). Their total economic value was estimated at over 6.1 trillion United States dollars in 2014, as outlined in the First World Ocean Assessment (WOA I) (United Nations, 2017).

Economically important, urbanized and industrialized, most estuaries and deltas have been transformed by human interventions. They are increasingly affected by the impacts of global change, including sea level rise, changes in precipitation and related natural hazards such as cyclones and storm surges (Renaud and others, 2013). Most megacities are coastal, with the attendant heavy industry, urbanization and recreation activities that can harm such areas (Todd and others, 2019). WOA I attempted a preliminary global, integrated assessment of the condition of estuaries and deltas. Based on limited data, few waterbodies were qualitatively assessed to be in very good condition, whereas the condition of 62 per cent of them was considered poor or very poor, and the quality of most was in decline.

The present Chapter updates WOA I and emphasizes the fact that estuaries and deltas provide unique habitats for many organisms, both of marine and coastal origins, as well as recreation, food provisioning and water sources for humans. These environments are affected by short-term, event-driven disturbances such as storms and longer-term trends such as climate change

(Doney and others, 2012; Harris and others, 2018), which are often interconnected (e.g. storms which result in nuisance flooding that is exacerbated by sea level rise). Advances have been made in observing systems, such as satellites, global observing networks and buoys, designed to capture rapid changes in environmental conditions. However, the capacity to monitor, model or interpret these observations is still inadequately developed for optimal management of estuary and delta environments.

2. Documented changes in the state of estuaries and deltas

2.1. Environmental changes (between 2010 and 2020)

2.1.1. Water and sediments

There has generally been a continuing decline in delivery of both water and sediments by rivers as a result of anthropogenic activities in catchments across the world, such as changing land management practices and construction of dams (Li and others, 2018; Day and others, 2019; Dunn and others, 2019); however, melting of terrestrial ice and permafrost may also increase freshwater inputs to high-latitude estuaries (Chapter 3). Reduced sediment input accelerates the loss of coastal wetlands due to erosion and affects soft-sediment deposit and suspension feeders, which is augmented by sand extraction (Anthony and others, 2015); whereas high levels of sedimentation can shade primary producers such as seagrasses and smother benthic organisms. Urbanization increases peak flow and decreases base flow into estuaries, resulting in potentially harmful variations in salinity and threatening intertidal ecosystems (Freeman and others, 2019).

2.1.2. Eutrophication

Nutrient loading (largely nitrogen and phosphorous) remains a serious problem in estuaries, due to their proximity to large cities and ever-increasing agriculture, silviculture and aquaculture (Pesce and others, 2018; Todd and others, 2019), along with domestic waste water, fertilizers and animal wastes which result in bottom water hypoxia (Yasuhara and others, 2017; Breitburg and others, 2018a, 2018b). Eutrophication can also lead to blooms of cyanobacteria, dinoflagellates, and sometimes of macroalgae (Teichberg and others, 2010), including harmful algal blooms. The situation is stabilized or partly recovering in developed countries (e.g. Chesapeake Bay, United States of America; Osaka Bay, Japan) due to improvements in sanitation and reduced nutrient loading (Lefcheck and others, 2018) but is rapidly getting worse along the coasts of populous Asian countries, due to poor sanitation, elevated nutrient flux and further population growth (Boesch, 2019). Bottom water hypoxia can lead to fish kills that affect local economies (Breitburg and others, 2018a, 2018b; Yasuhara and others, 2019).

2.1.3. Global change

Global change is already affecting estuaries and deltas. Poleward extension of fish and crustacean ranges has been observed (Hallett and others, 2017; Pecl and others, 2017). More frequent storms and weather extremes affect salinity and sedimentation (Prandle and Lane, 2015; Day and Rybczyk, 2019). Future increased temperatures could lead to localized extinctions as well as intensify microbial pathogen concentrations and public health risks (Robins and others, 2016). Higher sea levels will be compounded with riverine flooding, resulting in more extensive inundation of coastal areas (Moftakhari and others, 2015, 2017; Kumbier and others, 2018; Ikeuchi and others, 2017; Nichols and others, 2019). The annual cost of flooding of coastal cities could be in the order of 60 to 63 billion United States dollars by 2050 (Hallegatte and others, 2013), and it is projected that 1.46 percent of the world population will be displaced by permanent flooding by 2200 (Desmet and others, 2018). Flooding may lead to significant habitat losses due to coastal squeeze, where fixed infrastructure impedes landward migration of intertidal ecosystems (Doody, 2013; Phan and others, 2015).

2.1.4. Delta subsidence

Anthropogenic stresses are having a particular impact on deltas due to high rates of relative sea level rise and socioeconomic vulnerability (Tessler and others, 2015 Hiatt and others, 2019). The impact of rising sea levels is exacerbated by subsidence in large deltas (megadeltas) due to human activities, primarily groundwater extraction (Syvitski and others, 2009; Erban and others, 2014; Auerbach and others, 2015; Brown and Nicholls, 2015; Schmidt, 2015; Minderhoud and others, 2017, 2019; Wright and Wu, 2019). Protective infrastructure may be able to limit present-day threats; however, engineering solutions may not be feasible in densely-populated or lower-income countries (Tessler and others, 2016).

2.1.5. Invasive species

Many estuaries and deltas host large ports and have serious invasive species issues related to ballast water discharge from ships (Astudillo and others, 2014; Shalovenkov, 2019). They can directly influence the decline of resources and the health of estuaries and deltas, affecting their ecology and balance, posing significant dangers to the biodiversity of both systems. The rate of invasive species introduction has been accelerating, reflecting increased shipping (Seebens and others, 2017). Overall, numbers of invasive species are approximately 30 times greater in high-income countries than in low-income countries, due to trade and population, and the capacity to detect such invasions (Seebens and others, 2018). Observed rate of introductions has been getting slower in European seas, including the Mediterranean (Korpinen and others, 2019).

2.1.6. Degradation and restoration of ecosystem services

Estuaries and deltas provide essential provisioning, regulating, supporting and cultural ecosystem services (REF Ecosystem Services Chapter). The systems provide recreation through activities such as boating, swimming, wildlife watching and fishing (Whitfield, 2017). Some organisms perform important roles as foundational members and create, modify and maintain habitats. Oysters, for example, form reefs that construct habitat, reduce erosion and improve water quality. However, in degraded estuaries, oysters are affected by overfishing, sediment loads and disease, as well as increased ocean acidity (Janis and others, 2016; Day and Rybczyk, 2019). Loss of seagrasses, salt marshes and mangroves, and water quality degradation (Reynolds and others, 2016; Schmidt and others, 2017), lead to a decline in juvenile fish diversity and abundance (Whitfield, 2017). Restoration efforts have been successful in relatively few estuaries but can also be integrated into natural shoreline protection strategies (Bilkovic and others 2016; Ducrotoy and others, 2019).

2.2. Factors associated with the changes: drivers, pressures, impacts and response

Many human activities have degraded the health and productivity of estuaries and deltas, ranging from direct impacts such as development destroying habitat to longer-term indirect impacts via global climate changes (Cavallaro and others, 2018). There are increasing pressures from human habitation, intrusive coastal infrastructure, recreation, fisheries (finfish and shellfish), land reclamation and filling of wetlands (Sengupta and others, 2018), resulting in environmental degradation and loss of sensitive marine organisms (Buttigieg and others, 2018). These have led to increasing efforts to protect ecosystems for their intrinsic worth, for human health, and for sustainable resource use. Additional human pressures, such as development of large container ports with deep-draft shipping, also modify estuarine environments through dredging and the use of dredge spoils to nourish beaches or modify shorelines (IPCC, 2019).

It is still difficult to predict the intensity and scale of drivers and pressures, or response of biological communities and ecosystem functions. Temperature, rainfall anomalies and sea level rise cause substantial impacts on estuarine ecosystems over both the short and the long term (Elliott and Whitfield, 2011; McLeod and others, 2011; Condie and others, 2012; Turra and others, 2013; Bernardino and others, 2015, 2016). Both long term averages and shorter term exceedances of physiological ranges will affect metabolism, growth and reproduction of estuarine biota, which, combined with local eutrophication, may lead to acute oxygen depletion and mass mortality of organisms (Gillanders and others, 2011). On longer time scales, ecological pressures from fishing activities are affecting fish populations and ecosystems (Muniz and others, 2019). For example, in Río de la Plata, fishing effort for artisanal and industrial fleets has remained constant or even declined slightly, but catches for the two most important species have reached their lowest values in the last 35 years (Gianelli and Defeo 2017; García-Alonso and others, 2019).

Although many human activities have negative consequences for the health of individual estuaries and deltas, recent efforts have been made to restore the productivity of coastal waters, notably by developing nutrient and pollutant management plans, restoring ecosystems/keystone species and protecting estuaries and deltas in parks and marine protected areas (Lefcheck and others, 2018; Boesch, 2019). In some places, such as the United States of America and Hong Kong, China,, oyster reefs have been restored, so they now protect shorelines and filter the water column (Morris and others, 2019). In other locations, seagrasses, salt marshes or mangroves may serve similar purposes in protecting the coastline from storms and sea level rise as well as providing critical habitat for juvenile fish and other biota.

3. Consequences of the changes on human communities, economies and well-being

Estuaries and deltas have a socioeconomic and cultural importance by providing goods and services, including fishery resources and ecosystem processes. There are local traditional communities that rely on these resources for their livelihood, including subsistence fishing and income from tourist activities. Therefore, to understand changes and manage their impacts on estuaries and deltas, an integrated consideration of environmental, biological, cultural, economic and anthropologic issues is essential.

The World Health Organization has advocated the One Health concept to integrate the human-animal-ecosystem interface because it has been recognized that changes in any of these elements will affect the others. Declines in estuarine health due to increased pollutants or invasive species can pose a direct threat to human health. The level of impact on humans depends on socio-ecological factors. Whereas urban populations may suffer from reduced storm protection and from consumption of contaminated fish, local indigenous communities may also suffer loss of cultural values, sanitation issues and social inequality. Indigenous populations and local coastal communities have developed traditional knowledge and skills relevant to conservation, sustainable use and management of estuaries (Breitburg and others, 2018b). Changes in estuaries due to urbanization can lead to loss of identity and cultural practices in communities that depend on these resources for their livelihoods.

There is now greater awareness regarding ecosystem services in estuaries and conflicts that have arisen due to changes in these ecosystems (Nicholls and others, 2018). Science can be a powerful tool at the interface with policy to inform decision-making at local, regional and national levels and to integrate it into global goals, such as the 2030 Agenda for Sustainable Development[106] (Dietz, 2013; Howarth and Painter, 2016). Integration of public participation, including of indigenous peoples and local communities, with scientific analyses can lead to effective scientific communication, socialization and decision-making. Improved communication among stakeholders can enable an effective transfer of knowledge and adaptive management, for example, with social scientists helping to build trust among actors (Fischhoff, 2013). Citizen science, an innovative area with benefits for environmental and social sciences, could link traditional and scientific knowledge and help to develop integrated management in estuaries by including indigenous populations and local communities in scientific studies. Ecosystem complexity and connections with other habitats make co-management and collaboration between governments and local communities essential for maintaining coastal biodiversity and ecosystem functions (Teixeira and others, 2013; Brondizio and others, 2016).

Changes in estuarine and deltaic environments, ecosystem services and socioeconomic dynamics have implications for achieving the Sustainable Development Goals (SDGs) of the 2030 Agenda. For example, socioecological conflicts in estuaries, mainly related to indigenous peoples and local communities, are linked to aims related to poverty (SDG 1), gender equality (SDG 5), sanitation (SDG 6), resilient cities (SDG 11) and safe seafood resources (SDG 14). If it is possible to reverse impacts through positive actions consistent with the 2030 Agenda, a series of benefits for society could be achieved in a short time. The conservation of estuaries, their biodiversity and cultural diversity, is particularly relevant to SDG 14.2 and 14.5 related to promoting protection and conservation of coastal resources (Neumann and others, 2017), and could also provide other services, such as increased ecotourism. Promotion of human engagement with nature strengthens efforts towards nature conservation in associated ecosystems. To achieve this goal, it is valuable to adopt an innovative approach, together with decision makers and society, to supporting adaptive management, conservation and sustainable use of estuaries that will benefit human well-being for future generations (Szabo and others, 2015).

4. Key region-specific changes and consequences

Estuaries and deltas are widespread around the world, but there is no global inventory and this category encompasses a range of geomorphological types. It was suggested in WOA I that

[106] See United Nations General Assembly resolution 70/1.

there may be about 4,500 estuaries in total. However, a gridded global digital elevation model gives a more recent estimate of more than 53,000 estuaries (McSweeney and others, 2017). There are an estimated 1,200 intermittently closed partially saline lakes and lagoons, particularly along the swell-dominated coasts of southern Africa and eastern Australia. These will experience a different set of responses to climate change than estuaries that are continually open to the sea, including altered opening regimes, increased flooding and saltwater intrusion into surface water and groundwater (Carrasco and others, 2016). Adopting a similar approach, a recent study has suggested that there are around 11,000 deltas worldwide; of these 25% have undergone a net land gain over recent decades as a consequence of deforestation-induced increases in fluvial sediment supply, whereas damming has resulted in reduced sediment and land loss in ~1,000 delta systems (Nienhuis and others, 2020).

WOA I provided a preliminary assessment of the condition of selected estuaries, with a classification by continent. There remains inadequate data to improve on that evaluation or to consider estuaries and deltas following the region-specific framework of the present Assessment. Several recent compilations do provide data for several regions that were previously poorly documented. For example, little information was available on Arctic estuaries, which are likely to become increasingly important as global warming opens up access to shipping in these regions (Kosyan, 2017). Regional compilations have provided more information for the southern hemisphere, including a focus on estuaries on the east coast of Africa and the western Indian Ocean (Diop and others, 2016), and a review of Brazilian estuaries (Lana and Bernardino, 2018). Relatively little information was previously available on the numerous estuaries and deltas along the 18,000 km coastline of China which contains many large megacities, such as Shanghai and Guangzhou, that are very susceptible to coastal hazards from sea level rise and storm surges (Yin and others, 2012; Kuang and others, 2014; Chen and others, 2018). These urbanized megadeltas are home to millions of people, and often contain rich biodiversity which faces threats including from eutrophication, pollution, coastal modification and invasive species (Lai and others, 2016).

5. Outlook

Based on trends over recent decades, coastal zone populations will increase, with ongoing urbanization focused on estuaries and deltas. These human stresses will be the principal pressures that continue to impact the biodiversity and habitat health of these coastal ecosystems. Climate change will exacerbate the stresses - increased frequency of storms appears likely and sea level rise is anticipated to accelerate, particularly in the case of large deltas that are experiencing subsidence. Good governance has the potential to maintain or improve the status of ecosystems, although protection of low-lying metropolises will require upgraded engineering infrastructure.

Estuarine and deltaic sustainability can be considered in terms of functional processes using geomorphic, ecological or economic perspectives (Mahoney and Bishop, 2018). Changes can lead to either enhanced or diminished sustainability, but most changes have been detrimental (Day and others, 2016). Ecosystem consequences that can be anticipated include alteration of food webs due to loss of keystone, top predator or ecosystem engineer species; habitat losses due to sea level rise and land reclamation; as well as poleward migration of marine species to adapt to climate change. A reduction in wetlands through coastal squeeze and aquaculture activities is already apparent in many estuaries and deltas. Further increases in invasive species can be expected, although considerable progress has been made in identifying, setting priorities and eradicating invasive organisms.

It is more difficult to predict the socioeconomic consequences of continued change in the system. However, greater population pressures and expanding urbanization around estuaries and on deltas are likely to mean more dredging to maintain navigability, the silting of channels, and erosion of shorelines as well as losses of wetlands, with reduced access to recreation, fisheries and clean water. The desire to protect extensive residential, industrial and agricultural areas against storm surges and sea level rise will require huge investments in engineering solutions and the risks of failure of such infrastructure appear catastrophic. In many areas, it will become necessary eventually to move inland. Even where the pressures of expanding human populations can be contained, significant investments will be required to restore critical habitats. Assessments of changing ecosystem services and implications for human well-being would benefit from improved monitoring and investment in scientific research. Integrated coastal planning is necessary for sustainable use and to extend conservation beyond protected areas, which may require broader strategies for funding, for example from public sources, and multisectoral cooperation. Coastal management may need to include new standards for building and construction, eco-labelling, innovative economic instruments for financing conservation and payments for ecosystem services, such as blue carbon sequestration.

6. Key remaining knowledge and capacity-building gaps

There are major challenges in managing land use in estuaries and deltas so that future generations can also enjoy the aesthetic, cultural and sustaining services that they provide (Elliott and others, 2019). Existing models lack sufficient spatial and temporal resolution to simulate future extreme events (Haigh and others, 2016; Robins and others, 2018), including compound flooding from both fluvial and oceanic sources. Such floods result in environmental degradation, including wetland erosion and eutrophication, and expose people to harmful water-borne pathogens (Yin and others, 2018). Relatively little is known about the long-term effects of rapid human interventions in deltas. Characterization of socioeconomic tipping points will have to be improved to avoid unacceptable changes. More evidence is needed to target coastal wetland conservation in those areas where it can be most beneficial or might alleviate the need for engineered protection works (Van Coppenolle and others, 2018; Van Coppenolle and Temmerman, 2019). Future resilience of megadeltas, and megacities within them, will depend on advances in resource and emergency strategies and investments in flood protection through engineered and living shorelines. Modelling, engineering and natural sciences need to be integrated with social science and public outreach (Bonebrake and others, 2018). Innovative technologies and nature-based solutions are already helping to reduce vulnerability from coastal hazards but collaborative science is needed so that people living in estuarine and deltaic locations have environmental information, reliable short-term and long-term predictions and appropriate observations to validate models, thus improving data-driven approaches to coastal resilience (Nichols and others, 2019).

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Chapter 7I
Seagrass Meadows

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Keynote points

- Seagrass meadows continue to decline at alarming rates, particularly where they are in conflict with human activities.
- Marine ecosystems are reconfigured as a result of climate-driven changes in species distributions, with some species projected to be functionally extinct by 2100.
- Blue carbon sequestration will play a role in mitigating climate change impacts.
- Successful long-term solutions around conservation and restoration will require a balance between social, economic and environmental drivers.

1. Introduction

Seagrasses are marine flowering plants that inhabit coastal waters. The most recent global assessment found that seagrasses were disappearing at a rate of 110 km^2 yr^{-1} since 1980, and that 29 per cent of the known areal extent disappeared since seagrass areas were initially recorded in 1879 (Waycott and others, 2009). These rates of decline accelerated from a median of 0.9% yr^{-1} before 1940 to 7% yr^{-1} since 1990. Seagrass loss rates are comparable to those reported for mangroves, coral reefs and tropical rainforests, placing seagrass meadows among the most threatened ecosystems on earth. Declining seagrass health is the result of shifting environmental conditions due largely to coastal development, land reclamation, deforestation, seaweed and fish farming, overfishing and garbage dumping. Four main factors are responsible for seagrass degradation: poor water quality; physical disturbance; the degradation of food webs; and grazing.

Globally, seagrass meadows have continued to decline since the First World Ocean Assessment (WOA I) (United Nations, 2017; see also Unsworth and others, 2019). Effective management strategies need to be implemented to reverse this loss and enhance their fundamental role in coastal ocean habitats. A multifaceted and interdisciplinary perspective is needed to achieve global conservation of seagrass meadows (Table 1). Long-term solutions will require a balance of social, economic and environmental drivers. Good examples are emerging, particularly where Traditional owners and custodians are being consulted and enabled to resume broader custodial roles. Indigenous people have a culture that relates to the land and sea in a holistic way that also includes connections to powerful and significant places (National Oceans Office, 2002).

Table 1. Challenges and possible solutions to reduce seagrass meadow loss (Unsworth and others, 2019).

Challenge 1: Societal recognition of seagrass importance. Explain what seagrasses are and their importance in coastal systems.

Challenge 2: Up-to-date information on status and condition. Explain and record the status and condition of many seagrass meadows.

Challenge 3: Identify threatening activities at local scales to target management actions accordingly. Suggest what threatening local activities can be managed

Challenge 4: Balancing the needs of people and planet. Expand understanding of interactions between the socioeconomic and ecological elements of seagrass systems.

Challenge 5: Generating scientific research to support conservation actions. Use current high-profile seagrass research (food security and blue carbon) to engage wider research fields.

Challenge 6: Conservation action in an era of climate change. Use indicators that provide an early warning of seagrass climate change impacts. Innovate restoration techniques.

Global environmental changes have an effect on communities living near the sea or that are dependent on maritime resources. Loss and decline of meadows means that fishing grounds and nursery areas will continue to be lost and coastal areas will become less desirable to tourism, for erosion control, for marine education, for fisheries nursery areas, for clean water and clarity. The impacts of storm surges, erosion and inundation are being experienced in coastal communities around the globe. The science is clear that the protection and restoration of natural habitats can be a cost-effective complement to built infrastructure approaches for protecting communities (Ruckelshaus and others, 2016). Climate-driven range shifts in seagrasses (and many benthic marine species) are difficult to quantify due to a lack of long-term data sets across complete species distributions. Range shifting with changing climates may lead to often unforeseen and dramatic consequences which may ultimately lead to biodiversity loss and homogenization of communities (Brustolin and others, 2019). The combination of poleward migration of habitat-modifying species as a result of climate change (H. Kirkman, pers. comm.) and fishing pressure can result in reduced ecosystem resilience (e.g. Ling and Keane, 2018).

Specific means of recovery after seagrass loss are particularly difficult to quantify. O'Brien and others (2018) demonstrated four different scenarios of degradation and recovery for seagrass ecosystems. Recovery can be rapid, once conditions improve, but seagrass absence at landscape scales may persist for many decades. They proposed a framework modelling resilience.

2. Socioeconomic consequences

Coastal development is contributing to ongoing declines of marine and estuarine ecosystems globally. The increase in tourism and industrial and urban development in coastal areas will require more careful and sustainable management. Many socioecological systems rely on healthy seagrass meadows to support a multitude of important ecosystem services (Cullen-Unsworth et al., 2014). The loss of seagrass in one small area or estuary may seem negligible but, for an entire coastline, the cumulative effect of many disturbances is important to consider.

Seagrass grows in many estuarine areas, where development and ports often require extensive maintenance dredging. The physical removal of seagrass during dredging is minor, because the removal is only in the dredged channel, compared to the damage caused by shading from the dredge plume and the smothering of plants by sediment disturbed during the dredging. Risk mitigation opportunities have been assessed to reduce impact to seagrass (Wu and others, 2018). Proposed development and other anthropogenic changes should be treated using the precautionary approach. Offsets or new plantings should be considered when seagrass meadows are to be lost or decline in area. However, offsets should not be encouraged as they are rarely equal to lost habitat. Furthermore, in many areas there may not be suitable areas to replant seagrass, leading to a net loss of seagrass meadow, and restoration success is not guaranteed.

Economic valuations of seagrass systems have not been widespread (Constanza and others 2014) with most estimates undervaluing them. More derivative-based models linking ecological structure and function to all associated economic services will be essential for accurate estimations of their dollar value (Dewsbury and others, 2016).

Coral reefs (Chapter 7E of the present Assessment) and mangroves (Chapter 7J) act synergistically in the production of economically useful food, through connectivity of nutrients and biota. Marine health is also enhanced by seagrass associated with natural filtering of pathogens. Lamb and others (2017) found that, when seagrass meadows were present, there was a 50 per cent reduction in the relative abundance of potential bacterial pathogens of humans and marine organisms. Field surveys of more than 8,000 reef-building corals located adjacent to seagrass meadows showed twofold reductions in disease levels compared to corals at paired sites without adjacent seagrass meadows.

Seagrass meadows have an important cultural service - they play an unusual central role in preserving valuable submerged archaeological and historical heritage (Krause-Jensen and others, 2016). The age and growth rates of rhizomes can be determined by establishing the age of amphora, a realm of seagrass service that has been greatly overlooked.

3. Region-specific changes

There is a lack of data for many areas, or data are not being collected globally.
The lack of data is best illustrated with examples from islands throughout East Asian seas. Southeast Asia and Australia have the highest diversity of seagrass species and habitat types but basic information on seagrass habitats is still lacking. Fortes and others (2018) pointed out that the known distribution, extent, species diversity, research and knowledge gaps of seagrasses in Southeast Asia are not well presented. They estimated this biogeographic region of the Marine Ecoregions of the World as ~36,700 km^2 but this is likely an underestimate as some ecoregions were not well represented and updated information was lacking.

The shallow East Asian island biotopes have extensive coral reefs, bordered with seagrass and mangroves. The major seagrass meadows in India grow along the southeast coast in the Gulf of Mannar between India and Sri Lanka and Palk Bay and in the lagoons of islands of Lakshadweep in the Arabian Sea to Andaman and Nicobar in the Bay of Bengal. The Gulf is a national marine park, covers an approximate area of 10,500 sq. km. and comprises 21 islands located parallel to the coastline. Management, mapping and monitoring are required to sustain this valuable nursery area for the local people who are using the meadows as their fishing grounds. Awareness of the uses of seagrass and about this important ecosystem should be created among the local people. Seagrasses are a key part of Indonesia’s support for the world’s second largest production of seafood. The perilous state of its seagrasses will compromise their resilience to climate change and result in loss of their high ecosystem service value (Unsworth and others, 2018).

Eight hundred islands off Myeik, Myanmar, have coral reef and mangrove with seagrass on their lee side. These valuable seagrass habitats have not been mapped but are probably overexploited for fish and crustaceans (H. Kirkman, pers. comm.).

Arias-Ortiz and others (2018) reported damage to 36 per cent of seagrass meadows in Shark Bay, Western Australia, following a marine heatwave in 2010-2011. Shark Bay has the largest carbon stock reported for a seagrass ecosystem, containing up to 1.3 per cent of the total carbon stored within the top metre of seagrass sediments worldwide.

Large areas of seagrass along the Queensland coast of eastern Australia have been lost as a result of cyclones and associated increased turbidity and pollutant run-off. These cyclones are predicted to become more intense with climate change. *Posidonia oceanica* meadows in the Mediterranean are also declining at alarming rates due to climate change and human activities (Telesca and others, 2015).
There is also a lack of coordination concerning what types of data are collected and how the data are collected. This results in datasets that cannot be analyzed between regions.
Globally, not just in Australia and Asia, there are losses of seagrass. In the Caribbean there are large changes with the invasion of *Halophila stipulacea*. Also, the Mediterranean is experiencing tropicalization (Hyndes and others, 2016).

4. Outlook

General awareness of seagrass and the important ecosystem services offered are improving globally. Conceptual and mathematical models are helping managers to reach a science-based management process for seagrass. Seagrass services can be organized into a DPSIR (drivers, pressures, state, impact and response) framework, which has been adopted in some seagrass ecosystems around the world, including the European Union, for State of Environment Reporting (Kelble and others, 2013). The goal of such a framework is to reach a science-based consensus in defining characteristics and fundamental regulating processes of seagrass ecosystems that is sustainable and capable of providing diverse ecosystem services. It is necessary to consider regional, social, political, cultural, economic and public health factors, in a research and management context, with ecological variables, to achieve this goal.

Monitoring, evaluation and reporting to managers are essential in determining whether management action, recovery or deterioration is taking place. A tiered monitoring approach that is designed by both scientists and managers should be introduced wherever management of seagrass is required. Neckles and others (2012) provided a conceptual model to do this. Zimmerman and others (2015) used a mathematical model to predict the effects of ocean warming, acidification, and water quality on the Chesapeake region eelgrass.

5. Key remaining knowledge gaps

An assessment of gaps in seagrass knowledge for Australian seagrasses identified deficiencies covering many research fields including taxonomy and systematics, physiology, population biology, sediment biogeochemistry and microbiology, ecosystem function, faunal habitats, threats, rehabilitation and restoration, mapping and monitoring and management tools (York and others, 2017). These knowledge gaps apply globally and need to be addressed if these systems are to be effectively managed and capable of providing diverse ecosystem services. It is necessary to consider regional, social, political, cultural, economic and public health factors, in a research and management context, with ecological variables, to achieve these goals. Research programs that address interactions of multiple stressors simultaneously should be considered. these are really complex systems and it is really difficult to accurately predict all the "down-stream" impacts of multiple stressor experiments Progress in filling the knowledge gaps will rely on technological advances in remote sensing, genomics, microsensors, computer modelling and statistical analyses. Interdisciplinary approaches will continue to broaden our understanding of the complex interactions among seagrasses and their environment. Ecosystem services for seagrass meadows, with a focus on fisheries, and the damaging activities that threaten their existence should encourage expert opinion to elicit potential solutions to prevent further loss. It is expected that restoration will be increasingly necessary to mitigate seagrass disturbance (Statton and others, 2018).

There are also knowledge gaps in socio-cultural-economic themed research, despite growing awareness of the importance of seagrass-human relationships. Suggested solutions include more education in communities that do not understand the usefulness of seagrass, for example, on active removal of seagrass in the Maldives and other tourist destinations[107] and excessive build-up of beach wrack as a result of building inappropriate beach infrastructure such as groynes or marinas.

6. Key remaining capacity-building gaps

Mapping

The detail and definition of seagrass distribution maps need to be improved. The most current global map of seagrass distribution was made nearly ten years ago. It should be updated with further mapping of seagrass meadows and associated habitats. Mapping of seagrass meadows is being carried out in many different parts of the world, yet there are no centres for incorporating products into a global map and collecting metadata. The map would serve to indicate updated loss or gain in seagrass areas, seagrass diversity and the need for further information. Satellite technologies are also improving and being used more frequently in seagrass mapping efforts.

Seagrass meadows are dynamic systems which add to the challenges of mapping and monitoring, especially as some species are ephemeral (colonizing or opportunistic) and/or prone to storm damage. Duffy and others (2019) envisioned an ecosystem map with a marine biodiversity observation network linking biodiversity to environmental geophysical variables.

Now we do not have a repository where we can share information and track changes at ecologically relevant scales. This would require that seagrass ecologists and managers define a suite of metrics and sampling methodologies that result in data that can be shared and compared across regions. Detailed mapping can be done with drones or multi-sideband sonar. Hamana and Komatsu (2016) used a narrow multibeam sonar system to detect seagrass meadows and estimate their relative abundance. Gumusay and others (2019) reviewed the literature on seagrass mapping, monitoring and detection applications using acoustic systems.

[107] Available at http://www.maldivesresilientreefs.com/campaigns/seagrass/.

High quality aerial imagery databases can monitor local to regional change in seagrass cover (e.g. Evans and others, 2018). However, none of these options are species specific, so ground truthing is required. Water clarity is also an issue after storms, during dredging, land-based pollution and eutrophication. Eutrophication occurs when high levels of nutrients enter the sea and are taken up by macroalgae, these grow on seagrass leaves and can smother the seagrass and prevent photosynthesis.

Carbon sequestration

Seagrass ecosystems have better capacity to sequester carbon than terrestrial ecosystems MacCreadie and others, 2019. Together with tidal marshes, and mangroves, seagrasses contribute ~50 per cent of total carbon sequestered in marine sediments (blue carbon), despite occupying only 0.2 per cent of the ocean area, and with organic carbon sequestration rates exceeding those of terrestrial forests, per unit area, by 1–2 orders of magnitude. Seagrass meadows sequester carbon dioxide through photosynthesis and store large quantities in the plants but, more importantly, in the sediment below (Mcleod and others, 2011; Fourqurean and others, 2012). Sediment sequestration is highly variable across species. Large seagrasses, such as *Posidonia* spp., form mattes several metres deep that can remain stored for millennia (Mateo and others 1997). Mazarrasa and others (2015) estimated the mean particulate inorganic carbon (PIC) accumulation rate in seagrass sediments as 126.3 ± 31.05 g PIC m^{-2} yr^{-1}. Based on the global extent of seagrass meadows (177,000 to 600,000 km^2), these ecosystems globally store between 11 and 39 Pg of PIC in the top metre of sediment and accumulate between 22 and 75 Tg PIC yr^{-1}. Unfortunately, these dense meadows are under continuing threat (see earlier estimates of global loss rate) and with this loss comes the emission of the CO_2 stored within the meadows. For example, ongoing loss of seagrass in Australia has been estimated to emit up to 3 million tonnes of CO_2 to the atmosphere every year, and increasing annual CO_2 emissions from land use change by 12–21 per cent (Serrano and others 2019). Furthermore, damage and decline in seagrass meadows will lower the level of ongoing sequestration of carbon dioxide.

The potential exists to avoid the emissions of greenhouse gases, and enhance their sequestration, through conservation and restoration of vegetated coastal ecosystems. This has been recognized by many nations as a means of achieving their policy objectives in relation to greenhouse gas abatement (Martin and others, 2016). However, for this potential to be realized, a number of key information gaps and policy issues need to be addressed. A recent overview by Macreadie and others (2019) provides a comprehensive road map for the coming decades on future research in blue carbon science.

Climate Change

Changing climate and ocean conditions are impacting valuable marine resources and communities that depend on them. Climate change has an effect on seagrass meadows over a number of themes. Extreme climatic events were predicted to become more frequent and severe (IPCC, 2013), causing rapid ecosystem change, the scale of which is likely to be greater than that caused by a gradually changing climate (Wernberg and others, 2016). Climate vulnerability assessments with respect to key marine spp. and habitats should be conducted to better understand which species are most vulnerable and may require innovative management strategies. (See https://www.fisheries.noaa.gov/national/climate/climate-vulnerability-assessments) Ecosystem reconfigurations arising from climate-driven changes in species distributions are expected to have profound ecological, social, and economic implications, as temperate ecosystems are replaced by tropical species (Vergés and others, 2014). Range shifts can also be caused by invasive species which alter the ecosystem services delivered. For example the Caribbean has become infested with *H. stipulacea* over the last 20 years and research shows dramatic shifts in fish assemblages as well as impact to turtles. Non *native Z. japonica* has also altered the estuarine communities that it colonizes (:Vergs and others, 2014) It is predicted that climate change may lead to fewer but more intensive storms in many places (Gera and others, 2014) and hence local disturbance and loss of water quality for weeks to months at a time. This will disturb seagrass meadows and cause management and policy changes. Although loss of seagrass calcareous epiphytes may be beneficial through acidity (refer to Chap. 5 for details on ocean acidification), under high carbon dioxide, nutrients and temperature, Alsterberg and others (2013) predict that non-calcareous epiphytes such as filamentous algae and diatoms will increase. This may lead to shifts in the epiphyte community structure from less palatable calcareous to more palatable algae. Additionally, decreased production of grazing deterrent phenolics by seagrasses under high carbon dioxide (Arnold and others, 2012) may increase the palatability of seagrass leaves for a number of invertebrate and fish grazers. Positive effects of increased carbon dioxide on seagrass physiology may help to ameliorate negative effects of other environmental stressors known to impact seagrass growth and survival, although the combination of increasing temperatures and reduced light will likely negate increases in available carbon (Collier and others, 2018).

There may also be range shifting of some species, i.e. replacement of temperate seagrass species with tropical species and changes in community structure. There is limited evidence for range shifting in seagrasses at present, although current projections for warming range edges, such as the Mediterranean and Shark Bay, Australia, suggest functional extinction of their large temperate seagrass species by 2100 with accelerating warming (Hyndes and others, 2016).

Restoration and recovery

Conservation and mitigation of disturbance regimes have typically been the first line of defence (and cheaper), but ecological restoration or intervention is becoming increasingly necessary in a rapidly changing environment and potentially a more effective management strategy where seagrass habitat has already been lost or is heavily degraded (Statton and others, 2018). Restoration success has improved but is still really really limited. Restoration and recovery of seagrass meadows is an important activity, with some significant advances in restoration successes being documented (e.g. Orth and others, 2017; Wendländer and others, 2019). Although restoration will be increasingly necessary to mitigate seagrass disturbance it is critical to emphasize that restoration is never 100% successful, and is often far less than 50% successful. Further, restored and degraded beds rarely provide the same level of ecosystem services Thus, relying on restoration will lead to continued global loss of seagrasses. However, the protection of existing meadows from further wholesale destruction will be a far better use of resources.

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Chapter 7J
Mangroves

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Keynote points

- Despite their ecological and socioeconomic importance, especially as carbon sinks, mangrove forest areas have been decreasing annually.
- Although deforestation continues in most areas, afforestation and the replanting of mangroves on all continents have partially decreased the speed of mangrove area loss from ~2 per cent per year to < 0.4 per cent per year.
- Increasing human population density and unplanned development in the coastal zone are the main threats to mangrove forests.
- Global climatic change, such as rising sea levels and temperature, is causing expansion of mangroves towards the poles and landward into salt marsh in some areas.
- Local actions and international agreements, have helped mangrove conservation, but bureaucracy and the lack of commitment on the part of local, state, and national government, and local communities have limited their success.

1. Introduction

Mangroves occur in 118 countries and occupy estuaries and shores in tropical and subtropical regions (Tomlinson, 2016), and are home to a recorded 73 species and hybrids, with the highest diversity and the largest extent in Asia (Spalding, 2010). Mangroves are key ecosystems at the interface between sea and land, and influence, and are affected by, most human activities (United Nations, 2017b; Feller and others, 2017).

Mangrove forests, although they account for only 0.7 per cent of the total tropical forests in the world, provide seafood, firewood, and timber, and services such as shoreline protection, carbon export/sequestration, and bioremediation of wastes, as noted in Chapter 48 of the First World Ocean Assessment (WOA I) (United Nations, 2017a). Besides goods and services, mangroves also provide cultural ecosystem services that are an important part of the lives, livelihood, and cultural identity of the local communities and primary stakeholders (Mitra, 2020a).

Despite their ecological, socioeconomic, and cultural value, mangroves are among the most threatened ecosystems on the planet. Mangroves are being destroyed at rates three to five times greater than average rates of forest loss, and over a quarter of original mangrove cover has already disappeared (UNEP, 2014; Richards and Friess, 2016). Although mangroves continue to be degraded and have been lost from specific regions, conservation initiatives, rehabilitation efforts, natural regeneration, and climate change-related expansion have resulted in gains in other places (Feller and others, 2017).

Considerable changes in the extent of mangrove area have been observed in response to natural environmental drivers in areas far from direct human impacts (Rioja-Nieto and others, 2017; Lucas and others, 2018). Worldwide mangrove cover had been estimated at 181,000 km^2 by Spalding and others (1997), but this value was revised downward to 137,760 km^2 by Giri and others (2011), which was similar to estimates provided by the Global Mangrove Watch (Bunting and others, 2018).

Increasing human population density in the coastal zone is the main threat to mangrove forests, specifically unplanned urban development, aquaculture, conversion to agricultural use such as rice farming, and overexploitation of timber (United Nations, 2017b; Ferreira and Lacerda, 2016; Thomas and others, 2018; Romañach and others, 2018). However, globally, mangrove loss rates dropped by an order of magnitude of ~2 per cent to < 0.4 per cent per year between the late twentieth and early twenty-first century (Friess and others, 2019b, 2020).

In the past decade, the quality and availability of global-scale mangrove distribution data have been improving (Hamilton and Casey, 2016; Ferreira and Lacerda, 2016; Thomas and others, 2018; Romañach and others, 2018; Saintilan and others, 2019; Lucas and others, 2020) and many national initiatives (public and/or public-private partnerships) have been launched to try to better understand mangrove changes (Schaffer-Novelli and others, 2016). One of the main approaches to mangrove assessment has been use of satellite data (Giri and others, 2011; Li and others, 2013; Duncan and others, 2017; Jayakumar, 2019; Lymburner and others, 2019).

Recently, the advent of cloud computing platforms, such as Google Earth Engine (Gorelick and others, 2017) and Amazon Web Services (Chen and others, 2017; Lucas and others, 2020), which combine several pentabytes of orbital and geospatial data with statistical analysis resources, have enabled more reliable estimates of local, regional, and global mangrove cover and changes over successive years (Diniz and others, 2019).

The present Chapter builds upon the observations in Chapter 48 of WOA I. Mangroves are marine plants, which are covered in Chapter 6G of the present Assessment, are often found in estuaries and deltas, which are discussed in Chapter 7G, and share many characteristics with salt marshes (Chapter 7K) and seagrass meadows (Chapter 7I).

2. Documented change in state of mangroves (between 2010 and 2020)

The area occupied by mangroves has been declining annually worldwide. The status of mangrove forests varies by country and region (Romañach and others, 2018). Although deforestation continues in most areas, afforestation and the replanting of mangroves in some areas have decreased the speed of forest losses (Li and others, 2013; Cavanaugh and others, 2014; Ferreira and Lacerda, 2016; Friess and others, 2019b; 2020). A 12 per cent increase in mangrove area was recorded by Almahasheer and others (2016) in the Red Sea. In New Zealand mangroves have expanded rapidly during the past 50-80 years, as a result of accelerated estuarine infilling and vertical accretion of tidal flats (Horstman and others, 2018).

Mangrove loss due to human activities has been recorded across all regions where mangroves occur. The main driver of mangrove destruction is increased human density in the coastal zone (Branoff, 2017; Saifullah, 2017; Romañach and others, 2018). The most frequent anthropogenic activity in mangroves has been the conversion of mangrove areas to aquaculture or agricultural use (Thomas and others, 2018; see Chapter 16 of the present Assessment). Other factors associated with mangrove losses are logging, erosion and sedimentation (see Chapter 13), salt production (Feller and others, 2017), and cattle grazing (Ferreira and Lacerda, 2016; Thomas and others, 2018). In some countries mangrove destruction

Mangroves are unpopular in some communities because they are often perceived as 'taking over' or 'low value' (e.g., mangroves 'spoil' a beautiful sandy beach by making it muddy). Destruction of mangroves in New Zealand is mostly by local communities (with or without consent) due to lack of community/agency awareness of mangrove values, or fear of loss of support by elected members of government/community.

Global climate changes have also been associated with changes in mangrove distribution (see Chapters 4 and 9 of the present Assessment), such as poleward and landward expansion (Cavanaugh and others, 2014; Saintilan and others, 2019), except where hard infrastructure prevents retreat, resulting in wetland contraction, called coastal squeeze (Leo and others, 2019). Extreme climate events can increase mangrove mortality caused by extreme droughts (Sippo and others, 2018), and an increase in carbon dioxide, and nitrogen enrichment can augment the growth of other vegetation, thus suppressing growth of mangrove seedlings (McKee and Rooth, 2008; Zhang and others, 2012).

Extensive dieback of mangroves was recorded along 1,000 km of the southern Gulf of Carpentaria in Australia in 2015 and 2016. This is a sparsely inhabited area, and the event appears to have been associated with an unusually lengthy period of severe drought conditions, unprecedented high temperatures, and a temporary drop in sea level (Duke and others, 2017). Similar dieback also occurred at that time in other parts of northern Australia (Asbridge and others, 2019).

2.1. Impacts of the change on/interactions with other components of the marine system

2.1.1. Carbon sequestration in mangroves

Mangroves are well known for their ability to accumulate high amounts of carbon (Tomlinson, 2016; Donato and others, 2011, 2012; Estrada and Soares, 2017; Kauffman and others, 2018; Lagomasino and others, 2019) and, in fact, sequester four times more carbon than rainforests (Rovai and others, 2018; Twilley and others, 2018). Recent assessments have suggested that global mangrove biomass ranges from 1.91 to 2.83 Pg (Hutchison and others, 2014a; Tang and others, 2018), whereas global mangrove carbon stock has been estimated at 5.03 Pg by Simard and others (2018). At the global scale, the average aboveground biomass density has been estimated at between 1.46 Mg per square kilometre (Tang and others, 2018). Rovai and others (2018) predicted a total global budget of 2.26 Pg carbon in mangrove soils. Globally, mangroves stored 4.19 Pg of carbon in 2012, with Indonesia, Brazil, Malaysia, and Papua New Guinea accounting for more than 50 per cent of the global stock (Hamilton and Friess, 2018).

2.1.2. Loss of biodiversity

Mangroves are among the most productive ecosystems in the world (Alongi, 2008) and produce large amounts of litter (fallen leaves, branches and other debris) that are used by a diverse fauna. Mangrove trees also offer hard substrate (aerial roots, trunks, branches, pneumatophores, and leaves) for a myriad of invertebrates and plants (Hogarth, 2015; Rosa Filho and others, 2018). In addition to the substantial contribution to marine ecosystems, mangroves are used by more than 400 terrestrial mammal, amphibian, and reptile species around the world (Rog and others, 2016), and provide them with a refuge from anthropogenic disturbance. Global decline in mangrove habitats has impacted negatively on biodiversity, with cascading effects on the natural ecosystem functioning of other associated estuarine and coastal ecosystems, and thus affecting at least three critical ecosystem services: the number of viable fisheries (33 per cent decline); the provision of nursery habitats (69 per cent decline); and detoxification services provided by wetlands (63 per cent decline) (Worm and others 2006; Barbier and others, 2011).

2.1.3. Impacts on populations of invertebrates and fishes in adjacent habitats

High primary productivity and habitat complexity in mangrove forests make them important areas for larvae and juveniles of invertebrates, and fishes (Saenger and others, 2012; Lee and others, 2014). Some species of crustaceans and fishes that live in rivers and offshore ocean water or coral reefs need mangroves for breeding and/or juvenile growth (Sheaves and others, 2012; Bertini and others, 2014; Hogarth, 2015). In addition to ecological importance, some mangrove crustaceans and molluscs have high economic and cultural value in several countries (Abdullah et al., 2016; Beitl, 2018; Figueira et al., 2020). In recent years, considerable progress has been made in the bioprospecting of mangrove-derived microbes (Mitra, 2020b), and the microphytobenthic primary production in the mangrove forests (Kwon and others, 2020).

2.1.4. Reduction in coastal protection

Mangroves can directly attenuate waves, thus enhancing drag against wave energy, because of the density of their trunks and root systems, such as pneumatophores or prop roots. Their complex root systems, which are important for sediment stabilization, also reduce both storm surges and tsunami wave impacts further inland (Marois and Mitch, 2015; Sheng and Zou, 2017). The protective mangrove fringe in Vietnam has been lost in recent decades, initially through defoliation by herbicides, and subsequently by conversion to aquaculture and coastal development (Phan, de Vries and Stive, 2015; Thinh and Hens, 2017; Truong and others, 2017; Fagherazzi and others, 2017; Veettil and others, 2019).

2.1.5. Displacement of salt marshes

The poleward and landward expansion of mangroves as a result of increasing temperatures and sea level rise has been at the expense of salt marshes and has already been recorded in several regions (Record and others, 2013; Saintilan and others, 2014; 2019; Kelleway and others, 2016; Hickey and others, 2017; Feller and others, 2017; Osland and others, 2017). Mangroves continue to expand into adjacent salt marsh areas where the two wetland types occur together (Yando and others, 2016; Pérez and others, 2017). This can result in greater carbon storage, and also changes in associated fauna (Smee and others, 2017), although in some cases it remains unclear whether this is a consequence of climate change or other anthropogenic causes (Boon, 2017).

3. Consequences of the changes on human communities, economies and well-being

Mangroves play an important cultural and socioeconomic role for communities around the tropics (Walters and others, 2008; UNEP, 2014). Ecosystem services provided globally by mangroves and tidal marshes have been valued at 19.4 United States dollars per square kilometre per year (Costanza and others, 2014). The consequences of mangrove forest destruction are related mainly but not exclusively to the loss of biodiversity and related effects on fisheries, and to reduced coastal protection, which impacts coastal constructions and adjacent marine habitats (Bertini and others, 2014; Hogarth, 2015; Sheng and Zou, 2017).

A reduction in mangrove area will lead to decrease in the primary production of mangrove and the biodiversity and abundance of associated fauna, and, consequently, will affect coastal and offshore fisheries. A global meta-analysis designed to formally and statistically test the relationship between mangroves and fisheries, showed that mangroves have a strong effect on fisheries in a variety of mangrove settings around the world (Carrasquilla-Henau and Juanes, 2017). It has been estimated that each mangrove hectare produces 0.2 – 12,305 United States dollars of fishes and 17.5 – 3,412 United States dollars of mixed species (Hutchinson and others, 2014b).

Studies have shown that mangroves are able to protect coastal areas and habitats (coral reefs and/or seagrass meadows) against waves, cyclones, tsunamis, and flooding (Marois and Mitsch, 2015; Sheng and Zou, 2017; Veettil and others, 2019). The fragmentation of mangroves will significantly reduce their role in coastal protection (Lee and others, 2019). A fully established mangrove fringe can reduce wave energy by 20 per cent per 100 metres of mangrove (Mazda and others, 2006). Mangroves also have a significant effect on the extent of inundation and damages caused by coastal flooding. It has been estimated that if all mangroves were lost, 18 million more people would be flooded every year on average, an increase of almost 40 per cent, and the annual damages to property would increase by 16 per cent and 82 billion United States dollars (Reguero and others, 2018).

The effects of predicted expansion of mangroves are still poorly understood. Modelling studies have demonstrated that climate change will cause range shifts in species, expanding the geographical distribution of some species, and enhancing the number of species present in some areas (Record and others, 2013; Saintilan and others, 2014; 2019; Simard and others, 2018). These changes may cause an increase in primary production and the habitat complexity of coastal areas presently mangrove free, which in turn may favour local biodiversity, fishing activities, and coastal protection (Lee and others, 2014).

Local studies of mangrove carbon sequestration often contrast with regional models of likely response (Hayes and others, 2017; Sasmito and others, 2020). Over short timescales, the greater contribution that expanding mangroves make to blue carbon storage may be difficult to detect (Rogers and others, 2019a) but, over longer timescales, sea level rise appears to augment below-ground carbon sequestration in coastal wetlands (Krauss and others, 2017; Rogers and others, 2019b). The management of mangrove areas is not always based on research outcomes; site managers often identify anthropogenic disturbances as key threats while, in contrast, the bulk of research focuses on natural disturbances, including climate change and sea level rise (Canty and others, 2018). Although sea level rise has been regarded as a major threat to mangrove shorelines (Lovelock and others, 2015), it is becoming apparent that rapid sedimentation beneath mangroves can, at least partially, offset these impacts (Woodroffe and others, 2016; Schuerch and others, 2018).

Mangroves, with their strong link to coastal fisheries, are particularly relevant to Sustainable Development Goal (SDG) 14 (Life Below Water).[108] Mangroves may also contribute to the achievement of other Goals, including SDG 2 (Zero Hunger) and SDG 13 (Climate Action) through provisioning ecosystem services such as fisheries, and carbon sequestration and storage (Friess and others, 2019b). Several other Goals should benefit local communities that derive direct and indirect livelihoods from mangroves, including SDG 1 (No Poverty), SDG 11 (Sustainable Cities and Communities) and SDG 15 (Life on Land).

4. Key region-specific changes and consequences

As pointed out in previous sections, the area occupied by mangroves has been decreasing globally, which has serious economic, ecological, and social implications (Lee and others, 2014; Branoff, 2017; Saifullah, 2017; Romañach and others, 2018; Mitra, 2020a). Mangroves have been threatened worldwide, in large part due to anthropogenic impacts, including logging, conversion to aquaculture and agricultural use, urbanization, pollution, and climate change (UNEP, 2014; Ward and others, 2016; Thomas and others, 2018).

In the seminal work that warned of "a world without mangroves", Duke and others (2007) predicted that, if nothing was done, the world could be deprived of mangroves and their ecosystem services by the end of the twenty-first century. However, since then, huge efforts, including local action and international agreements, have been put into mangrove rehabilitation and creation (Feller and others, 2017). Globally, between the late twentieth and early twenty-first century, mangrove loss rates have dropped by an order of magnitude of ~2 per cent to <0.4 per cent per year (Friess and others, 2019b). These results have prompted speculation that mangrove conservation just may have shifted from a pessimistic to a more optimistic trajectory (Friess and others, 2020).

Despite recent mangrove conservation successes, it is still too soon to assume that there is a general decrease in mangrove loss, as such progress in not evenly distributed worldwide. In some countries in South-East Asia, mangroves have been destroyed at rates of between 0.70 and 0.41 per cent per year (Friess and others, 2019b). New deforestation frontiers are also beginning to emerge in regions that have not previously experienced significant mangrove loss, particularly in South-East Asia and West Africa (Friess and others, 2020).

Various national and international conservation policy instruments have helped to reduce the loss of or increase mangrove area in some countries (Ferreira and Lacerda, 2016; Friess and others, 2019a, 2020). In Brazil, for example, 75 per cent of mangroves have remained unchanged for two decades or more; 10 per cent have remained stable for between one and two decades; and 15 per cent have remained stable for ten or fewer years (Diniz and others, 2019). An analysis of multi-temporal Landsat data (1972, 2000 and 2013) showed that the area covered by mangroves in the Red Sea has increased by about 0.29 per cent per year, with a total expansion of 12 per cent over the 41 years from 1972 to 2013 (Almahasheer and others, 2016).

In some regions, in addition to human-assisted rehabilitation, natural increases of mangroves have been recorded. More than 15 per cent of mangroves deforested in South-East Asia between 2000 and 2012 reverted to mangrove area (Friess and others, 2019b), in part through natural colonization. Episodic mangrove colonization has also increased mangrove area on the

[108] See United Nations General Assembly resolution 70/1.

north coast of South America (Gardel and others, 2011) and on the Firth of Thames coast in New Zealand (Swales and others, 2015).

Climate change, mainly increases in temperature, decreases in low temperature and freeze events, and changes in water availability (Saintilan and others, 2014; Cavanaugh and others, 2014), has favoured the poleward expansion of mangroves, as already recorded in the United States of America (Atlantic coast), Peru, Mexico (Pacific coast), China, Australia, and South Africa (Saintilan and others, 2014, 2019; Cavanaugh and others, 2014; Osland and others, 2017; Smee and others, 2017). Although increases in mangrove area at their range limit are unlikely to drastically increase global mangrove area, they can make substantial contributions to mangrove extent in these locations (Friess and others, 2019a).

5. Outlook

Based on the information presently available, it is possible to predict the continued reduction of mangrove area, in view of the continuity of human actions that have led to the loss of mangrove forests in most areas around the world (Friess and others, 2020). In areas where reforestation initiatives and management and conservation measures are being implemented, a reduction in the speed of mangrove destruction may occur.

As a result of further mangrove destruction, a reduction in productivity in estuarine areas is expected, which will have a cascading effect. Accordingly, loss of biodiversity is likely to continue in coastal areas, including mangroves, seagrass meadows, and coral reefs. In view of the role mangroves play as nursery grounds for invertebrates and fishes, a reduction in fish stocks in coastal and even offshore fisheries can be expected (El-Regal and Ibrahim, 2014). This may lead to further increases in economic losses resulting from the absence of mangroves.

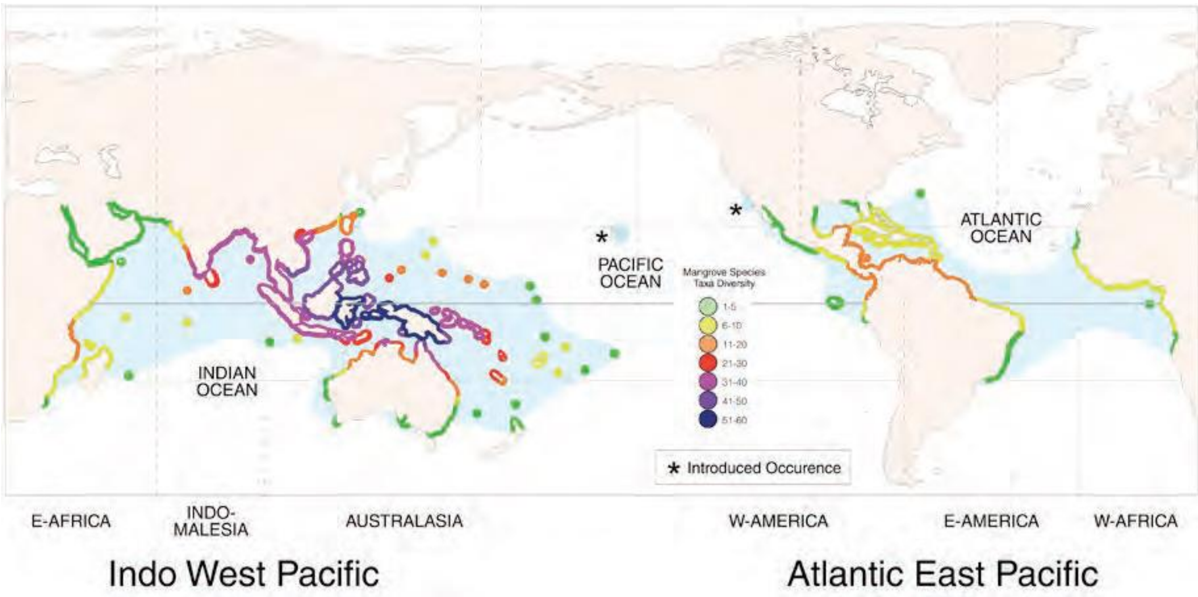
The total or partial (loss of structure) destruction of mangroves, whether it be natural, for example following subsidence related to earthquakes (Albert and others, 2017), or anthropogenic, will diminish their coastal protection function. Loss of mangroves is likely to increase damage resulting from cyclones (Cavanaugh and others, 2014; Asbridge and others, 2018; Montgomery and others, 2019; Zhang and others, 2020), tsunamis and floods (Asbridge and others, 2016; Menéndez and others, 2020), thus raising costs for reconstruction and maintenance of coastal facilities, as well as increasing the threat to the lives of populations living near the coast.

6. Key remaining knowledge and capacity-building gaps

A range of new methodologies have been developed to study mangrove forests, including use of terrestrial, airborne, and satellite sensors (Kamal and Phinn, 2011; Koedsin and Vaiphasa, 2013; Zhu and others, 2015; Mackenzie and others, 2016; Olagoke and others, 2016; Duncan and others, 2017; Owers and others, 2018; Warfield and Leon, 2019; Wang and others, 2020). However, there remains a lack of reliable surveys on the status of mangroves at global and regional scales, and of standardization of methods for assessing mangroves. Although there has been a recent drive to address these knowledge gaps, especially in South America and South-East Asia, further research is required to enable researchers to determine the processes that influence both vulnerability and resilience to climate change (Ward and others, 2016). This gap is even more prominent in the poorest developing countries.

There are few detailed studies (distinct taxonomic groups, large temporal and spatial scales) demonstrating the interconnectivity, and mechanisms involved, between mangrove forests and the biodiversity of adjacent coastal environments (Saunders and others, 2014). Further research needs to be done on the sustainability and interrelationships of these habitats (marshes, seagrass, and coral reefs) and between mangroves and fisheries (coastal and oceanic) in order to increase the capabilities of coastal managers and to empower local communities in more effective conservation of these resources.

A gap remains with respect to capacity-building in the restoration of degraded mangroves and abandoned aquaculture ponds within former mangrove areas (Paul and others, 2017; Worthington and Spalding, 2018; van Bijsterveldt and others, 2020). Restoration of mangrove areas needs to be more widely adopted; in some cases, restoration efforts have owed more to economic incentives than conservation objectives (Aheto and others, 2016). Wider rehabilitation could lead to much healthier mangroves throughout the tropics.



The global distribution of mangroves (blue shading) showing diversity as numbers of specific taxa (species and nominal hybrids). (UNEP, 2014**).**

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Chapter 7K
Salt Marshes

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Keynote points

- Salt marshes, as defined in the First World Ocean Assessment (WOA I) (United Nations, 2017) are intertidal, coastal systems that are regularly flooded with salt or brackish water and dominated by salt-tolerant plants adapted to regular or occasional immersion by tides.
- Salt marshes serve as nesting, nursery and feeding grounds for numerous species of birds, fish, molluscs and crustaceans, including some commercially important species.
- Salt marshes are very effective "blue carbon" sinks, as they sequester carbon dioxide (CO_2) due to their high levels of primary production and low rates of decomposition, but they can also produce greenhouse gas emissions.
- Salt marsh area is declining globally despite protective measures in many areas.
- Sea level rise poses the biggest threat, and marshes must either increase their elevation to keep pace with rising seas or move inland. Since WOA I, this has changed from a future issue to a present reality. If coastal development or restrictions on sediment supply and delivery make either adjustment difficult, salt marshes are converted to mudflats and open water.
- Many marshes worldwide are already showing signs of waterlogging, which indicates that they are not elevating rapidly enough.
- Some evidence suggests that marshes with certain invasive plants may be better able to keep up with sea level rise.

1. Introduction

Salt marshes occur on every continent except Antarctica (Mcowen and others, 2017; Figure 1). They are more prevalent in temperate climates than in subtropical and tropical regions where mangrove forests occur. Salt marshes are highly productive ecosystems that provide critical ecosystem services such as coastal protection, erosion prevention, nutrient cycling, habitat for various fish and bird species and carbon sequestration (Barbier and others, 2011).

Figure 1. Global distribution of salt marshes (using ArcGIS Version 10.4, with data from Mcowen and others, 2017).

The global extent of salt marshes is shrinking, primarily due to sea level rise, and more frequent and intense coastal storms (Cahoon, 2006; Duarte and others, 2013). Global historical coverage has declined 25–50 per cent since 1980 (Crooks and others, 2011; Duarte and others, 2008) due to many factors, including filling for agriculture and development. Many remaining wetland ecosystems are showing evidence of eutrophication, waterlogging and disease (Short and others, 2016). Impacts on salt marshes will largely depend on the relative rate of sea level rise and other factors, such as those mentioned above (Adam, 2002). Salt marshes are losing ground to mangroves at the low latitude end of their distribution due to warming (Saintilan and others, 2014). The expansion of mangroves into salt marshes may result in increased storm protection and carbon storage (Doughty and others, 2016) but may also result in a decline in habitat for some animals.

Salt marshes are key coastal ecosystems that provide ecosystem services to humans, such as food, protection from storm surge and waves, by attenuating flooding (due to wave height reduction), protection from pollutants, and “blue carbon” sequestration. According to Macreadie and others (2013), the global carbon burial in salt marshes (up to 87.2 ± 9.6 Tg C yr^{-1}, based on preliminary assessments) appears to exceed that of tropical rain forests (53 Tg C yr^{-1}), although they occupy a much smaller area (0.1–2 per cent). However, greenhouse gas emissions can also be significant at some sites, particularly in wetlands with lower salinities and high organic matter content (Bartlett and other 1987; Poffenbarger and others 2011; Huertas and others, 2019). As concerns methane emissions, bubble-mediated fluxes (ebbulition) can also play an important role in shallow areas with significant tidal variations, promoting gas release in low tide, due to the lower water pressure (Duarte and others, 2007; Baulch and others, 2011; Call and others, 2015; Huertas and others, 2019). . These atmospheric fluxes of greenhouse gases, mainly methane (CH_4) and nitrous oxide (N_2O), have greater global warming potential than CO_2 (Duarte and others, 2007; Roughan and others, 2018). Anthropogenic stressors, including nutrient pollution and salinity changes, may increase these greenhouse gas fluxes in the future (Chmura and others, 2016; Yin and others, 2015; Roughan and others, 2018; Doroski and others, 2019).

WOA I stated that the key threats to salt marshes are land reclamation, coastal development, dredging, sea level rise (SLR) and eutrophication, and SLR was identified as the largest climate-related threat to salt marshes. According to US National Oceanic and Atmospheric Administration (NOAA, 2019) the global mean water level in the ocean rose by 3.6 millimeters per year from 2006–2015, which was 2.5 times the average rate per year throughout most of the twentieth century. By the end of the century, global mean sea level is likely to rise at least 0.3 meters above 2000 levels, even if greenhouse gas emissions follow a relatively low pathway in coming decades. Nicholls and others (1999) predict that SLR of one meter will eliminate 46 per cent of the world’s coastal wetlands. SLR varies regionally and differences from the predicted mean global range could exceed ±30 per cent (Oppenheimer and others, in press). Salt marshes may be able to migrate inland or increase their elevation in response to SLR, but this varies with local conditions including subsidence in some areas. Subsidence is due primarily to groundwater withdrawal but also to glacial isostatic readjustment, soil compaction, and settling of fill (Eggleston and others 2013). Managed realignment may be precluded by coastal development which limits inland area available for relocation. This “coastal squeeze” occurs when rising sea levels advance the low-water mark, while high water is fixed by shoreline structures (Doody, 2004). A meta-analysis by Kirwan and others (2016) indicated that marshes are generally building at rates similar to or exceeding historical sea level rise, and that process-based models predict survival under a wide range of future sea level scenarios. They argue that marsh vulnerability tends to be overstated because assessment methods often fail to consider feedback processes that accelerate soil building with sea level rise, and the potential for marshes to migrate inland, a phenomenon affirmed by a recent global analysis by Rogers and others (2019). These enhanced accretion rates are accompanied by enhanced rates of carbon burial, suggesting a potential negative feedback on future climate change (McTigue et al., 2019). Sea level rise may may also enhance rates of carbon burial. Scheider and others (2018) found that historical marsh loss in Chesapeake Bay US, was compensated for by conversion of upland to marshes. Schuerch and others (2018) stressed the importance of upland space ("accommodation space") for marsh migration, which requires the absence of human built infrastructure. If coastal squeeze were not an issue, marsh migration inland would be much easier in most places but could be restricted by steep slopes.

Since WOA I, the loss of marshes to rising sea levels has become an issue for the present, rather than the future. The use of recent surface elevation tables (SET) and assessment tools to examine the rate of marsh accretion as compared to SLR provide data documenting this loss. Remote sensing techniques such as LIDAR and aerial photography also show the extent of losses and can be used periodically to monitor rates of change.

2. Description of the environmental changes (between 2010 and 2020)

At the global level, the extent of salt marshes is shrinking. However, as the rate of SLR is not identical at all sites, there are regional differences. Crosby and others (2016) synthesized available data and found that the rate of local SLR outpaced salt marsh accretion rates in many sites in Europe and the United States, indicating that under even the most optimistic Intergovernmental Panel on Climate Change (IPCC) emissions scenario, 60 per cent of the marshes studied will accrete less than the rate of SLR by 2100. The observed worldwide increase in storm surges over the past few years affects the water level and salinity in tidal salt marshes which, in turn, may affect greenhouse gas emissions (CO_2, CH_4 and N_2O) from these sites (Capooci and others, 2019).

While SLR is the major driver of wetland loss, eutrophication can also contribute (Deegan and others, 2012). Eutrophication increases above-ground biomass, decreases root biomass and increases microbial decomposition, resulting in plant instability, which causes creek-bank collapse, with areas of marsh converted to unvegetated mud (see also Chapter 10 of the present Assessment). Overfishing of some fish species has led to increased populations of herbivorous marsh crabs (*Sesarma reticulatum*) whose consumption of marsh grasses has caused marsh die-back in some areas (Bertness and others, 2014) (see also Chapter 15). The death of rhizomes, from waterlogging and drought, is responsible for marsh die-back in other areas (Elmer and others, 2013). Marshes with inadequate sediment supply are most vulnerable to SLR (see Chapter 13).

The loss of coastal marshes has an impact on other components of the marine system. With reduced marshes, there is likely to be less overall productivity in associated estuarine systems.

3. Consequences of the changes on human communities, economies and well-being

Narayan and others (2017) found that tidal wetlands in New Jersey, USA, prevented flood damages amounting to 625 million United States dollars in the wake of Hurricane Sandy. They estimated a reduction of 16 per cent in annual flood losses attributable to salt marshes, with greater reductions at lower elevation. Coastal wetlands have the capacity to reduce property damage and prevent costs associated with storm surge (Rezaie and others, 2020).

With less marsh area and more intense and frequent coastal storms and extreme events, there will be less protection for human communities, and greater storm damage, and reduced resilience. Fish stocks may also decline with the reduction of habitat for juvenile and larval stages (see Chapter 15 regarding commercial fisheries), contributing to disruptions in income and food security for seafood-reliant communities.

Loss and degradation of salt marshes and the reduction of the ecosystem services and protection they provide will impact achievement of the Sustainable Development Goals (SDGs),[109] in particular SDGs 1, 2 and 8, through reduced ecosystem services and food supply, SDG 11, due to reduced protection of coastal areas to extreme events, SDG 13, through their potential to sequester blue carbon, but also of their potential for emitting greenhouse gases, and SDGs 14 and 15, due to impacts on ecosystems. Loss of tidal marshes will also have socioeconomic consequences. Reduced numbers and types of goods provided would most likely lead to reduced yield of fisheries, less sequestration of pollutants, less carbon storage and storm abatement and increased nitrogen and methane emissions to the atmosphere. Effects on human health may also result from increased pollutants in salt marsh animals used for human consumption, as well as poorer water quality if salt marshes do not remove pathogens and pollutants from wastewater.

4. Key region-specific changes and consequences

Salt marshes occupy a considerable area with variable vegetation along European coasts. Protection of much of the salt marsh area is increasing within the Natura 2000 network (European Commission, 2007). In terms of vegetation, North Atlantic salt marshes are mainly colonized by *Salicornia* spp. and other annuals, as well as *Spartina* (Bortolus and others, 2019) swards (*Spartinion maritimae*), whereas Mediterranean species higher up on the shore are usually more desiccation resistant. In general, salt marshes along the Mediterranean experience minimal tidal differences and are considered micro-tidal, whereas those on Atlantic shores generally experience significant tidal variations. In general, areas with greater tidal amplitude will have more severe effects from sea level rise (Devlin and others, 2017).

Salt marshes in South Africa include many rarely-flooded supratidal marshes that support halophytic communities (Adams and others, 2016). Due to wave action and high sediment availability, over 90 per cent of the estuaries have restricted inlets, with most closing temporarily when a sandbar forms (Cooper, 2001). Sea level rise, increased storms and wave height and changed river discharge will influence inundation patterns, salinity gradients and sediment biogeochemistry (Van Niekerk, 2018). If there is available land, salt marshes will migrate inland (Tabot and Adams, 2013; Veldkornet and others, 2015). SLR will produce more open conditions, particularly if the mouth of the estuary is sheltered from wave action and little sediment is available (Van Niekerk, 2018). However, drought and reduced freshwater inflow will result in mouth closure, flooding and die-back of salt marsh plants.

Chinese salt marshes are dominated by native *Phragmites australis* or *Spartina alterniflora*, which was introduced from England and North America (Gu and others 2018; Wan and others 2009). The areal extent of salt marshes declined by about 59% between the 1980s and 2010s, largely due to land reclamation (Gu and others 2018; Tian and others 2016). To combat this trend, China has implemented policy measures to restore and conserve salt marshes, such as establishing protected areas, ecological red lining, and strictly regulating reclamation. These management

[109] See United Nations General Assembly resolution 70/1.

strategies are recent and therefore their effectiveness is yet to be proved (Bai and others 2018).

5. Outlook

In order to persist, salt marshes must either elevate at a rate equal to SLR, which requires obtaining enough new sediment, or migrate inland, which requires undeveloped land immediately inland of the marsh and an appropriate slope. A continued loss of marshes, with concurrent loss of ecosystem services and biodiversity, is anticipated in many areas. A decrease in their spatial extent will reduce ecosystem service provision. The loss of salt marshes not only reduces their capacity to act as carbon sinks, the related degradation and disturbance also contribute to the release of carbon back into the atmosphere in the form of CO_2 (Pendleton and others, 2012) and the emission of other greenhouse gases such as N_2O and CH_4.

Peteet and others (2018) found that urban development greatly reduced inputs of mineral sediment, but organic matter allowed vertical accumulation to outpace sea level for a time. However, reduced mineral content caused structural weakness and edge failure, and they concluded that marsh survival will require mineral sediment addition. Borchert and others (2018) further showed that migration corridors are particularly important in urbanized estuaries with coastal development where there is no space for wetlands to move inland and adapt to SLR.

A meta-analysis by Davidson and others (2018) found that certain invasive plants enable biomass and carbon storage potential to increase over 100 per cent. Because plants like the invasive *Phragmites australis* grow larger and faster, the ecosystem can store more carbon, and this plant also promotes increased marsh elevation. Rooth and Stevenson (2000) found greater rates of litter production and of mineral and organic sediment trapping in *P. australis.* Therefore, this species may provide a strategy to combat sea level rise, albeit with a reduced diversity of plants in the marsh and some faunal changes. This information has not yet altered restoration policies and projects in which the plant is removed. The invasion of *Spartina alterniflora* in salt marshes in China (Zhang and others, 2004; Zuo and others, 2012) and South America (Bortolus and others, 2015) has created new vegetated areas, thus reducing the degree of wetland loss.

Since marshes are one of the most highly productive ecosystems on the planet and are home to many endangered species, their loss will have significant repercussions on overall productivity, biodiversity and ecosystem services. Significant impacts are expected from the loss of their nursery function for juvenile fish and invertebrates. Marsh loss will also affect birds as they are important breeding, foraging, overwintering and migration stop-off points (UNEP, 2019).

Indices of resilience developed for tidal salt marshes by Raposa and others (2016) suggest that Pacific marshes are likely to be more resilient than their Atlantic counterparts, largely due to differences in the percentage of vegetation currently located below mean high water. Such indices provide a way to evaluate resilience, inform management and prioritize areas of marsh restoration.

The loss of tidal marshes will also have socioeconomic consequences. Reduced numbers and types of goods provided by the habitat would most likely lead to reduced yield of fisheries, less sequestration of pollutants, less carbon storage and storm abatement and increased nitrogen and methane emissions to the atmosphere. Effects on human health may also result from increased pollutants in salt marsh animals used for human consumption, as well as poorer water quality if salt marshes do not remove pathogens and pollutants from wastewater.

6. Key remaining knowledge gaps

While there has been some study of carbon dioxide fluxes in marshes (Forbrich and Giblin, 2015; Wei and others 2020) we need to know more about greenhouse gas fluxes at the sediment-water and water-atmosphere interfaces in salt marshes. The influence of tides on methane escape from the sediment-water interface has been documented (Duarte and others, 2007; Poffenbarger and others 2011; Baulch and others, 2011; Call and others., 2015; Segarra and others, 2013; Huertas and others, 2019) but the quantification of greenhouse gas fluxes from these systems is still largely unknown. The same applies to N_2O emissions, where experimental studies have shown the influence of nutrient input (Bulseco and others, 2019) but, again, there is no sustained long-term measurement and quantification of the fluxes involved. The future role of salt marshes in the global carbon and greenhouse gas budgets is largely unknown due to the ongoing changes in their extent and hydrographic, nutrient and salinity (Poffenbarger and others, 2011) regimes.

Another gap relates to how to increase salt marsh resilience to SLR. The best techniques for leaving some *Phragmites* in place and how well this can accelerate marsh elevation are not yet known. Maintaining migration corridors for marshes to migrate inland is important in many areas and needs more investigation and political will. One possible way of increasing marsh elevation is “thin layer deposition”, that is, spraying sediments from tidal creeks onto the marsh surface (Ford and others, 1999). Additional actions may include the artificial supply of dredging materials to reach a sufficiently high accretion rate that allows the tidal flat to adapt to SLR (Mendelssohn and Kuhn, 2003). The long-term effectiveness and how often the procedures will have to be done is unknown. When marshes are eroding at the edge, “living shorelines”, in the form of oyster reefs, “reef balls,” or rocks, can be placed at the edge to prevent further erosion (Bilkovic and others, 2017). Living shorelines have enhanced the resilience of marshes to hurricanes more than either hard edges or natural marshes (Smith and others, 2016). Another approach is to create floating marshes (Streb and others, 2019). However, since these are relatively new approaches, their continued effectiveness in the face of SLR remains to be seen.

7. Key remaining capacity-building gaps

As of 2020, 985 coastal wetlands are designated Ramsar Convention sites.[110] These sites, covering nearly 75 million hectares, are recognized for their significant value to humanity and are to be managed in such a way as to maintain their ecological character and to promote wise use.[111] The number of Ramsar sites has steadily increased since the Convention entered into force in 1975. However, since global wetland extent has decreased markedly over this time, the efficacy of Ramsar policy implementations is questionable (Finlayson, 2012). According to scientists around the world, immediate action is urgently needed to transition to more sustainable practices (Ripple and others, 2017) and to reduce the loss of critical natural habitats that provide ecosystem services, such as wetlands and salt marshes (Finlayson, 2019;

[110] The Convention on Wetlands of International Importance especially as Waterfowl Habitat (United Nations, *Treaty Series*, vol. 996, No. 14583).
[111] List of sites available at https://rsis.ramsar.org.

Finlayson and others, 2019).

Some countries lack adequate expertise or resources to study and rehabilitate salt marshes. In the United States, the State of Louisiana has one of the most comprehensive coastal restoration plans in North America, the largest investment in marsh creation (17.1 billion US dollars), and will use dredged material and sediment diversion to build and maintain coastal land. Investments like these underlie the high monetary and organizational costs of major restoration projects. In many areas of the world, such intervention would be beyond the capacity of individual States. Also, some countries have the capacity but have not yet prioritized the conservation of coastal wetlands. It will take large investments of time and resources on a global level, with large-scale governmental awareness, agreements and common commitments to reverse the deleterious trends observed in salt marshes today. Together, sea level rise and human development threaten marsh extent globally. Conservation and restoration efforts must acknowledge that with accelerating SLR, marsh habitat is a moving target. Undeveloped coastal lands could convert to marsh in the next century; however, human development is the main obstacle to this.

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Chapter 7L
Continental Slopes and Submarine Canyons

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Keynote points

- Continental slopes represent 5.2 per cent of the ocean, with over one-fifth of the slope comprised of submarine canyons; they are critical transition areas between the continental shelf and the deep sea; and are important for carbon burial, and as habitats for species of ecological and economic importance.
- Strong vertical hydrographic gradients, complex geomorphic features and fluid fluxes from the sea floor make canyon and slope faunal communities highly heterogeneous.
- Hundreds of newly discovered methane seep, coral and sponge habitats enhance biodiversity and host novel interactions with surrounding sediments.
- Canyons can be hotspots of biological activity but their communities do not always differ from those on adjacent slopes which are also highly productive; slope and basin sediments can be an archive of historical information about climate effects on biodiversity.
- Naturally occurring oxygen minimum zones reveal that biodiversity is highly sensitive to oxygenation; expansion of low-oxygen zones will reduce biodiversity; projected declines in pH and food supply are likely to affect cold-water coral ecosystems.
- Due to their proximity to shore, slopes and canyons are subject to expansion of deep-water oil and gas activities, offshore energy installations, bottom fisheries and, potentially, minerals mining activities, as well as to increasing contamination, including litter and mine tailings from land.
- Exploration has accelerated discovery of new ecosystem functions and services, including novel productivity and carbon transfer mechanisms, nursery grounds, contaminant and waste transfer. However, most canyons and slope areas remain largely unexplored, with major questions about species ranges, ecological connectivity, bentho-pelagic linkages, sensitivity to climate and direct disturbance remaining unanswered, particularly in the southern hemisphere and along African and South American margins.
- Better integration of climate science, connectivity research, conservation biology, and resource management, combined with increased taxonomic and geographic expertise, will improve the distribution of knowledge, technology, analytical tools, and methodologies required to advance global understanding and promote sustainability of slope and canyon ecosystems.

1. Introduction

The continental slope represents a deepening of the sea floor out from the shelf edge (~200 m depth) to the upper limit of the continental rise, where steepness decreases. It covers a total of 19.6 million km^2, representing 5.2 per cent of the ocean (Table 1) (Harris and others, 2014). This environment was discussed briefly in the First World Ocean Assessment (WOA I) (United Nations, 2017c), in Chapter 36F, (United Nations, 2017a) as a component of deep-sea margins.

The continental slope is typically cut by steep-walled canyons (see WOA I, Chapter 51) (United Nations, 2017b), with as many as 9,477 known canyons covering nearly 4.4 million km^2 (Table 1) and many more undiscovered. The slope also encompasses other geomorphic and geochemical features such as basins, banks, scarps, seamounts and methane seeps (Figure 1). Slopes and canyons are major transition areas between shallow and deep waters, transporting (and transforming) sediments, organic matter (OM), water, organisms, contaminants and debris (Puig and others, 2014; Leduc and others, 2018). Continental slopes can be highly productive, accounting for extensive carbon burial and nutrient recycling, and are consequently therefore important in societal well-being (Levin and Sibuet, 2012).

Table 1. Cover and number of slopes and canyons in the world ocean (from Harris and others, 2014).

Feature	Total Ocean	Arctic (km^2)	Indian Ocean (km^2)	Mediterranean Sea (km^2)	North Atlantic (km^2)	North Pacific (km^2)	South Atlantic (km^2)	South Pacific (km^2)	Southern Ocean (km^2)
Area of Slope	19,606,260	913,590	4,189,700	906,590	3,436,150	4,752,240	1,591,830	3,201,000	615,170
Percent of total slope area	100.00	7.03	5.88	30.00	7.68	5.80	3.94	3.67	3.03
Total area of canyons	4,393,650	359,650	760,420	163,040	738,430	816,580	291,290	694,790	569,440
Percent of total canyon area	100	16.1	11.2	13.8	10.4	11.2	8.9	10.2	15.1
Number of canyons	9477	404	1590	817	1548	2085	453	2009	571
Percent of slope that is canyon	11.2	16.1	11.2	13.8	10.4	10.2	8.9	10.2	15.1

The strong (usually vertical) gradients in temperature, oxygenation, CO_2, hydrodynamics, particulate fluxes and sediment transport that characterize slopes and canyons shape their biological communities (Figure 1). Fluxes of particulate organic carbon (POC) and large organic falls (dead marine mammal and fish carcasses, wood and algae) from surface and shelf waters, and geochemical fluxes (methane, sulfide and hydrogen) from within the seabed create significant heterogeneity of energy sources for slope and canyon ecosystems. Additional environmental heterogeneity on slopes at scales 10 m to 100s km, derives from variation in sedimentary sources, oceanographic conditions, dynamic geologic processes and frameworks created by habitat-forming species (Kelly and others, 2010).

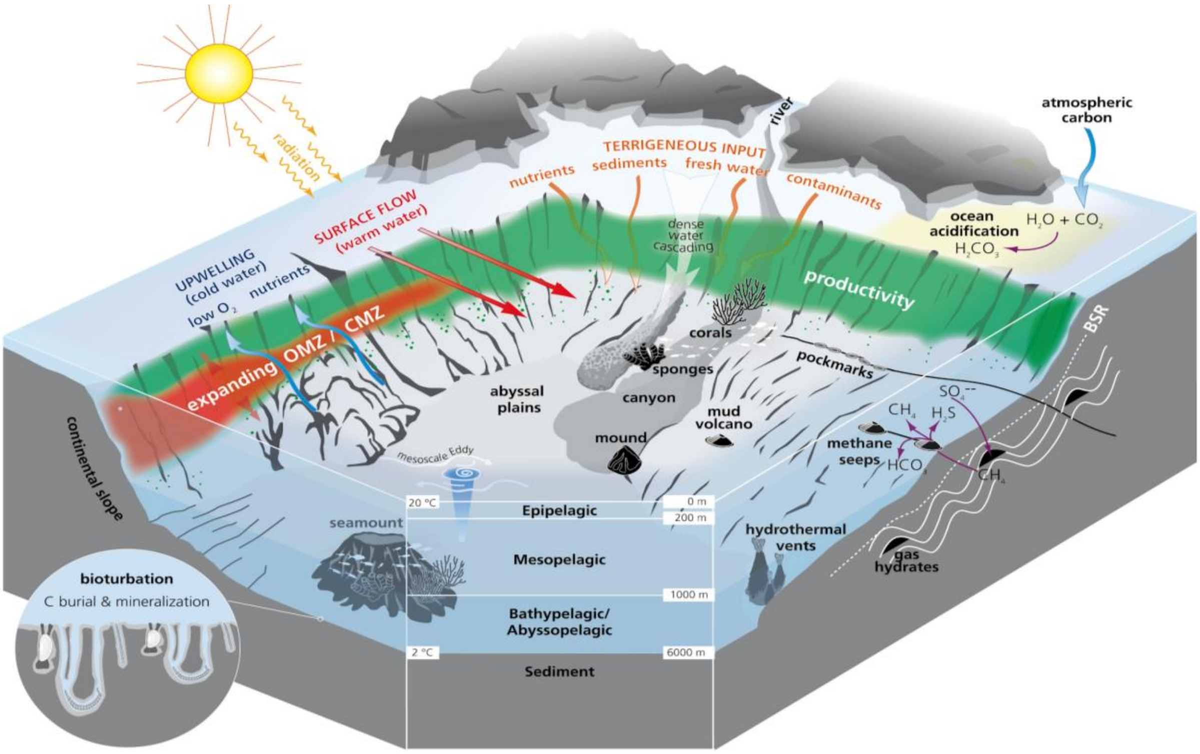

Figure 1. Schematic illustrating habitat features on continental slopes and canyons, with effects of changing conditions.

Slopes and canyons are strongly influenced by climate change, and because they are the closest deep-sea environments to human populations, they experience greater pressures from human activity than other deep-sea systems. Major anthropogenic influences include physical and biological disturbance from fishing, shipping, intentional and unintentional disposal of waste from land (e.g. mine tailings disposal, litter and contaminants), OM loading (e.g. sewage, nutrients and industrial inputs), oil and gas activities and potential minerals mining. Climate-related changes leading to warming, oxygen loss and changes in storm intensity and frequency superimpose effects on these other human disturbances.

2. Developments in understanding of slopes and canyons

2.1. Slope biodiversity

Continental margin fauna exhibits strong depth zonation, with major changes in composition at the shelf-slope transition (300–500 m depths), along the upper slope (1,000 m depth) and between 2,000 and 3,000 m (Carney, 2005). Water mass layering across continental slopes contributes to depth zonation and to high beta diversity in macrobenthos (e.g. Narayanaswamy and others, 2010), meiobenthos (Danovaro and others, 2009; Bianchelli and others, 2010), fishes (e.g. Priede and others, 2010), and megafauna (e.g. Hunter and others, 2011), and depressed alpha diversity within low-oxygen water masses (Sellanes and others, 2010; Gooday and others, 2010). Faunal diversity is generally highest at mid-slope depths (1,500–2,500 m) (Rex and Rowe, 1983; Rex and Etter, 2010, Menot and others, 2010), linked to heterogeneity of sediments, productivity and water flow (Levin and others, 2001). Faunal density maxima on slopes (e.g. crustaceans, brittle stars, sponges) routinely occur at the edges of low-oxygen water masses beneath upwelling areas, on topographic highs and in canyons (Levin, 2003; De Leo and others, 2010; Domke and others, 2017), where increased particle fluxes enhance food supply.

2.2. Changing environmental conditions on slopes and canyons

2.2.1. Oxygen minimum zones and ocean deoxygenation

Continental slopes and canyons beneath the highly productive waters in upwelling areas are exposed to naturally occurring hypoxic waters called Oxygen Minimum Zones (OMZs) at depths of 100–1,200 m throughout much of the Eastern Pacific Ocean, the Northern Indian Ocean and off the coast of West Africa (Helly and Levin, 2004). Oxygen availability on slopes is highly dynamic on seasonal, inter-annual and glacial-interglacial timescales (Levin and others, 2015a; Huang, and others, 2018, 2019). These low-oxygen waters shape the composition, diversity and functional attributes of the water column and benthos (Levin, 2003) as well as individual body size, growth, calcification and reproduction (Sato and others, 2018), and causes strong zonation of megafauna and macrofauna across OMZ oxygen gradients on slopes (Wishner and others, 1995; Levin, 2003; Gooday and others, 2009, 2010; Hunter and others, 2011; Levin and Gallo, 2019) and canyons (De Leo and others, 2012; Domke and others, 2017). Macrofaunal invertebrate diversity (Levin and Gage, 1998; Sperling and others, 2016) and fish diversity (Gallo and others, 2020) drop dramatically at oxygen concentrations below 7 μMol O_2, and patterns of fish abundance, catch and effort can vary with oxygen availability (Bertrand and others, 2011; Keller and others, 2015; Salvatteci and others, 2017; De Leo and others, 2017).

Planktonic communities within OMZs also respond strongly to oxygenation in space and time (Ekau and others, 2010; Gilly and others, 2013; Seibel and others, 2016, Tutasi and Escribano, 2020), exhibiting distinct zonation, edge effects, density maxima and sharp diversity thresholds (Wishner and others, 2008, 2013). Very small oxygen gradients can induce large changes in community composition over relatively small spatial scales (Wishner and others, 2008, 2018). However, some crustacean plankters exhibit surprising hypoxia tolerance (Seibel and others, 2016, 2018). Some copepods exhibit ontogenetic zonation, with different life stages thriving at different oxygen levels (Wishner and others, 2000; Hidalgo and others, 2005).

Many OMZs are expanding as a result of climate change (Stramma and others, 2008, 2010), (Levin, 2018). This expansion will cause anticipated loss of diversity (Sperling and others, 2016) that will coincide with reduced resilience (Levin and others, 2013), reduced bioturbation (Smith and others, 2000; Levin and others, 2009; Schimmelman and others, 2016), shifts from macrofaunal to protozoan carbon processing (Woulds and others, 2007, 2009) and altered food webs (Sperling and others, 2013; Gallo, 2018). Long-term monitoring in the Southern California Bight reveals declines in abundances of mesopelagic fish larvae (Koslow and others, 2011) and shoaling of the daytime upper and lower boundaries of the deep scattering layer (fish and large invertebrates) (Netburn and Koslow, 2015) in conjunction with shoaling hypoxia over the past 25 years. Vision of squid, octopus and crab larvae in southern California can be impaired by reduced oxygen availability (McCormick and others, 2019). In the southeast Pacific the OMZ is highly sensitive to climate variability, with high seasonal to interannual oxygen variability generated by El Nino Southern Oscillation, fluctuations in the Peru-Chile Undercurrent, the Equatorial Undercurrent and eddies, (Czeschal and others, 2015; Pizarro-Koch and others, 2018; Espinoza- Morriberón and others, 2019). Multiple proxies suggest recent oxygenation (recorded since 1999) has occurred, associated with deepening of the OMZ (Graco and others, 2017; Cardich and others., 2019).

2.2.2. Ocean acidification

Slopes and canyons are increasingly vulnerable to ocean acidification. Under RCP 8.5 (a business-as-usual climate scenario), the average pH is expected to decline by 0.14 units on slopes and 0.11 units in canyons by 2100 (Table 2) (FAO, 2019; Bindoff and others, 2019). The North Atlantic Ocean is particularly vulnerable because deep-water formation propagates surface-derived changes in carbonate chemistry to the ocean interior, and the western boundary current advects these further away; RCP 8.5 projects pH declines of 0.3 units for 14 per cent of the slope below 500 m and 15 per cent of canyons by 2100 (Gehlen and others, 2014). Taxa where low oxygen and high CO_2 occur naturally may be less vulnerable to the impacts of ocean acidification, but ocean basins differ. In the Indian Ocean, macrofaunal biodiversity is more influenced by elevated CO_2 than lowered oxygen, whereas the reverse is true in the East Pacific Ocean, where low oxygen better explains biodiversity trends (Taylor and others, 2014; Sperling and others, 2016; Sato and others, 2018). It is necessary to strengthen monitoring systems such as the Global Ocean Acidification Observing Network to evaluate changes in the seawater carbonate system on slopes and canyons.

Table 2. Projected climate changes given as mean (min, max) at the deep seafloor for continental slopes, canyons, and cold water corals mapped from 200 m to 2500 m under RCP 8.5 and 2.6 from the present to 2081-2100 using 3 earth system models (IPCC, 2019).

	Temperature (°C)	**pH**	**DO (μMol kg^{-1})**	**POC flux**
	RCP 2.6	**RCP 2.6**	**RCP 2.6**	**RCP 2.6**
Continental slopes	+0.30 (-0.44, + 2.30)	-0.06 (-0.19, -0.02)	-3.1 (-49.3, + 61.7)	-0.39 (-16.0, +3.9)
Canyons	+0.31 (-0.27, +1.76)	-0.05 (-0.13, +0.01)	-3.54 (-44.66, +29.30)	-0.33 (-10.53, + 3.53)
Cold water corals	+4.3 (-0.29, +1.85)	-0.07 (-0.13, 0.0)	-3.5 (-25.6, + 24.7)	-0.7 (-10.5, + 3.4)
	RCP 8.5	**RCP 8.5**	**RCP 8.5**	**RCP 8.5**
Continental slopes	+0.75 (-8.4, +4.4)	-0.14 (-0.02, -0.44)	-10.2 (-67.8, +53.82)	-0.66 (-33.33, + 10.3)
Canyons	+0.19 (-0.03, +1.14)	-0.11 (-0.35, +0.02)	-0.80 (-28.76, +10.07)	-0.80 (-28.76, +10.07)
Cold water corals	+0.96 (-0.42, +3.84)	-0.15 (-0.39, +0.001)	-10.6 (-59.2, + 11.1)	-1.69 (-20.1, + 4.6)

2.2.3. Food supply

Food supply to slope and canyon ecosystems derives largely from the flux of OM from ocean surface waters. Slopes and canyons are projected to experience reductions in POC flux by 2081–2100 under a range of emissions scenarios (except in the Southern and Arctic Oceans) with concomitant reductions in benthic biomass (Jones and others, 2014; Yool and others, 2017, IPCC, 2019); however, the declines in POC flux are projected to be 30–50 per cent less under RCP 2.6 than RCP 8.5 (IPCC, 2019) (Table 2). The overall contributions of chemosynthetic production to slope and canyon foodwebs has yet to be quantified, but future warming-induced dissociation of methane from buried gas hydrates (Biastoch et al. 2011) could increase this contribution.

2.3. Continental slopes as a unique paleoecology archive

The continental slope serves as a unique setting, critical to understanding historical deep-sea biodiversity dynamics. Areas experiencing very high sedimentation rates allow for the reconstruction of past oceanographic conditions and biodiversity response at decadal–centennial timescales for the past tens of thousands of years based on ostracods (Yasuhara and Cronin, 2008; Yasuhara and others, 2017; Yasuhara, 2018). For example, in the North Atlantic Ocean, abrupt temperature change has affected deep-sea benthic abundance and biodiversity based on paleorecords from the past 20,000 years (Yasuhara and others, 2008; 2014; 2016; Yasuhara and Danovaro, 2016).

2.4. Habitat heterogeneity

2.4.1. Slope-canyon comparisons

Canyons are considered a key source of heterogeneity and biodiversity. The prokaryotic and eukaryotic microbial plankton communities appear similar in Mediterranean canyon and slope settings (Celussi and others, 2018; Diociaiuti and others, 2019), although more viruses and viral infections were documented within the Bisagno Canyon than on the adjacent slope (Corinaldesi and others, 2019a,b). A strong link between mesoscale processes, and cascading of dense water in particular, can influence biogeochemistry (Chiggiato and others, 2016), microbes (Luna and others, 2016), OM deposition, microbial production and viral activity (Rastelli and others, 2018) of canyons, and may be particularly critical for supporting deep-water coral habitat (Taviani and others, 2019). Recent comparisons suggest no significant differences in biomass, density or composition in foraminifera (Di Bella and others, 2019), metazoan meiofauna (Bianchelli and others, 2010; Bianchelli and Danovaro, 2019; Carugati and others, 2019) and macrofauna (Harriague and others, 2019) between slopes and canyons of the Mediterranean Sea. In contrast, higher densities of deposit feeders (sipunculids and holothurian species) and meiofauna occur within New Zealand canyons (700–1,500 m depth) rather than on the adjacent slope (Rowden and others, 2016; Rosli and others, 2016), possibly due to differences in topographic complexity and higher OM availability (Leduc and others, 2014, 2016; Rowden and others, 2016). High heterogeneity also promotes enhanced diversity locally and regionally within the Mediterranean canyons (Gambi and others, 2019; Bianchelli and Danovaro, 2019; Carugati and others, 2019) and the Northeast Atlantic (Ingels and Vanreusel, 2013; Ingels and others, 2011), with high species turnover between canyons (Harriague and others, 2019). The presence of deep-water ahermatypic corals (scleractinian and octocorals) at bathyal depths enhances the density and influences the composition and diversity of adjacent sediment communities in the Gulf of Mexico (Demopoulos and others, 2014, 2016; Bourque and Demopoulos, 2018), with different corals associated with different infaunal communities, possibly mediated by habitat differences. The presence of deep-water corals decouples normal depth-density and diversity patterns in the region (Wei and others, 2010). Disruption of coral habitats will therefore likely affect nearby slope infauna (Bourque and Demopoulos, 2018). Overall, variability between habitats in benthic species composition and abundance by region (Bowden and others, 2016; Leduc and others,

2016) can limit our ability to draw general conclusions on the differences between canyons and slopes. Zooplankton, and particularly krill are often observed in higher abundances over the shelf break and slope (Lu and others, 2003; Lowe and others, 2018). A variety of processes can lead to such aggregations of zooplankton and fish (Genin 2004), and it appears that canyons may also contribute greatly to krill hot-spots (Santora and others, 2018), although their impact on smaller zooplankton is poorly documented.

2.4.2. Geomorphic heterogeneity

Finer-scale geomorphological aspects of slopes and canyons, including water depth, sediment type, acoustic backscatter, wave exposure and seabed rugosity can be used to identify slopes and canyons as habitats and predict benthic communities in the absence of sampling (Harris and Baker, 2020; Kenchington and others, 2014; Pierdomenico and others, 2015, 2019; Fanelli and others, 2018; Huang, Zhi and others, 2018). Geomorphic feature, shaped by erosion, sediment transport, deposition and tectonic instability (Lastras and others, 2008), as well as by biology (Marsh and others, 2018; Lo Iacono and others, 2019) can now be mapped effectively via remotely operated vehicles and autonomous underwater vehicles (Huvenne and others, 2018). Geomorphic landscape features may underpin spatial planning, marine protected area design, research planning and economic resource assessment (Harris and Baker, 2020; Ismail and others, 2015; Hogg and others, 2016), emphasizing the relevance of ongoing efforts to map the entire deep-sea floor (Mayer and others, 2018). Interaction of large bathymetric or tectonic features with bottom currents can lead to exposure or deposition of mineral hard grounds, crusts and nodules, including those formed of Fe-Mn and phosphorites (Muiños et al., 2013) as well as cause slope instability (Teixeira et al., 2019).

2.4.3. Geochemical heterogeneity

Biodiversity of slope and canyon ecosystems is influenced by seafloor seepage of methane and other hydrocarbon-rich fluids (Levin, 2005; Egger and others, 2018). Methane seeps host distinct megafaunal communities and are dominated by chemoautotrophic fauna (See Chapter 7R). The recent advent of acoustic bubble plume detection methods has revealed the ubiquitous nature and high abundance of seeps (Riedel and others, 2018; Skarke and others, 2014). Ocean warming and altered circulation, which may promote degassing, may already be increasing the number of slope seepage sites (Phrampus and Hornbach, 2012; Johnson and others, 2015). New explorations reveal seep influence on the background slope and canyon communities (Levin and others, 2016a) by providing chemosynthetic food sources (Seabrook and others, 2019; Rathburn and others 2009; Goffredi and others, in press), nursery habitat (Treude and others, 2011; Sen and others, 2019) and hardground (carbonate) as substrate (Levin and others, 2015b, 2017), and by stimulating water column production (D’souza and others, 2016).

2.5. Connectivity of populations

Fragmented populations, communities and ecosystems can remain viable or recover from disturbance through ecological connectivity, defined as the exchange of individuals, species or resources. On continental slopes and canyons, heterogeneously distributed hard substrate supports deep-water corals and sponges that are vulnerable to disturbance from fishing, and exhibit life-history characteristics not conducive to population resilience or recovery, such as longevity, slow growth and recruitment (Reed and others, 2007; Huvenne and others, 2016; Bennecke and Metaxas, 2017). Understanding spatial variation in reproductive potential

(Fountain and others, 2019) and use of hydrodynamic models to assess patterns of connectivity can assist in developing effective conservation strategies (Kool and others, 2013, 2015; Metaxas and others, 2019). Recent genetic studies have advanced understanding of dispersal distances and source-sink dynamics, which vary among cold water coral and sponge species in slope environments at the regional to geomorphic feature level (Zeng and others, 2017, 2019; Holland and others, 2019), and regional and local currents can a ct as routes or barriers for larval dispersal (Dueñas and others, 2016; Holland and others, 2019; Zeng and others, 2019).

3. Ecosystem services and benefits on slopes and in canyons

Ecosystem services provided by slopes and canyons include carbon sequestration and nutrient recycling, fisheries, biodiversity support, and waste disposal, with emerging interest in mining of non-renewable resources (Fernandez-Arcaya and others, 2017).

3.1. Fisheries

Numerous deep-water fisheries rely on outer shelves and bathyal slopes, even within some OMZs (Keller and others, 2015). Canyons serve as key feeding, spawning and recruitment grounds for economically valuable fish (D'Onghia and others, 2015) and shellfish (Sardà and others, 2009). Fish often, although not always (Ross and others, 2015), occur in greater abundance, are larger and have faster rates of maturity in canyons, as shown for sharks, conger, hake and common pandora (Sion and others, 2019). The discovery of close associations of some commercial fish and shellfish species with canyon and slope methane seeps (Sellanes and others, 2008; Bowden and others, 2013; Grupe and others, 2015; Seabrook and others, 2019) suggests possible contribution of chemosynthetic ecosystems to continental margin fisheries (Levin and others, 2016a), and led the United States Pacific Fishery Management Council to designate methane seeps as an Essential Fish Habitat for Pacific coast groundfish (Amendment 28, Pacific Coast Groundfish fishery management plan).[112]

3.2. Supporting and regulating services

Exploration of slopes and canyons accelerates ongoing discovery of new functions and services, such as the emerging role of demersal and deep-water fish on continental slopes in transferring carbon from the deep scattering layer to greater depths in the ocean (Trueman and others, 2014; Gallo, 2018; Vieira and others, 2019). Nursery support functions have been found on slopes off the coast of Costa Rica for octopus at 3,000 m and fish eggs attached within xenophyophores (giant protozoans) (Levin and Rouse, 2019), and for elasmobranch egg cases associated with methane seeps on slopes off Chile and the Mediterranean (Treude and others, 2011) and in gorgonian coral fields (Etnoyer and Warrenchuk, 2007). Physical processes within canyons contribute to the upwelling of nutrients to the shelf and the offshore transport of shelf productivity to deeper waters (Fernandez-Arcaya and others, 2017). Other canyon processes remove and bury contaminants and wastes and support biodiversity by providing refugia from fishing pressure .

[112] Available at https://www.pcouncil.org/groundfish/fishery-management-plan/

3.3. Energy

Oil and gas exploitation has expanded to > 3,000 m on continental slopes in the Gulf of Mexico, off the coasts of Angola and Brazil and elsewhere (Merrie and others, 2014). Canyons accumulate OM and are increasingly targeted for hydrocarbon extraction. For example, 24 per cent of Australian canyons occur within oil and gas leases (Fernandez-Arcaya and others, 2017). For some countries, oil and gas represent an important source of income. However, environmental impacts result from exploration, routine operations and hydrocarbon spills (Cordes and others, 2016).

Although still in early stages of development, offshore renewable energy in the form of wind infrastructure may eventually use floating structures over deep waters up to 1,000 m (Bosch and others, 2018).

3.4 Natural Products

There is growing interest in prospecting of bioactive compounds the deep sea, although as of 2016 <3% of known marine metabolites were derived from organisms in cold water (Soldatu and Baker, 2017). Bacteria and fungi from deep-sea sediments on continental slopes have been revealed to be a rich source of compounds with anti-bacterial, anti-fungal, anti-cancer and cytotoxicity properties (Skropeta and Wei, 2014). Invertebrates, particularly octocorals and demosponges - common in canyons - are also targets for biodiscovery (Winder, Pomponi and Wright, 2011; Leal and others, 2012; Blunt and others, 2013; Fernandez-Arcaya and others, 2017), as deep-sea sponge metabolites with antitumor properties (Wright and others, 2017).

4. Human impacts

A recent review identified four major categories of human impacts on canyons: bottom contact fisheries; oil and gas exploration and exploitation; contaminants, litter and mine tailings from land; and climate stressors (Fernandez-Arcaya and others, 2017). These same activities impact continental slopes, along with potential mining of minerals (e.g. sand, phosphorites) and gas hydrates.

Commercial fisheries on continental slopes and in canyons, as covered in WOA I, remain a major source of direct disturbance to deep-sea benthic communities (Pusceddu and others, 2014; Clark and others, 2016). Bottom trawling causes considerable modification of the sea floor, increasing suspended sediment concentration (Daly and others, 2018; Paradis and others, 2018a), changing sediment distribution and properties (Martín and others, 2014a; 2014b; Paradis and others, 2018b) and acting as a cumulative stressor in ecosystems under oxygen stress (De Leo and others, 2017; Levin and Gallo, 2019). Fishing activities produce litter and debris through lost lines, nets and pots (e.g. Pham and others, 2014; Maldonado and others, 2015; Quattrini and others, 2015; Vieira and others, 2015; Tubau and others, 2015; Woodall and others, 2015; Lastras and others, 2016; Cau and others, 2017; Giusti and others, 2019), which entangle or physically damage a variety of marine species, including cold water coral (Aymà and others, 2019). Invasive species can spread through attachment or associations with such debris and litter, which is a further concern.

Contaminants, sediments, detrital OM, plastics and other marine debris readily move from shelf waters into canyons (Salvadó and others, 2017, 2019; Tamburrino and others, 2019) and the deep sea (Puig and others 2014; Leduc and others, 2018). Toxic metal accumulation (e.g. cadmium) in sediments promotes microbial metal tolerance (Papale and others, 2018). Plastic litter (e.g. wrappers, bags, bottles) is ubiquitous on the seafloor on the continental slope throughout the world, particularly under well-travelled ship routes (Gerigny and others, 2019; Mecho and others, 2020). Microplastics, which transport adsorbed persistent organic pollutants, have been found in animals sampled from deep slopes and canyons (Woodall and others, 2014; Taylor and others, 2016; Courtene-Jones and others, 2017, 2019). Disposal of mine tailings produced as fine particle waste after extracting metals from ore on land can introduce metals such as arsenic, cobalt, nickel, mercury, lead and zinc and processing wastes (sodium cyanide, lime) to slopes and canyons (Reichelt-Brushett, 2012; Ramirez-Llodra and others, 2015). In 2015 alone, 7 countries piped tailings from 16 mines into the ocean (Vare and others, 2018). Tailings may cause faunal mortality through smothering or poisoning directly or through altered species interactions, as well as bioaccumulation.

The emergence of potential mining of slope areas to exploit phosphate resources (off the coasts of Namibia, South Africa, New Zealand, Mexico) and sea floor massive sulphides in seamount/pinnacle or back-arc settings represent additional threats to slope environments (Levin and others, 2016b). Gas hydrates (frozen methane) buried on continental margins attract significant exploitation interest (Chong and others, 2016). Gas hydrate exploitation and release may generate environmental impacts on continental slopes and in canyons that resemble or exceed those documented for traditional oil and gas exploitation in deep water (Cordes and others, 2016, Olsen and others, 2016). The physical instability of slopes and canyons is an important issue to consider in the management of human activities in these habitats.

5. Key remaining knowledge gaps

Most canyons and slopes remain uninvestigated, particularly in the southern hemisphere and on the margins of developing countries. Half of all relevant publications focus on only 11 canyons globally (Matos and others, 2018). Several knowledge gaps were identified in WOA I, but they still exist, for the most part. They include characterization of small-taxon biodiversity on hard substrates (such as in canyons) that are difficult to sample. Furthermore, species ranges, connectivity patterns and long-term trends in resilience and sensitivity to natural, climate and other anthropogenic disturbances remain poorly known for many slope environments around the world. The greatest climate-induced changes in the deep-sea environment are expected at bathyal depths coinciding with extensive areas that support productive fisheries or high biodiversity (Sweetman and others, 2017; see Table 2).

Current conservation of canyon and slope ecosystems generally depends on use of physiographic, geomorphological, and oceanographic proxies and species-community inventories to locate vulnerable resources for planning and management (e.g., van den Beld and others, 2017, Auster and others, 2020). Such knowledge allows use of species distribution models (e.g., for deep-sea corals and sponges as in Ross, Wort and Howell, 2019; Kinlan and others, 2020; Pearman and others, 2020, Morato and others, 2020) to inform policy about the geospatial extent of conservation targets and could guide programs such as Natura2000, which provides a mechanism to include deep-sea areas of canyons and slopes under protective management (Serrano and others, 2017; van den Beld and others, 2017).

For sustainable management of slope and canyon ecosystem and resource use, key scientific questions need to be addressed, including: the major influences on connectivity of populations and their ability to recover from disturbance; the roles of source-sink dynamics, niche specialization and species interactions in structuring diversity; whether extreme conditions (low oxygen and pH, high H_2S, low carbonate saturation states) and highly-developed mutualistic/facilitative relationships (e.g. symbioses, commensalism) change species assembly rules, adaptability or diversity-function relationships; and whether there are suitable indicator taxa or assemblages for ecosystem health that can be used as proxies (see Levin and Sibuet, 2012 supplemental appendix). Such information will inform the designation of ecologically important or vulnerable habitats, such as Ecologically or Biologically Significant Areas (CBD, 2009) and Vulnerable Marine Ecosystems (FAO, 2009). Other key management questions include: (i) sustainability of deep-sea tailings disposal and environmental impacts relative to those on land; (ii) how to incorporate hundreds of newly discovered locations of seeps into management of human activities; and (iii) how benthopelagic coupling and carbon transfer carried out by demersal fishes (that feed on migrating plankton) will be affected by fishing and by climate-induced changes in surface production and phytoplankton composition, oxygenation and acidification.

Challenges in addressing these knowledge gaps result from undersampling associated with the remoteness, vastness and heterogeneity of these environments. Sixty-six per cent of the continental slope seabed bathymetry from 200–1,000 m and 72 per cent from 1,000–3,000 m remain unmapped (Mayer and others, 2018). An even larger area of the sea floor has never been surveyed for biology, including significant portions of the African and South American margins. Often, pre-exploration assessments for the oil and gas industry provide the first characterizations of deep margins (Pabis and others, 2019). Time series (or continuous) observations are needed on slopes and canyons to characterize natural variability and response to climate change, and evaluate sensitivity to the impacts of human activities, which will require collaborations across sectors and jurisdictions (Evans and others, 2019; Garcon and others 2019; Levin and others, 2019; Vieira and others, 2019). Accelerated transfer of knowledge and technology as well as science infrastructure in developing countries can go a long way towards filling these gaps, as outlined in the section below.

6. Key remaining capacity-building gaps

For most of the deep ocean, lack of taxonomic expertise is a major roadblock in advancing studies on biodiversity (Fontaine and others, 2012; Horton and others, 2017). Some researchers increasingly favour using DNA as an alternative tool to morphology-based taxonomy (Sinniger and others, 2016), while others argue a need for naming species in order to support marine conservation and the development of ocean-based industry (Horton and others, 2017; Glover and others, 2018). Geographic bias in slope and canyon research, towards the exclusive economic zones of developed States bordering the North Atlantic and North Pacific Oceans, and around Oceania, reflects the reality of access, financial resources and the interests of industries involved in resource extraction. This leads to limited global understanding of biodiversity patterns and drivers and has consequences for the distribution of expertise, which for slopes and canyons, is based in developed regions, as well as in India, China, and to a lesser extent, Brazil and Chile. It has also resulted in uneven distribution of the technology, analytical tools, and methodologies required to advance global understanding of slope and canyon ecosystems.

Some solutions may be sought through expanded engagement of developing country scientists in offshore observing programs (e.g. Argo, Go-SHIP, OceanSITES), observing networks (e.g. Global Ocean Acidification Observing Network, Global Ocean Oxygen Network) and scientific networks (Deep Ocean Observing Strategy, Deep Ocean Stewardship Initiative, International Network for Submarine *Canyon* Investigation and Scientific Exchange). This goal can be achieved in part through training courses, cruise opportunities, synthesis workshops or steering committee membership, but personal mentoring providing scientific support and financial resources are critical elements. The United Nations Decade of Ocean Science for Sustainable Development could provide the catalyst for bridging these capacity gaps.

Slopes and canyons represent a large source of deep-sea biodiversity in part due to high geomorphic, geochemical and environmental heterogeneity. This biodiversity is still in a discovery phase and largely unprotected, but is increasingly vulnerable to the confluence of changing climate and growing human extractive activity, contamination and waste disposal on continental margins. Improved ocean observing, biodiversity characterizations, taxonomic knowledge and technology transfer are needed, particularly in the southern hemisphere.

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Chapter 7M
High-Latitude Ice

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Keynote points

- High-latitude ice habitats are characterized by high, but geographically variable, declines in sea-ice extent as a consequence of climate change.
- The loss of Arctic sea-ice habitat and Antarctic ice shelves allows expansion of both pelagic and benthic species into the newly open water environments.
- In general, however, many ice-dependent species are decreasing in abundance and their spatial distributions may also be reducing, particularly in the Arctic.
- Decreasing sea-ice extent in the Arctic provides increased opportunities for a range of human activities, including fishing, navigation and hydrocarbon exploration, with positive implications for several United Nations Sustainable Development Goals (SDGs).[113]
- Many of these activities, however, will remain marginal for some time as a seasonally ice-free Arctic is not expected until later this century.
- Decreasing sea ice will, however, reduce local community access to subsistence hunting opportunities.

1. Introduction

The present sub-chapter updates Chapter 46 of the First World Ocean Assessment (WOA I) (United Nations, 2017a). It also extends coverage of high-latitude sea-ice environments to include discussion of habitats associated with icebergs and ice shelves. The sub-chapter overlaps with high-latitude biodiversity aspects of many of the sub-chapters of Chapter 6 of the present Assessment. However, here the emphasis is on use of marine ice habitats and interactions between organisms within these habitats. Further, because high-latitude ice is intrinsically both a coastal and open ocean habitat, the sub-chapter interacts with several other habitats (e.g. benthic, open ocean and coastal-related habitats) covered in Chapter 7.

The baseline state for the discussion of high-latitude ice habitats in WOA I (United Nations, 2017b) was one of massive and rapid change. This degree of change is to some extent intrinsic to the habitat itself, which experiences strong seasonal fluctuations between minimal ice coverage in high summer and maximal ice coverage in late winter. However, the mean sea-ice habitat itself was altering dramatically, with ice extent, ice thickness and mean ice age all declining rapidly in the Arctic. In the Southern Ocean, change in the sea-ice habitat was less notable, although, several ice shelves on the Antarctic Peninsula had collapsed over previous decades (Vaughan and others, 2013). These changes to habitats had concomitant responses in associated ecosystems (United Nations, 2017b). Iconic marine and terrestrial species that have adapted to the sea-ice habitat, for example, polar bears, narwhals, seals and various sea birds, were found to be in decline both in abundance and geographic distribution. Sea-ice algae were identified as playing a major role in the primary production of these

[113] See United Nations General Assembly resolution 70/1.

habitats; the expansion of open ocean environments led to increased phytoplankton blooms. Both of these changes imply an altered base to the high latitude food chain. In general, expansion of open ocean environments was leading to a concomitant increase in the abundance and geographic distribution of open ocean species. In the Southern Ocean, it was uncertain whether changes in sea-ice habitats were impacting keystone species and, in particular, krill populations.

While major advances in understanding of marine biological polar sciences (Robinson, 2009; Stoddart, 2010) during the International Polar Year (2007–2008) provided novel information for WOA I, advances in knowledge available for WOA II have been the result of a variety of more limited initiatives.

2. Description of the environmental changes (between 2010 and 2020)

The overriding environmental change in the high-latitude ice habitat since WOA I has been a continuation of past change (Figure 1, see also Chapter 5 of the present Assessment). The greatest advances in knowledge, capacity and establishment of trends are largely associated with national and international programmes such as the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) and Antarctic Circumnavigation Expedition and long-standing international organizations such as the multinational Arctic Council and the Commission for the Conservation of Antarctic Marine Living Resources. Annual, and regularly scheduled, summaries of Arctic change, including ice habitats, are issued by States, such as the National Oceanic and Atmospheric Administration's Arctic Report Card (Richter-Menge et al., 2019) and others such as Fisheries and Oceans Canada's State of the Arctic Ocean Report 2019 (Niemi and others, 2019) or by international committees, such as the International Arctic Science Council's State of the Arctic (IASC, 2020) and the Scientific Committee for Antarctic Research (SCAR, 2020). More global summaries, again including ice habitat change, are issued through the American Meteorological Society (Blunden and Arndt, 2019). The Arctic Council has produced 25-year pan-Arctic summaries of change of the cryosphere (AMAP, 2017) and of biodiversity (CAFF, 2017).

2.1. Sea-ice habitats

In the Arctic, ongoing long-term declines in sea-ice extent (see also Chapter 5), both in summer and winter, have occurred. The summer Arctic sea-ice extent has, reached a new, reduced, mean position although this may be temporary (Vaughan and others, 2013). This new minimum also applies to sea-ice thickness, through the loss of significant amounts of multi-year ice after 2007, and the maintenance of this reduction in years since then (Serreze and Meier, 2019). It is worth noting that, while there is general Arctic sea-ice decline, the Pacific sector of the Arctic is losing its ice much quicker than is the case for other sectors of the Arctic, including the Canadian Arctic archipelago (see Figure 10 of Chapter 5).

In the Southern Ocean, although there has been strong interannual variability, similar to that noted in WOA I, there has been essentially no long-term change in the sea-ice extent for summer or winter (Figure 1; see also Chapter 5). From 2017 to 2019, however, January (minimum) levels have been consistently below levels registered since satellite records began in 1979, especially in the regular ice-covered zones of the Weddell and Amundsen Seas. This may be a consequence of recent oceanographic warming in the Southern Ocean (Meehl and others, 2019).

The rapidly changing nature of the physical environment, combined with the relative inaccessibility of the polar oceans, means that studies have largely focused on climate change scenarios (see also Chapter 5), especially at the base of the trophic system, rather than identification of historical change. Limited studies of sea-ice brine communities suggest no change as yet in relation to increased CO_2 concentrations or decreased pH (McMinn and others, 2017). However, under-sea-ice phytoplankton productivity has been found to be unexpectedly high (Arrigo and others, 2012). Such changes may have positive impacts on benthic organisms and upper ocean organisms by increasing food supply of particulate organic carbon to lower trophic levels (Oxtoby and others, 2017; Yasuhara and others, 2012; Xu and others, 2018), and diatoms from within the sea-ice have been found to sustain under-ice production during winter in the northeast Chukchi shelf (Wegner Koch and others, 2020).

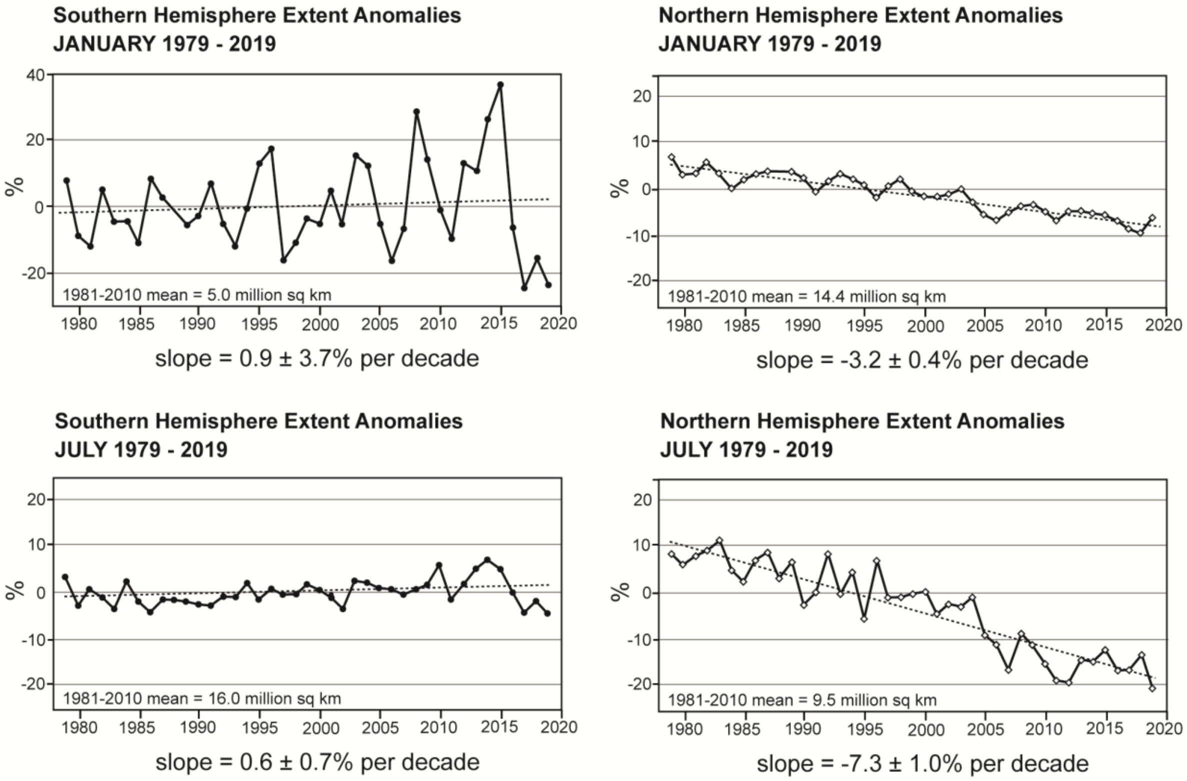

Figure 1. Trends in summer (upper left and lower right) and winter (upper right and lower left) sea-ice extent for both the Northern and Southern Hemisphere polar regions since satellite imagery became available in 1979 (Fetterer and others, 2017; source table ref.1). The slope of the trend line in each panel is shown. The Northern Hemisphere trends are statistically significant at the 0.01 level, while the Southern Hemisphere trends are not significant.

The impact of the decreasing Arctic sea ice on populations of marine mammals and seabirds is species-specific and depends on the extent to which individual species rely on the sea-ice habitat. While ivory gulls (*Pagophila eburnea*) have been identified as utilizing the Arctic's marginal ice zone and nearby open sea, Gilg and others (2016) found that approximately 80 per cent of seabird species were foraging in the increasingly rare high concentration sea ice. This variable use of ice habitat may indicate adaptability under a changing climate. Decreasing Arctic sea ice has led to general reductions in seabird numbers in the Bering Sea by approximately 10 per cent (Renner and others, 2016). There is some evidence that as prey habitats are changing species such as the beluga whale (*Delphinapterus leucas*) are exploiting expanded marine habitats (Hauser and others, 2018), and generally showing flexible feeding responses to environmental change (O'Corry-Crowe and others, 2016). In contrast, reduction in sea-ice has reduced the abundance of ringed seals (*Pusa hispida*) in Hudson Bay (Ferguson and others, 2017) and their distributional range in the Svalbard Archipelago has also contracted, which is leading to a major reduction in range overlap in these islands with the Arctic's top predator, the polar bear (*Ursus maritimus*). In response, polar bears have been observed feeding increasingly on ground-nesting birds (Hamilton and others, 2017) and whale carcasses (Pagano and others, 2020), with a concomitant increase in energy expenditure. In the Antarctic, the rapid warming has been shown to lead to southward movement of krill (*Euphausia superba*) populations, with decreases in density but increases in individual body length (Atkinson and others, 2019). Hückstädt and others (2020) suggest that this is likely to have negative consequences for species dependent on krill, such as crabeater seals (*Lobodon carcinophaga*).

2.2. Ice-shelf and iceberg habitats

The ice habitats of both ice shelves and icebergs extend up to hundreds of metres below the ocean surface. This means that their marine signatures are very different to those of sea ice, both in terms of their impact on the surrounding ocean and in the type of habitat that their sub-aerial and submarine surfaces provide. Ice shelves provide stable breeding platforms with direct access to the ocean where terminal thickness allows, and have been utilized by species dependent on ice shelves for breeding, Emperor penguins (*Aptenodytes forsteri*) for example, for many years (Wienecke, 2012; Fretwell and others, 2014). The sub-aerial surfaces of ice shelves provide habitats for microbial mats, especially where aeolian or glacially entrained sediments are present (Mueller and others, 2006), and provides a mechanism for long-distance transport of these organisms (Cefarelli and others, 2016). However, it is the dark environments under ice shelves that provide the surprisingly diverse habitats. Most of these are in the benthos, to which material from the ice shelves can provide nutrients (Hawes and others, 2018), leading to microbial activity (Vicks-Majors and others, 2016) and a range of species present in the meiobenthos (Pawlowski and others, 2005; Ingole and Singh, 2010). Some organisms utilize the submarine ice shelf surface more directly, such as the bald rockcod (*Pagothenia borchgrevinki*) which forages for prey along the ice surface (Gutt, 2002) and the sea anemone *Edwardsiella andrillae*, which uses the ice surface as a supporting substrate (Daly and others, 2013; Murray and others, 2016). The break-up of ice shelves in both the Arctic and Antarctic has led to the regional loss of this unique, dark environment, but significant biodiversity has spread into the regions newly exposed to surface inputs, leading to major carbon drawdown (Barnes and others, 2018).

Icebergs vary in size from free-floating fractures from ice shelves, particularly but not exclusively in the Antarctic, to fragments of ice a few tens of metres in size broken off from the calving terminus of a tidewater glacier. As ecosystems, they therefore vary in their marine contribution greatly. At one extreme, they are effectively free-moving pieces of ice shelves, with the capacity for significant seabird nesting and feeding platforms in both the Antarctic (Ruhl and others, 2011; Joiris, 2018) and Arctic. In the latter, both ivory gulls (Nachtsheim and others, 2016) and kittiwakes (*Rissa tridactylia*; Joiris, 2018) have been found in abundance on and near icebergs of various sizes. It has been speculated that past movement of giant icebergs in the Antarctic may have helped to facilitate the distribution of Adélie penguins (*Pygoscelis adeliae*) through ice transport (Shepherd and others, 2005). Such large icebergs can also have negative impacts on ecosystems. If a giant iceberg grounds for long periods off an existing penguin colony, its presence, and the associated spread of fast ice, can block the passage of individual birds, preventing access to foraging grounds and leading to considerable chick mortality (Kooyman and others, 2007; Wilson and others, 2016). In addition, the grounding and scouring of bottom sediments by large icebergs is a physical disturbance and has a serious impact on benthic organisms (Kaiser and others, 2013; Yasuhara and others, 2007). In areas with frequent iceberg passage, such as extensive areas along the Antarctic and Greenland coastlines (Bigg, 2015), as much as 30 per cent of the seabed may be disturbed in any one year, with up to two-thirds of the benthic fauna in that area killed (Barnes, 2017). With an ecosystem recovery time of several years, this destruction could lead to significant loss in the short term in the ability of the area to act as a carbon store, particularly in shallow seas (Barnes and others, 2018).

Melting of icebergs allows input of nutrients and trace elements held in or on the ice into the water, creating a distinctive and productive local ecosystem (Smith and others, 2007; Smith and others, 2013). The melting process, with its associated upwelling of relatively fresh plumes, aids this input of nutrients into the surface waters (Figure 2), which can be 4–10 times over the background level. In association, near icebergs there is an elevated bacterial population and a different community composition to that in the undisturbed water nearby (Kaufmann and others, 2011; Dinasquet and others, 2017). Further away, the combination of increased nutrients around the iceberg (Helly and others, 2011), as well as iron (Raiswell and others, 2008; de Jong and others, 2015) and silica (Hawkings and others, 2017) from the englacial debris released by the melting leads to increases in phytoplankton levels (Vernet and others, 2011) and potential impacts on carbon sequestration (Cefarelli and others, 2016; Duprat and others, 2016).

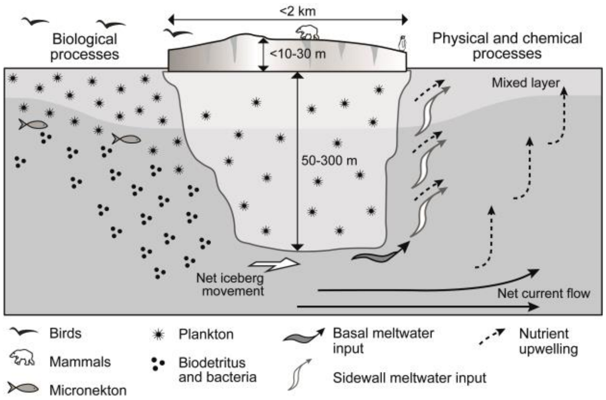

Figure 2. Schematic of the Arctic/Antarctic ecosystem on and around an iceberg. From Bigg (2015). Reprinted with permission.

Decay of ice shelves (e.g. Fettweis and others, 2017; Rignot and others, 2019) would be expected to lead to greater iceberg numbers, however comprehensive, long-term iceberg number estimates both in the Arctic and Antarctic are lacking. Records of icebergs off Newfoundland (Bigg and others, 2014), and satellite-derived records of medium-small icebergs north of 66^{o}S in the Southern Ocean (Tournadre and others, 2016) both report increasing numbers. The calving of giant icebergs (> 18 km in length) from ice shelves in the Antarctic, while very episodic in nature, also shows some evidence for recent increase in both number (Figure 3; source table, ref. 2) and magnitude.

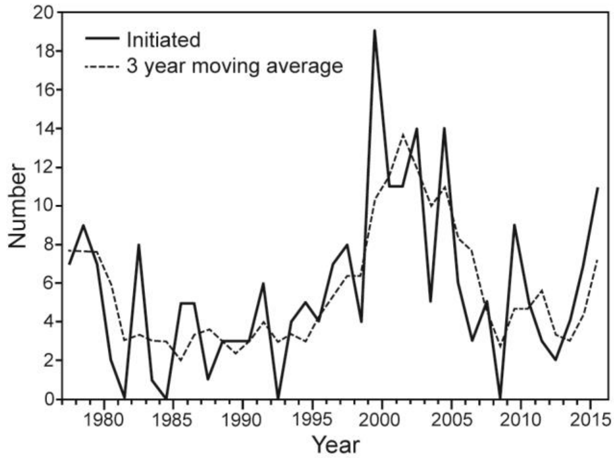

Figure 3. Number of annual Antarctic giant iceberg calving events. Giant icebergs are > 18 km in one length dimension, but there is no consistent area/volume estimate available over this timescale. Solid line is annual number of events, dashed line is 5-year running mean. (See Budge and Long (2017) and source table ref. 2).

The likely increase in icebergs in both hemispheres has probably led to increased production and impact on coastal benthic ecosystems in recent years, but there is currently little evidence, with information on the impacts of iceberg flux largely derived from the Southern Ocean.

3. Economic and social consequences

Historically, high-latitude ice habitats have experienced low levels of human activity, principally by indigenous inhabitants of the Arctic and its periphery. The continuing retreat of this habitat as a result of global warming, and the advance of human use of polar regions, is rapidly changing the relevance of this habitat for humanity, with associated economic and social consequences. While the decrease in sea ice increases opportunities for trans-ocean shipping and exploitation of sea floor hydrocarbon resources, the main driver for increased use of the Arctic so far is fishing (Eguíluz and others, 2016). More open ocean species can move north into now ice-free waters, increasing fishing opportunities, although the fish which rely on the sea-ice habitat, such as polar cod, will likely become less common (Christiansen, 2017). There are currently few marine protected areas (MPAs) in the Arctic offering protection from fishing or other exploitation (Harris and others, 2018), although a ban on Arctic fishing, instituted by an international agreement that was signed in October 2018 will limit expansion of fisheries activities in the Arctic for the next decade or more once 10 countries have ratified the agreement (European Commission, 2019). As of June 2020, however, only 8 countries had done so. This initiative links directly to SDG 14.**Error! Bookmark not defined.**

The direct impact of sea level rise from glacier melting and associated freeing of once frozen coastlines in the Arctic is affecting, yet providing many opportunities for, communities and industries (Richter-Menge and others, 2019). Negative impacts include loss of coastal ice roads, elevation of flood levels, change in nesting areas and along-shore coastal sediment transport, reduction in subsistence hunting ranges, the release of previously trapped pollutants, and even the loss of some coastal communities. Potential economic opportunities include the opening up of areas for ocean fisheries, maritime transportation and new shipping routes and enhanced opportunities for renewable energy installations, and increasing opportunities for hydrocarbon exploitation. These opportunities, however, have the potential to increase the risks associated with these activities, for example, habitat contamination from catastrophes such as oil spills (Cappello and others, 2014). It is worth noting that oil encased in sea-ice does not readily degrade (Loftus and others, 2020).

As the time when there were ice-free and therefore viable routes either via the Arctic north of Russia (the Northern Sea Route) expanded, so too the number of vessels using these routes increased, with over 70 vessels sailing through the Northern Sea Route in 2013. However, the number, if not the tonnage, of vessels using this route has decreased in recent years, not exceeding 40 since 2014 (Northern Sea Route Information Office, 2019; source table ref. 3).

Oil and gas activities in the Arctic are variable. A Canadian moratorium on issuing new drilling licences in Canada's Arctic Exclusive Economic Zone has recently been expanded to prohibit all offshore oil and gas activities until the end of 2021 (Vigliotti, 2019). In the Arctic waters of the United States of America, the analogous drilling ban introduced in 2016 was removed in 2017 but restored in 2019. Its future remains subject to legal appeal (Gilmer, 2020). Western Russian Arctic waters have seen limited drilling in recent years but expansion is on hold due to economic reasons and United States sanctions, although recent reports suggest drilling may resume in 2020 or 2021 (Arctic Today, 2019).

Most changes observed in the Arctic's ice habitat have mixed consequences in terms of the SDGs, with hydrocarbon exploitation providing greater access to energy sources (SDG 7) and, with increased shipping, tourism and fisheries enhancing local economic activity (SDG 8). However, these activities may work against creating a sustainable environment enriched by biodiversity (SDG 14) by causing further climate change and emissions (SDG 13), with associated pollution (SDGs 12 and 14).

Some fisheries in the Antarctic, such as those for krill, occur in coastal waters in the South Atlantic and Weddell Sea, where sea ice has shown signs of decrease. The broader implications of these decreases on the broader ecosystem and associated fisheries, however, are not yet clear. In light of the importance of krill as a food source for a growing aquaculture industry, long-term management strategies for this species are beginning to be implemented in the area protected by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR, 2019). Hydrocarbon exploration has started on the plateau surrounding the Falklands Islands (Malvinas)[114] (MacAulay, 2015), although assessment of associated environmental risks has only just begun and this area lies outside of the Antarctic governance system (Bigg and others, 2018). MPAs in some particular locations might help to address some of these management issues and it will require more changes to be undertaken by the Antarctic Treaty System, in particular CCAMLR. Although a Ross Sea MPA was established in 2016, some other proposed MPAs, such as in the Weddell Sea, East Antarctica and near the Antarctic Peninsula are yet to be created, waiting for a consensus of CCAMLR members.

4. Outlook

The outlook for polar ice habitats remains very much as it was for WOA I. Arctic sea ice is expected to continue to retreat and thin, with the prospect of a seasonally ice-free Arctic very likely within this century, although the timing of this key environmental event is still very uncertain (Serreze and Meier, 2019). Antarctic sea ice, while currently stable, is projected to

[114] A dispute exists between the Governments of Argentina and the United Kingdom of Great Britain and Northern Ireland concerning sovereignty over the Falkland Islands (Malvinas).

decrease over this century (Naughton and others, 2018), mostly because of ocean warming. The latter is expected to impact Antarctic ice shelves by encouraging subsurface melting of up to 41–129 per cent by the end of the century (Naughten and others, 2018), with associated increases in iceberg calving. Continued warming in the Arctic is expected to result in increased melting of the Greenland Ice Sheet (Barry, 2017) and probably increased, if episodic, iceberg production.

The decrease in sea ice and ice shelves will continue to open up opportunities for expansion of both pelagic and sea-floor species, which will benefit from wider and improved feeding conditions (Christiansen, 2017), while threatening the viability of fish, in particular polar cod (*Boreogadus saida*) (see Christiansen, 2017), and marine mammal populations for sea-ice dependent species (United Nations, 2017). Many studies suggest sea-ice algae will become vulnerable to climate change, with reduced biodiversity and population declines (Hardge and others, 2017; Kiko and others, 2017). On the other hand, phytoplankton blooms may become more widespread, at least early in the summer before nutrient limitation occurs, under thinner, more lead-prone, snow-covered sea ice in the Arctic Ocean (Assmy and others, 2017; see also Chapter 6A of the present Assessment). Such changes may have more wide-ranging impacts on carbon export, with seasonal sea-ice zones switching to carbon sinks (Abelmann and others, 2015; Rapp and others, 2018). Decreasing sea-ice may also reduce inputs of plastics to the Arctic Ocean, as sea-ice currently contains orders of magnitude more microplastics than the Arctic Ocean itself (see Chapter 12 and Kanhai and others (2020)). In the Southern Ocean, where sea ice has demonstrated little long-term trend to date, it is known that individual level specialization is lowest at sites where the inter-annual variability in sea ice is highest (McMullin and others, 2017), suggesting that there is scope for adaptation in a more variable future climate.

The opening up of the Arctic to navigation, fishing and exploitation of the sea floor and deeper resources will have major implications for the ecosystems (Harris and others, 2018) and a number of SDGs for human populations, both indigenous and incoming, reliant on high-latitude ice habitats. However, despite the first vessel sailing through the Passage in August 2017 without being accompanied by an icebreaker (High North News, 2018), it is likely that cargo shipping will continue to need accompaniment, unless it is an “ice class” vessel, for the foreseeable future (Kiiski and others, 2018). As a result, Arctic routes will likely remain of secondary importance for some decades. Factors also limiting the use of these new shipping routes are the potential negative impact of increased shipping on Arctic marine mammals (Hauser and others, 2018), the unwanted facilitation of transfer of non-indigenous species and the possible complex radiative feedback of ship exhaust fumes on Arctic climate (Stephenson and others, 2018), the latter potentially slowing the tendency for increases in ice-free periods.

5. Key remaining knowledge and capacity-building gaps

The inaccessibility of the high latitudes means that the ice habitat remains relatively poorly understood. Sea-ice environments are currently the best studied of the marine ice habitats considered here but, even in these, a comprehensive food web study is yet to be conducted; while many publications mention this, most focus on just one aspect (Dickinson and others, 2016). In general, our understanding of the three-dimensional nature of ice habitats (Bluhm and others, 2018), the range and number of species within them and their spatial and temporal variability is still very limited (Christiansen, 2017). This lack of data extends also to the impact of the presence or absence of these habitats on the surrounding ocean and carbon sequestration (Barnes, 2017).

Similarly, the difficulty of access to ice shelves, marine areas near glaciers (Zappalà and others, 2017) and, particularly, the submarine environment beneath them, makes gaining new information about this ice habitat rare. Much analysis has been, and will remain, from remote sensing, with new satellite systems promising to revolutionize first order knowledge of these habitats. It will be important to ensure ready and universal access to the new data produced by these observing platforms in order to address current knowledge and capacity gaps.

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Source table

Ref.	Source name	URL	Description
1	National Snow and Ice Data Center sea-	https://nsidc.org/data/seaice_index/compare_trends	Daily and monthly updates of Arctic and Antarctic sea-ice extents and trends

	ice index		
2	The Antarctic giant iceberg tracking database	http://www.scp.byu.edu/data/iceberg/	Regular updates of the history of positions and sizes of giant icebergs in the Antarctic, including a table of current positions. The Consolidated database v3.0 zip file can be accessed from the URL and it is the individual giant iceberg position files that were used for Figure 3.
3	Northern Sea Route transit statistics	http://arctic-lio.com/category/statistics/	Northern Sea Route transits per year

Chapter 7N
Seamounts and Pinnacles

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Keynote points

- Seamounts and pinnacles are common topographic features of the global ocean.
- Sampling effort has increased in recent years but only a small percentage of seamounts has been sampled in detail.
- Limited sampling, combined with high environmental variability among seamounts, constrains biodiversity knowledge.
- Fishing, especially bottom trawling, constitutes the greatest current threat to seamount ecosystems but marine debris/litter, climate change and potential seabed mining are additional concerns. However, initiatives to protect seamounts are increasing.
- Recent time-series research on deep seamounts shows limited, if any, recovery of stony coral communities over 15–20 year periods.

1. Introduction

Seamounts, knolls and pinnacles, collectively termed seamounts here, are submerged volcanoes, rising hundreds to thousands of metres above the sea floor. Estimates of their numbers vary, depending on the data source and algorithms used, from several tens of thousands of seamounts and over 100,000 knolls (Yesson and others, 2011; Harris and others, 2014) to extrapolations of >100,000 seamounts and 25 million knolls and pinnacles (Wessel and others, 2010). They collectively cover up to 20 per cent of the deep-sea floor (Yesson and others, 2011).

Three important characteristics distinguish seamounts from surrounding deep-sea habitat (Clark, 2009): their topography provides a range of depths for different communities; their typical hard rock surfaces contrast with fine unconsolidated sediments that cover much of the sea floor; and their physical structure can alter local hydrography and currents, concentrating species and productivity. These factors can result in richer and more diverse benthic communities than on adjacent slope or abyssal plain habitats.

Depth-related environmental parameters strongly influence seamount species composition, together with sea floor type and character (Clark and others, 2010). Seamounts provide significant ecosystem services and often host aggregations of fishes, with substantial commercial activity. Annual landings of primary seamount species have fluctuated around 100,000 t since the 1990s, dominated by armourheads, alfonsinos, oreosomatids and orange roughy (Clark and others, 2007; Watson and others, 2007).

Several "ecological paradigms" developed around seamounts, regarding them as unique environments and hotspots of biodiversity and endemicity. However, many seamounts are not highly isolated (Rowden and others, 2010a), and most do not have high levels of endemism. They share many species with other deep-sea habitats (Howell and others, 2010; Narayanaswamy and others, 2013), although variability in seamount topography and physical dynamics can induce high species turnover and distinct assemblage or abundance characteristics (Schlacher and others, 2014).

Chapter 51 of the First World Ocean Assessment (WOA I) (United Nations, 2017a), and parts of Chapters 34, 35 and 36.F, drew on multiple seamount reviews (e.g. Pitcher and others, 2007; Clark and others, 2010; Staudigel and others, 2010) and findings of the Census of Marine Life programme (e.g. Rowden and others, 2010a; Stocks and others, 2012; Clark and others, 2012). However, limited sampling constrains our understanding of seamounts. There are about 700 seamounts with data in SeamountsOnline (Stocks, 2010) and Seamount Ecosystem Evaluation Framework databases (Kvile and others, 2014), but only about 300 have been surveyed in detail, with few in equatorial latitudes or with summits deeper than 2000 m. Therefore, the structure, function, and connectivity of seamount ecosystems remains largely unknown (Clark and others, 2012).

2. Description of changes in knowledge between 2010 and 2020

Over the last five years, several national or international research programmes have yielded considerable ecological information on seamount environments. These are briefly described in section 5, but key ecological results are synthesized below, drawing on a review of seamount ecology (Rogers, 2018).

While seamounts rarely exist in steady-state oceanographic flows (Lavelle and Mohn, 2010), there can be circulation entrainment and homogenization of the water column (Meredith and others, 2015). Internal wave formation can upwell nutrients enhancing primary productivity in summit areas (Turnewitsch and others, 2016; Read and Pollard, 2017). However, elevated primary productivity may be transient (e.g. Lemos and others, 2018), rarely increasing zooplankton abundances. Zooplankton communities over seamounts reflect the surrounding oceanic waters (e.g. Carmo and others, 2013; Denda and Christiansen, 2014; Denda and others, 2017), but blockage of migrating zooplankton and micronekton by seamount topography can enhance predation by fishes and shrimps (e.g. Nishida and others, 2016; Preciado and others, 2017; Letessier and others, 2017).

Seamounts with shallow summits can support macroalgae, and macroalgal forests have recently been recorded in the North Atlantic (Ramos and others, 2016; Stefanoudis and others, 2019), and Northeast Pacific (Du Preez and others, 2016). Extensive rhodolith beds have been discovered on seamounts and ridges in the Southwest Atlantic (Meirelles and others, 2015), Northwest Atlantic (Stefanoudis and others, 2019) and Southwest Pacific (Clark and others, 2017). Such algae can be important in the carbonate budgets of mesophotic ecosystems. Pereira-Filho and others (2012) estimated carbonate production from rhodoliths of four seamounts of the Vitoria-Trinidade Seamount chain off Brazil was 1.5×10^{-3} gigatonnes per year.

Knowledge of seamount communities has improved through modelling of species distributions related to physico-chemical conditions. This modelling, especially for deep-sea corals which can be abundant on seamounts (e.g. Tracey and others, 2011; Rowden and others, 2010b), suggest that key environmental variables include calcite/aragonite saturation depths, topographic aspect, temperature, salinity, oxygen levels and particulate organic carbon (e.g. Davies and Guinotte 2011; Yesson and others, 2012, 2017; Anderson and others, 2016a). Nevertheless, models can perform poorly, depending on the resolution of environmental data (Anderson and others, 2016b; Rowden and others, 2017). New data will also influence such models, as seen by the discovery of stony coral reef on seamounts in the Northwest Pacific Ocean, in poor aragonite saturation conditions (Baco and others, 2017). Environmental parameters may also influence species replacement and species richness differently (Victorero and others, 2018).

Connectivity mechanisms between seamounts have been a focus of recent research. Seamounts can act as “stepping stones” across large regions, but there is no consistent pattern (Rowden and others, 2010a). The reef-building stony coral *Solenosmilia variabilis* and the cup coral *Desmophyllum dianthus* have similar widespread distributions across the southern hemisphere, but similar genetic structure for *D. dianthus* over large areas (1,000s km) contrasts with variation in *S. variablis* between individual seamounts in close proximity (10s km) (Miller and Gunasekera, 2017). This latter mechanism of “self-recruiting” populations also occurs in bivalve molluscs (Beeston and others, 2018). Spatial patterns of connectivity vary among species (e.g. Zeng and others, 2017) and even within the same genus (Pante and others, 2015). Currents can provide routes or barriers for larval dispersal (Dueñas and others, 2016; Holland and others, 2019).

This research highlights variability in environmental factors and faunal communities between seamounts, making it impossible to generalize about the ecology of seamounts, and emphasizes the importance of sampling across a wide range of physical and geographical seamount characteristics (Clark and others, 2012).

3. Description of economic and social changes

Artisanal fisheries date back to the 1500s and, even today, small-scale fisheries close to oceanic islands are important for employment with estimated catches (mainly tuna) of between 150,000 and 250,000 t per year (da Silva and Pinho, 2007). Deep-sea demersal fisheries for species such as alfonsino and orange roughy have generally declined since the mid-1990s (Clark and others, 2007; Watson and others, 2007; Pitcher and others, 2010), to current levels below 100,000 t. In addition to fish, small invertebrate fisheries on seamounts have targeted lobsters in the South Atlantic and Southern Indian Oceans and deep-sea red crab in the Northeast Atlantic (Rogers, 2018).

Seamounts host ferromanganese crusts that contain cobalt, nickel and rare earth elements with commercial potential (Hein and others, 2013). Five exploration contracts for these crusts exist with the International Seabed Authority (ISA): four cover seamounts in the Northwest Pacific, and the other the Rio Grande Rise off Brazil.[115] There is currently no mining for deep-sea minerals, but mining operations could significantly impact seamount ecosystems (e.g. Levin and others, 2016; Miller and others, 2018). Hence, regulations are being developed by ISA to balance potential exploitation with environmental conservation.

[115] Available at https://www.isa.org.jm/deep-seabed-minerals-contractors.

Litter and plastic debris represent a growing concern. Lost fishing lines, nets, and pots (e.g. Maldonado and others, 2015; Vieira and others, 2015; Woodall and others, 2015) entangle or physically damage seamount-associated species. Microplastics have been found in animals sampled from Southern Indian Ocean seamounts, as well as in the sediment (Woodall and others, 2014; Taylor and others, 2016). There is also concern that invasive species can spread through such debris and litter.

Recovery from fishing or potential mining, along with a return to economic or social value, could be very slow. Seamount fisheries can remove much of the benthic fauna, leading to declines in biodiversity and abundance (Clark and others, 2015). Seamounts in the Emperor Seamounts chain still yield sporadic, small catches (e.g. Bensch and others, 2008) and several small orange roughy fisheries off New Zealand and Tasmania have reopened (FAO, 2018). Benthic habitats, however, may require decades to recover. Time series surveys off New Zealand show few signs of change in stony coral communities 15 years after closure to trawling (Clark and others, 2019) although anemones and small corals may have increased on some seamounts off Tasmania (Clark and others, 2010). A recent survey in the North Pacific shows some potential recovery from trawling in the 1970s (Baco and others, 2019), but Japanese research on a seamount previously fished for precious corals indicates no sign of recovery (Bruckner, 2014).

4. Key region-specific research in recent years

4.1. Arctic

Little work has been undertaken on seamounts in Arctic waters. However, in 2017, high levels of sponge density and diversity were found on the Schultz Massif seamount, possibly associated with the occurrence of warmer, oxygen-rich and food-rich currents (Jones and others, 2018).

4.2. North Atlantic

Recent work has focused on seamounts in the Northeast Atlantic. Data from the Anton Dohrn Seamount have revealed 13 biotopes, 10 of which met the criteria for vulnerable marine ecosystems (VMEs) (Davies and others, 2015). The Hebrides Terrace Seamount was surveyed for the first time in 2012, and cold water coral habitats (Henry and others, 2014) and a spawning site for the deep-water skate *Bathyraja richardsoni* (Henry and others, 2016) were identified. The European Union ATLAS programme has completed surveys of Bowditch Seamount (Bermuda) and Formigas Seamount (Azores) and, on Tropic Seamount, reported extensive areas of sponge *Poliopogon amadou*, octocorals, *Solenosmilia variabilis* coral reefs, xenophyophores and crinoid fields (Ramiro-Sánchez and others, 2019). Tropic Seamount has extensive areas of ferromanganese crusts of potential mining interest (Murton and others, 2017).

4.3. South Atlantic

Recent work associated with mineral and oil and gas exploration has advanced physico-chemical descriptions of the Vitoria-Trindade Seamount Chain and Rio Grande Rise (Bernardino and Sumida, 2017; Montserrat and others, 2019). Seamounts share species pools with nearby continental slopes, but there are structurally distinct substrates across regions (O’Hara and others, 2010; Bernardino and others, 2016; Almada and Bernardino, 2017) which suggests a high diversity of benthic and pelagic fauna (Perez and others, 2018).

Surveys by the United Kingdom of Great Britain and Northern Ireland have also been carried out on seamounts off the Ascension, Tristan da Cunha and St Helena islands.[116]

4.4. Indian Ocean

Seamounts in this region remain poorly studied, although several seamounts on the Southwest Indian Ocean Ridge and Madagascar Ridge have been surveyed in recent years (Rogers and others, 2016). These surveys found distinct microbial and phytoplankton communities across the ridge (Djurhuus and others, 2017; Sonnekus and others, 2017), high cephalopod diversity (Laptikhovsky and others, 2017) and high benthic faunal diversity between seamounts.

4.5. North Pacific Ocean

The United States of America has been active in the North and Central Pacific Ocean with campaigns in 2015, 2016 and 2017 that included mapping and remotely operated vehicle (ROV) dives on seamounts and ridges of the Papahanaumokuakea Marine National Monument (including Hawaiian Seamount Chain) around a number of the American Islands in the central Pacific and extended down to Samoa, Tokelau and the Cook Islands. There were 18 dives on seamounts of the Musician Seamounts Chain. Most seamounts had only one ROV dive but revealed diverse and abundant benthic deep-sea coral and sponge communities (Kennedy and others 2019). Further work with ROV dives, coring and trawls on 4 seamounts in the Gulf of Alaska was carried out in 2019.

Chinese researchers have carried out a number of surveys of seamounts in the Northwestern Pacific, including Caroline, Yap and Magellan Seamounts.

There is also increased survey work by deep-sea minerals contractors with exploration licences for cobalt-crust in the Northwestern Pacific. Contractors (COMRA (China), KIOST (Republic of Korea), Russia, JOGMEC (Japan)) in 2017 and 2018 sampled 11 seamounts and found many new species amongst benthic communities of sponges, corals and echinoderms (e.g. Wang and others, 2016; Dong and others, 2017). Some sampling of abyssal hills and seamounts in the Clarion-Clipperton Zone has also occurred. In the Canadian North Pacific, Fisheries and Oceans Canada (DFO) have conducted baseline characterization of several seamounts. In 2018, an autonomous monitoring array was deployed to collect environmental data on Dellwood Seamount, along with hydrophones to detect whale presence. Thirty potential long-term monitoring sites have been established with photographic surveys. A science plan is being developed for SGaan Kinghlas-Bowie Seamount and other Pacific seamounts.

4.6. South Pacific Ocean

Research has focused on investigating potential recovery of benthic communities from bottom trawling. Further time series surveys were completed off New Zealand in 2015 (Clark and others,

[116] Available at https://www.bas.ac.uk/project/protecting-marine-ecosystems-in-the-south-atlantic/.

2019) and off Tasmania in 2018.[117] The original stony coral reefs show little recovery in the 15–20 years since trawling stopped.

Recent seamount surveys have occurred off the Galapagos Islands (Ecuador) (2015, 2016) down to 3000 m, as well as in the Nazca-Desventurados Marine Park (Chile) (2016) and Australia (Nanson and others, 2018).

4.7. Southern Ocean

A number of seamounts and ridges have been sampled in Antarctic waters in recent years. New Zealand surveys included "Long Ridge" (part of the Pacific-Antarctic Ridge) in 2018, and the Scott Seamount chain in 2019.

5. Outlook

Significant research has occurred in the last decade. Planned future international initiatives by the Global Seamounts Project[118] , a new InterRidge Seamounts and Islands Working Group, and UN Decade of Ocean Science initiatives to survey more seamounts can complement ongoing national research directed at local biodiversity or fisheries impacts issues. In 2017 the European Union, South Africa and Brazil signed the Belém Statement, a pan-Atlantic framework funding iAtlantic (2019-23)[119] through which several seamount surveys will take place in the Atlantic.

The emergence of potential deep-sea mining on seamounts is a threat, but ISA requires considerable baseline environmental data as a condition of exploration in areas beyond national jurisdiction, and this will increase seamount knowledge in several regions over the next ten years.

Climate change effects over the next decade are difficult to predict but reviews by Rogers (2015) and Sweetman and others (2017) suggest climate change remains a major threat to seamount communities, with rising temperatures, declining oxygen concentrations and shallowing of the aragonite saturation horizon. Some seamount fauna, such as cold-water corals, are vulnerable to changes in water mass characteristics (e.g. Guinotte and others, 2006; Matos and others, 2017; Hebbeln and others, 2019), and the greatest changes at bathyal depths (Sweetman and others, 2017) include seamounts that support productive fisheries or high biodiversity. However, because seamounts cover a wider depth range, they may be less susceptible to ocean acidification changes than the surrounding sea floor and act as temporary refugia (Tittensor and others, 2010).

Globally, seamount protection may increase, adding to national conservation efforts in the North Atlantic, Southwest Pacific and Northeast Pacific (Morato and others, 2010), and more recent closures to fishing activities off the west coast of Canada, Chile, the North Atlantic (Natura 2000) and throughout Hawaiian waters. Tourist funding may also increase future seamount conservation (Ison and others, submitted). Some seamount areas in the eastern Pacific have been protected from potential seabed mining by a regional environmental management plan adopted by ISA. Regional fisheries management organizations will likely identify increased numbers of seamounts as VMEs (FAO,

[117] Available at https://ecos.csiro.au/deep-sea-life/.
[118] Available at https://osf.io/xtg5c/.
[119] Available at https://www.iatlantic.eu/

2009), and numerous seamounts are classified as Ecologically or Biologically Significant Areas (EBSAs) (CBD, 2009).

6. Key remaining knowledge gaps

Knowledge gaps identified in WOA I (United Nations, 2017b) largely remain: limited number of seamounts sampled to date (some progress); predictive habitat suitability models developed, but not tested (some progress); pelagic components of seamount ecosystems poorly known (especially deep bathyal) (still largely true); multiple stressors need evaluation, including habitat disturbance, pollutants, climate change, acidification and deoxygenation, and need to be considered together (remains a major gap); and a limited understanding of the efficacy of closed areas to date (some progress).

Several global and national seamount data sets exist, including Seamount Catalog (mainly geological);[120] Seamounts Online (biological); Seamount Ecosystem Evaluation Framework (ecological); for New Zealand (Rowden and others, 2008); Azores (Morato and others, 2008), and western South Pacific (Allain and others, 2008). However, these have not been extensively updated as to which seamounts have been sampled since WOA I. An updated register of seamount surveys and sampling effort is urgently needed.

Given that so few seamounts have been surveyed globally, major gaps in scientific understanding of biodiversity scales and patterns on seamounts and resilience to climate change and human activities remain (Clark and others, 2012). Collection of such baseline data requires a suite of multiple tools, including remote sensing, direct sampling and visual surveys (see Clark and others, 2016). Accurate and consistent taxonomic identification of seamount fauna is a problem common to many deep-sea habitats. The need to improve consistency in sampling across multiple disciplines inspired development of the General Ocean Survey and Sampling Iterative Protocol (GOSSIP) (Woodall and others, 2018). New techniques such as artificial intelligence for species identification, eDNA, seascape genetic approaches, deep ARGO floats, and others, will likely be used widely and are necessary to improve knowledge of seamount environments. More time series studies are needed to address the long-term resilience and recovery potential of impacted seamount communities and inform their future management.

7. Key remaining capacity-building gaps

Seamount environments can play an important role in the deep-sea ecosystem.. Deep-sea surveys must include seamounts to improve understanding of their ecosystem structure and function as a prerequisite to human activities. However, the capacity gap in scientific capabilities, the remote and unexplored nature of deep-sea habitats in general, indicates significant capacity and information gaps even in well-developed, industrialized countries. Across all countries there are seamounts that overlap in distribution with current or proposed industrial activities, such as fisheries in the western Pacific, offshore oil and gas development in the Caribbean and Africa, and potential deep-sea mining in seamount and ridge areas of the Northwest and Southwest Pacific and Indian Oceans. There needs to be considerable collaboration and cooperation between developing and developed nations to build scientific and management capacity.

[120] Available at https://earthref.org/.

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Chapter 7O
Abyssal Plains

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Keynote points

- The abyss lies between 3 and 6 km water depth and covers more of the Earth's surface than all other habitats combined.
- This is the first World Ocean Assessment chapter dedicated to the abyss, covering biodiversity, regional differences, biogeography, and changes and impacts as a result of natural stressors and anthropogenic activity.
- Abyssal biodiversity is not well understood, and many gaps exist in current understanding of abyssal evolution, biogeography and organisms' distributions, connectivity, and responses to changing conditions.
- Fragmentary knowledge of abyssal taxonomy largely results from difficulties in sampling this vast and remote area, and hence limited research effort, thus hindering advancement of scientific knowledge.
- Most abyssal environments support the processes that drive deep-sea and global ecosystem functioning and are linked closely to surface production and pelagic processes.
- Climate change and anthropogenic impacts affect the abyss, despite its remoteness.

1. Introduction

1.1. Situation as recorded in the First World Ocean Assessment (WOA I)

The First World Ocean Assessment (WOA I) (United Nations, 2017d) briefly described abyssal environments, in Chapter 1 (United Nations, 2017a), Chapter 36F (United Nations, 2017c) and in Chapters on biodiversity in different ocean regions. They noted the dependence of abyssal habitats on flux of food from above, the possible impacts of climate change, and the likely impact of deep-seabed mining. We acknowledge continued uncertainty about abyssal biodiversity and its potential connections to pelagic and surface water organisms and future changes therein. WOA I did not contain the comprehensive description of abyssal biodiversity provided in the present Chapter.

1.2. General

The abyssal zone (3–6 km water depth) (Gage and Tyler, 1991) encompasses the largest area on Earth (~58 per cent of the planet's surface). It mainly comprises vast areas of seafloor plains covered in generally fine sediments, punctuated by sporadic hard substrate at topographic highs in the form of knolls, seamounts, mid-ocean ridges and island arcs, as well as lows in the form of valleys and deeper trenches. The total absence of sunlight penetration and in-situ primary production, apart from some chemosynthesis (see Chapter 7R of the present Assessment), characterize an ecosystem based on a variable rain of material from shallower euphotic zones. Although food-limited, with low abundances compared to most deep-sea habitats (Gage and Tyler, 1991), the abyss supports high levels of alpha and beta diversity of meiofauna, macrofauna and megafauna (Rex and Etter, 2010). The quantity and quality of food particles sinking from the ocean surface strongly modulate ecosystem structure and function (Smith and others, 2008; McClain and others, 2012a), but feedback mechanisms through nutrient cycling back into the water column are poorly understood (Thurber et al., 2014). Abyssal regions differ from each other in physical variables, surface water characteristics, and biogeographical distinctions, which are reflected in their organisms, communities, and biodiversity.

Abyssal biodiversity varies in space (Glover and others, 2002; Woolley and others, 2016; Simon-Lledó and others, 2019a) and time (Ruhl and others, 2008). Despite poorly-known biodiversity patterns on regional to global scales, some regions, such as the abyssal Southern Ocean (Brandt and others, 2006; Griffiths, 2010) and the equatorial Pacific (Amon and others, 2016a; Glover and others, 2002), house major biodiversity reservoirs. For the few taxa studied, connectivity appears high (Baco and others, 2016; Taboada and others, 2018), whereas studies of deep-sea functional diversity have just begun (e.g. Chapman and others, 2019), including the abyssal seafloor (e.g. O'Hara and others, 2019; Christodoulou and others, 2019). Biodiversity knowledge varies by region and, in recent years, interest in seabed mining (see Chapter 19 of the present Assessment) has helped to generate new information for regions such as the Clarion-Clipperton Zone in the Central Pacific (e.g. Glover and others, 2016a; Dahlgren and others, 2016; Amon and others, 2017a, 2017b; Marsh and others, 2018; Wiklund and others, 2019), with evidence of biodiverse, yet vulnerable life (Vanreusel and others, 2016).

Climate change will likely affect the abyss (Yasuhara and Danovaro, 2016; Sweetman and others, 2017). Projections suggest increased abyssal ocean temperatures and acidification, and decreased oxygen concentrations and downward flux of organic matter (OM). Other oceanographic processes will likely respond, increasing stratification and reducing water mass exchange. Given the narrow environmental niches of abyssal biota, these changes could produce geographic shifts and increase vulnerability of abyssal organisms to other anthropogenic impacts (Levin and others, 2020). Current understanding of anthropogenic impacts on abyssal ecosystems remains poor, but highlights a vulnerability that will very likely increase in the future.

2. Shifting baselines and documenting status and change in abyssal biodiversity

The challenges of sampling in remote locations at depths >3,000 m contribute to abyssal under-sampling (Glover and others, 2018). Biodiversity records reflect this deficiency (Figures 1 and 2). Sampling effort has also focused more on the seafloor than on the highly variable and vast pelagic realm.

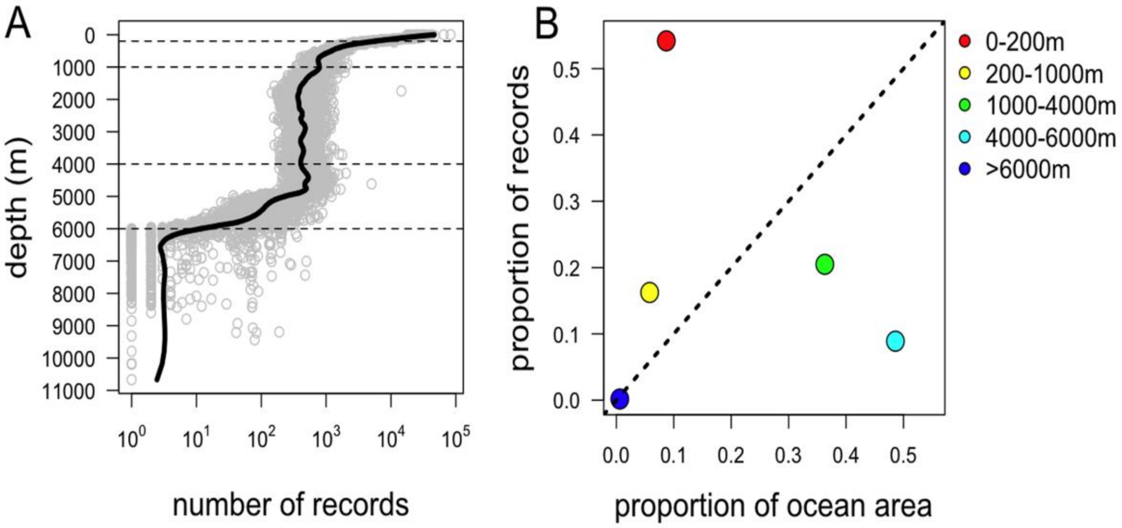

Figure 1. The depth distribution of Ocean Biodiversity Information System (OBIS) records of global marine biodiversity. (A) Number of OBIS records plotted against ocean depth (grey symbols); a lowess smooth (solid line) illustrates the general trend. (B) Proportion of all OBIS records occurring in different depth zones, plotted against the proportion of the global ocean that occurs at those depths. The 1:1 line identifies those areas of the ocean with proportionately more (points above the line) or fewer (points below the line) records than expected given their area. This depiction provides a conservative view of under- and over-representation based on the volume of each habitat. Figure retrieved from Webb and others (2010).

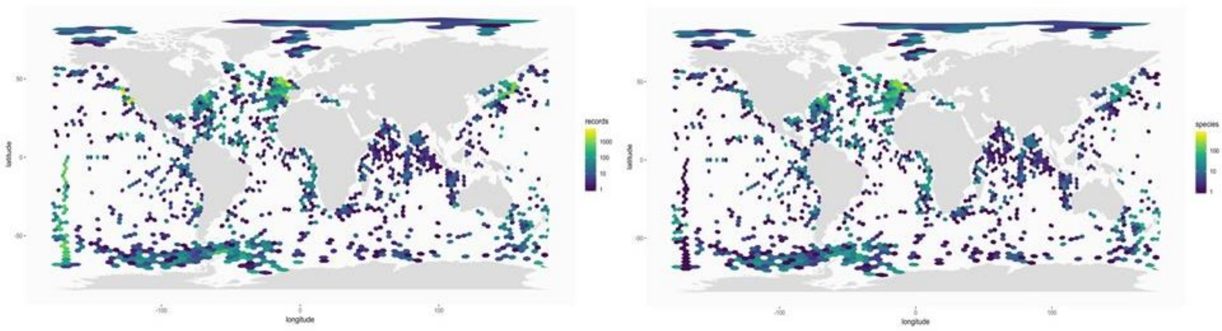

Figure. 2. World map of OBIS abyssal records (left) and species presence (right) between 3,000 and 6,000 m depth. **Left** data available rarely exceed 1,000 records per 75,000 m^2 area; gaps exist, especially in the Pacific, South Atlantic and South Indian Oceans. **Right** species presence between 3,000 and 6,000 m depth; the North-East Atlantic has more samples as compared with all other oceans. Note the correlation between records and species presence. (OBIS, 16 May 2019) (Intergovernmental Oceanographic Commission, UNESCO. Retrieved from https://obis.org).

2.1. Benthic abyssal biodiversity and benthic-pelagic coupling

Biogenic habitat comprises much of the fine-scale habitat structure on sediments. The patchy food resource also contributes fine-scale structure to the seafloor (McClain and Schlacher, 2015). Characteristically low current speeds result in minimal sediment erosion (Smith and others, 2008) but affect sediment composition (McCave, 2017). Abyssal waters are cold (<5 °C) and relatively constant in temperature (Sweetman and others, 2017), and characterized by extremely high hydrostatic pressure.

The transfer of OM to the abyss occurs mainly through sinking particulate organic carbon (POC), largely produced in surface waters through photosynthetic primary production and zooplankton, the latter generating secondary production and byproducts (Cavan and others, 2015). In addition, carcasses of marine vertebrates can sink to the abyssal plain within a few days, temporarily increasing local food (Amon and others, 2016b). Surface export of organic material can reach abyssal depths within a few days but rates fluctuate (Smith and others, 2008). . Particle export dynamics, such as summer export from upper layers, can strongly influence abyssal biogeochemical processes (Bouef and others, 2019). However, remineralization throughout the water column results in very low quantities of OM reaching the abyssal seafloor (~0.5-5 per cent of surface production) (Smith Jr. and others, 2009; Smith and others, 2008; Lutz and others, 2007). The arrival of food influences abyssal communities, their diversity, abundance, density and composition, whereas important microbial groups affect processes such as C- and N- cycling, and vertical OM transport shapes the composition and biogeography of deep-ocean prokaryotic (and eukaryotic) communities (Mestre and others, 2018). The low energy availability results in generally low abyssal abundances, biomasses, and biological rates (metabolism, growth and reproduction) (Smith and others, 2008; Wei and others, 2010).

The total biomass of all benthic size classes generally declines with increasing water depth, except for bacteria and archaea, which dominate the biomass of the abyssal plain and deeper (Wei and others, 2010). Modelling estimates suggest global prokaryotic biomass on the seafloor of approximately 35 Mt C (Wei and others, 2010). Thus, the activities of microbial communities strongly influence the type and abundance of nutrients released back into the pelagic realm. These microbes also experience top-down forcing from viral populations (Suttle, 2005) and grazing by different-sized animals (e.g. Howell and others, 2003; Ingels and others, 2010).

2.2. Abyssopelagic zone

Much less is known about pelagic fauna that primarily occupy depths between 3–6 kilometres and that live more than 200 metres above the seafloor. OBIS shows minimal sampling of these ecosystems, which results in major knowledge gaps spanning over a billion cubic kilometres of habitat - potentially the largest reservoir of unknown diversity on Earth (Robison, 2009). The abyssopelagic zone facilitates the largest carbon sink on the planet, a critical ecosystem service of the global ocean (Atwood and others, 2020). Daily vertical migration between deep-sea pelagic layers can move dissolved nutrients that contribute to primary production in the photic zone (Houghton and Dabiri, 2019), along with long-term deep ocean circulation.

2.3. Key region-specific differences/contrasts

Broad-scale variation in physical and chemical environments (e.g., organic flux, oxygen) in the abyss result in geographic differences in biodiversity. Salinity, however, varies too little to produce such variation. These geographic differences could also lead to contrasting responses to human impacts within different regions, but we lack the data necessary to evaluate this possibility.

Carbon availability. Numerous studies on carbon availability demonstrate that a variety of processes contribute to POC levels in the abyss, thus shaping communities (Carney, 2005; Smith and others, 2008; Rex and Etter, 2010; McClain and others, 2012a; McClain and Schlacher, 2015; Woolley and others, 2016). POC flux to the deep varies in time and space (Lutz and others, 2007; Lampitt and Antia, 1997) (Figure 3). Factors such as depth, distance from productive coastal waters and/or upwelling regions can produce considerable local effects, generally limiting POC flux to the deep-seafloor. For example, upwelling in the Equatorial Pacific results in high levels of POC flux (2-6 g m^{-2} yr^{-1}) compared to the extremely low POC (<1 g m^{-2} yr^{-1}) in adjacent regions to the south (Watling and others, 2013). Intense areas of coastal upwelling, combined with narrow continental shelves, place abyssal habitats in the North-East Pacific and South-East Atlantic closer to productive coastal waters, resulting in higher POC input (Lutz and others, 2007; Lampitt and Antia, 1997). Moderately high POC fluxes also occur in the North Atlantic (6.6 g m^{-2} yr^{-1}) because of spring bloom pulses (Lampitt and Antia, 1997).

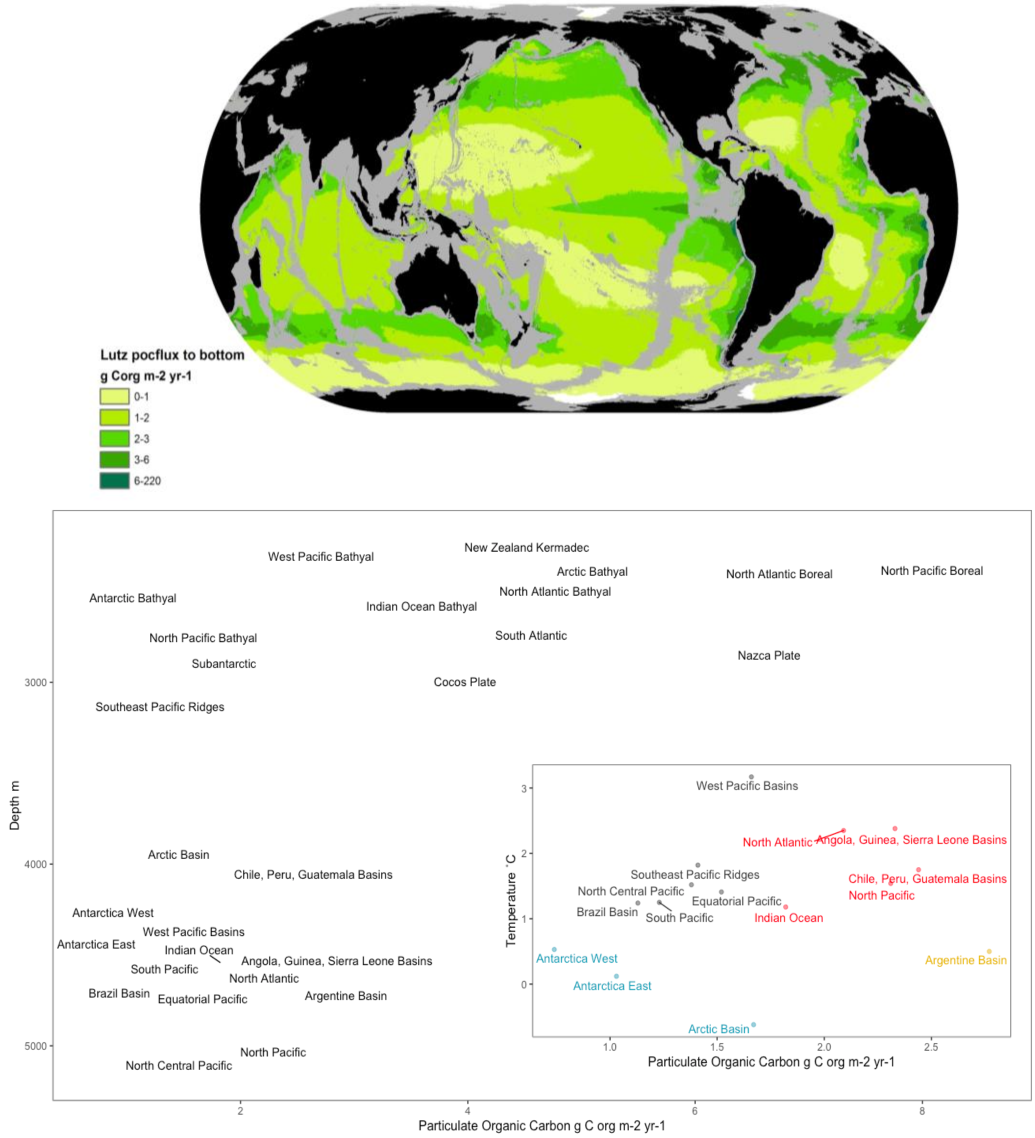

Figure 3. **Top**: POC flux to the bottom at depths between 3,500 and 6,500 m (data from Lutz and others, 2007); **Bottom**: Main plot: depth-POC plot illustrating differences in POC flux and flux variability between bathyal and abyssal regions. Insert shows variability between abyssal regions (temp-POC flux).

Temperature. Temperature often shows a statistically significant relationship with diversity in the abyss (Cronin and Raymo 1997; Hunt and others, 2005; Yasuhara and Danovaro, 2016). Temperature may also limit the biogeographic distribution of some species (McClain and others, 2012b). Temperatures >10 °C occur in the Mediterranean Sea, even on its abyssal plains. Higher temperatures in some other marginal seas, such as the Gulf of Mexico and the

Sulu Sea, also exceed those at open-ocean abyssal depths. Slightly colder abyssal temperatures occur in the Pacific than in the Atlantic, with substantially colder polar sea abyssal temperatures (see Figure 4; Yasuhara and Danovaro, 2016). Gebbie and Huybers (2019) recently reported a significant difference between Pacific (continuing to cool as a result of the Little Ice Age) and Atlantic (beginning to warm because of recent climate change) circulation. These changes may alter carbonate compensation depths (water depth at which carbonate supply and dissolution are equal) within the different basins. Regional differences result from influences of depth and bottom-water formation, down-welling, as well as other water mass exchanges.

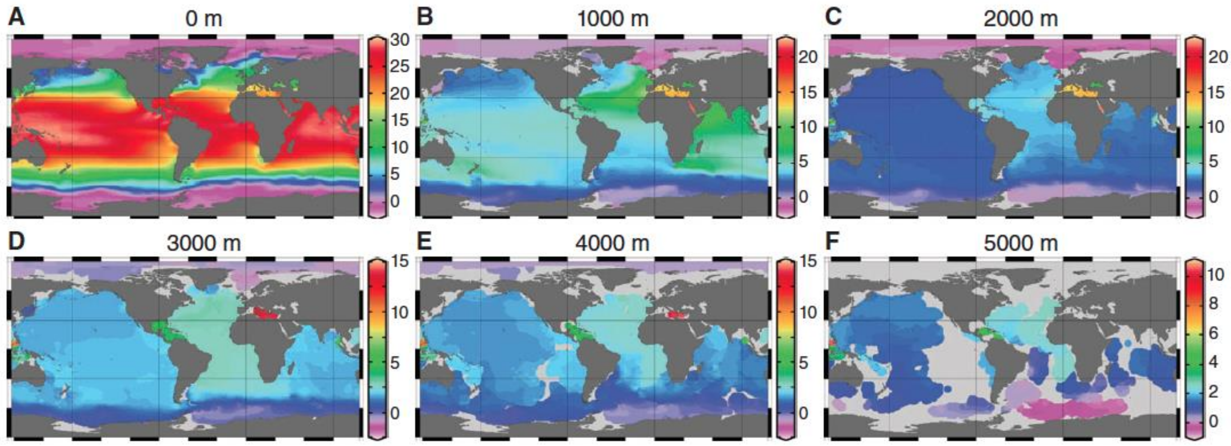

Figure 4. Global temperature (°C) distributions at (A) 0 m, (B) 1,000 m, (C) 2,000 m, (D) 3,000 m, (E) 4,000 m, and (F) 5,000 m water depths. Data from World Ocean Atlas 2009 (http://www.nodc.noaa.gov/OC5/WOA09/pr_woa09.html). The map was created using Ocean Data View (http://odv.awi.de) (Yasuhara and Danovaro, 2016).

Oxygen. Dissolved oxygen concentrations affect the ecology and distributions of deep-sea animals (Levin, 2003; Stramma and others, 2010), and may determine the presence and absence of species in specific regions and restrict species dispersal. Oxygen can vary between 1 to >6 ml/L in the abyss (Watling and others, 2013). Well-oxygenated Antarctic Bottom Water moving northward increases dissolved oxygen concentrations in the extreme south Indian, Pacific and Atlantic Oceans (3-4 ml/L). Likewise, the southward-flowing North Atlantic Deep Water oxygenates the North Atlantic (5.5-6.5 ml/L) resulting, with the Antarctic, in some of the most oxygenated abyssal waters on Earth (Watling and others, 2013).

Depth. The minimum depth at which the abyssal plains begin varies regionally, with shallower abyssal plains in both the Gulf of Mexico (3,000–3,900 m) and the Mediterranean (average depth 1,500 m, maximum 5,267 m) than in other regions. The average depth of the Arctic Ocean and the Chile, Peru and Guatemala Basins approach 4,000 m, in contrast to average depths closer to 5,000 m in the North and Central Pacific. Greater depth, ceteris paribus, reduces POC flux. Depth, as a proxy for pressure, may also limit biogeographic distributions (Somero, 1992; Carney, 2005). Regional abyssal depth differences may thus cause taxonomic compositional shifts and influence biodiversity. Nonetheless, despite broad biogeographic differences among regions, little evidence points to depth as a strong correlate of diversity within abyssal plains.

Topography. Topographic features can impede exchange of individuals between deep-sea populations and influence biogeographic classification (McClain and Hardy, 2010). The Pacific and Atlantic share only 15–20 percent of species (Vinogradova 1997). The Gibraltar Strait limits colonization of the relatively species-poor Mediterranean by Atlantic fauna (Sardà and others, 2004). Mid-oceanic ridges may also limit dispersal on the abyssal plains. Half of the known species of deep-sea bivalves are restricted to either the eastern or western Atlantic (McClain and others, 2011), likely because of the Mid-Atlantic Ridge.

Researchers recently recognized that abyssal hills rising less than 1,000 metres off the seafloor create topographic, depth, and sediment differences that support different taxonomic assemblages and higher biomass levels (Yesson and others, 2011; Durden and others, 2015) than in flatter abyssal sediments.

Sediment and substrate. Sediment types can vary dramatically in composition within different abyssal regions. Most diatom oozes occur at abyssal depths but radiolarian oozes occur, inter alia, in the Southern Ocean, equatorial Pacific, and Peru Basin. Sponge spicules form a major component of sediments in the Australian-Antarctic Basin. Clay dominates large seabed regions off South America, in the Indian Ocean, and dominates the South Australian Basin (Dutkiewicz and others, 2015). Sediment diversity affects biodiversity, but linkages between sediment type and biodiversity patterns remain underexplored. In abyssal-plain sediments, polymetallic nodules can also affect biodiversity. Assemblages on nodules differ fundamentally from both near-bottom seawater and sediment communities (Shulse and others, 2017; Simon-Lledó and others, 2019a). Increased nodule presence promotes increased megafaunal and xenophyophore abundance (Simon-Lledó and others, 2019b). Thus, increased habitat complexity generated by polymetallic nodules increases diversity in all levels of abyssal biota.

Riverine influences. Riverine input can influence the abyss through: (i) input of terrestrial carbon; (ii) creation of a dispersal barrier, thus affecting biogeography; and (iii) disturbance that alters deep-sea sediments. Significant discharges are shown below.

Recipient	River	Megatons carbon/year
Indian Ocean	Ganges and others	30.0
SE Atlantic	Congo and others	30.0
SW Atlantic	Amazon	37.6
NW Pacific	Yangtze, Yellow and Mekong	16.2
Arctic	Siberian rivers	12.8
Gulf of Mexico	Mississippi	3.6
SW Pacific	Indonesian rivers (with high annual rainfall)	90.0

Sediments from large rivers may also deliver substantial loads of anthropogenic contaminants, with unknown effects on abyssal biodiversity (Davies and Moore, 1970). OM influx from large rivers to the continental margins, slopes, and canyons, are easily channeled through various processes to the abyss where it may disturb and drive seafloor biomass and community diversity.

Ice cover. Polar ice cover influences primary production and thus POC flux to the abyss. Permanent ice cover reduces or prevents surface production, thus limiting biodiversity and biomass in the Arctic Ocean, where known species richness of polychaetes may be lower than in other, similar-sized basins (Bodil and others, 2011). Summer ice absence can bolster surface production and increase biodiversity and biomass (Wlodarska-Kowalczuk and Pearson, 2004).

Geological age. Geological changes likely affected distribution of abyssal biodiversity by altering connectivity among ocean regions. These include (Yasuhara and others, 2019a):

Connection	**Opening**	**Closing**	**Source**
	Million years ago		
Mediterranean/Atlantic and Indian Oceans (Tethys Seaway)		~19–14	Coles, 1990
Drake Passage	~30		Lawver and Gahagan, 2003; Livermore and others, 2007; Scher and Martin, 2006
Central American Seaway		~3	Schmidt and others, 2007; O'Dea and others, 2016; Schmidt and others, 2016
Bering Strait (Arctic/Pacific)	~4.8–7.4		Marincovich Jr. and Gladenkov, 2001; Hu and others, 2012
Fram Strait (Arctic/Atlantic)	~10–20		Engen and others, 2008; Ehlers and Jokat, 2013

2.4. Abyssal biogeography

In contrast to well-recognized boundaries among benthic assemblages on continental margins, uncertainty remains whether such abyssal boundaries exist (Carney, 2005). Researchers have attempted to establish biogeographic realms below 3,000m. Some early attempts based on temperature, topography, or faunal similarities suggested Atlantic, Indo-Pacific, Antarctic and Arctic divisions; others linked the Arctic and Atlantic, or questioned such linkages and split the Indian and Pacific Oceans or proposed more subregions (Menzies and others, 1973; Vinogradova, 1979, 1997; Carney, 1994).

A scheme sponsored by UNESCO, the Global Open Oceans and Deep Seabed (GOODS) biogeographic classification, used environmental parameters, including temperature, salinity, dissolved oxygen, carbon flux, primary production, bathymetry, and plate boundary layers, to delineate biogeographic provinces, resulting in 14 abyssal provinces (Briones and others, 2009).[121]

A more recent proposal revised the 14 abyssal provinces (Figure 5), by giving greater weight to hydrographic patterns, POC flux, dissolved oxygen and the effects of cold Antarctic waters and warmer North Atlantic waters (Watling and others, 2013).

[121] See Intergovernmental Oceanographic Commission, IOC Technical Series, No. 84 (IOC/2009/TS/84 and Corr.).

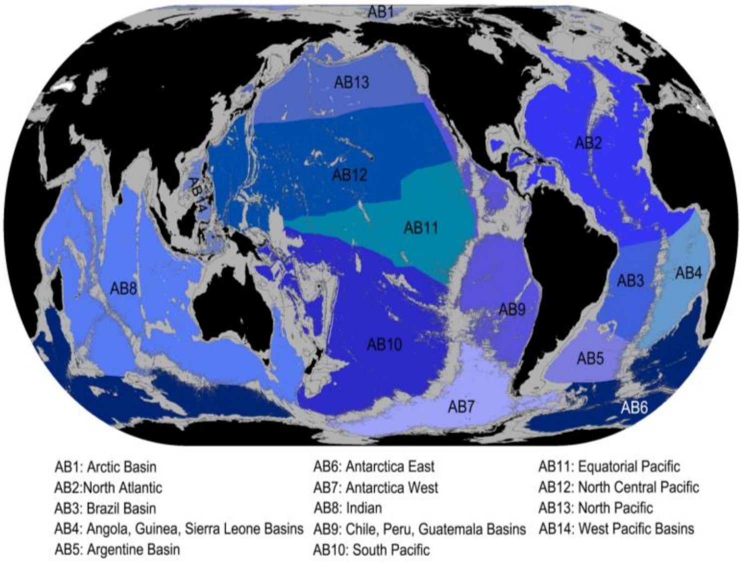

Figure 5. Proposed biogeographical regions based on Watling and others (2013).

2.5. Documented change in abyssal biodiversity

2.5.1. Evidence from paleoecological studies

Fossil records from deep-sea sediment cores provide the only time series data longer than a few decades (Yasuhara and others, 2017; 2019b), and these paleoecological records clearly point to long-term impacts of climatic change on abyssal biodiversity. Abyssal diversity correlates positively with bottom water temperature over 1,000–10,000 years (Cronin and Raymo, 1997; Cronin and others, 1999; Yasuhara and Cronin, 2008; Yasuhara and Danovaro, 2016). Dynamic deep-water circulation and associated temperature changes have occurred even at multi-decadal–centennial time scales (Yashayaev and others, 2007; Hoffmann and others, 2018; Thornalley and others, 2018; Yasuhara and others, 2019b). Researchers infer great stability in abyssal biotic and environmental conditions compared to those at bathyal or shallower depths. Over larger timescales, fossil data show that present-day deep-sea fauna established during the Miocene, ~ 13 million years ago (Thomas and others, 2000; Thomas, 2007). Latitudinal diversity gradients in the deep sea established during the late Eocene, ~ 37 million years ago, persist today (Thomas and Gooday, 1996).

2.5.2. Evidence from long-term observatories

Few long-term research programmes have obtained sufficient data to draw conclusions regarding long-term natural versus anthropogenic changes. Those that do, indicate a strong connection between surface production and abyssal sea-floor communities; often with a high degree of dynamism. These studies suggest that one-time or short-term investigations in the abyss cannot adequately assess biological community changes mechanistically, particularly in the context of deep-sea stewardship.

Monitoring studies of Station M off central California since 1989 strongly correlated surface ocean processes and POC supply to the abyss, where fluctuations affect community structure and processes. Short-term variations in Station-M abyssal communities (Kuhnz and others, 2014) link to inter-annual variation in climate (El Niño/La Niña) (Ruhl and others, 2014), but long-term consequences are poorly understood. Sporadic, intense food pulses to the abyss could provide food surplus following many years of undersupply.

Porcupine Abyssal Plain. Sustained observations (PAP-SO, 4,850 m) in the North-East Atlantic have produced high-resolution surface-to-seafloor data since 1989. Dramatic community and abundance shifts occur in response to OM influx changes (e.g. Billett and others, 2001), resulting from the tight correlation between surface productivity and export fluxes (Frigstad and others, 2015). These shifts (1989–2005) dramatically alter carbon storage. Most abyssal biota respond to food influx, environmental change and competitive interactions (Kalogeropoulou and others, 2010; Lampitt and others, 2010; Gooday and others, 2010; Soto and others, 2010). Biogeochemical results show that pCO_2 has decreased with increasing anthropogenic CO_2 emissions (Hartman and others, 2015).

LTER observatory HAUSGARTEN. Data from this observatory (Fram Strait, Arctic, 250–5,500 m depth,, since 1999), point to seasonal forcing of communities related to regional sea-ice and hydrodynamic conditions (Soltwedel and others, 2005, 2016). Fifteen years of pelagic and benthic data indicate rapid responses of the entire ecosystem to water-column changes. However, uncertainty remains as to whether we should attribute trends to anthropogenic changes or natural multi-year variability.

3. Major natural and anthropogenic pressures

3.1. Natural pressures

Natural disturbances in the form of near-bottom currents, sediment resuspension, or settling food particles can dramatically alter benthic communities (Hessler and Jumars, 1974; Snelgrove and Smith, 2002). In the Atlantic, the mass movement of sediment downslope can affect transport of OM to adjacent abyssal basins (Levin and Gooday, 2003). Similar processes occur during dense shelf-water cascading through canyons and slopes to abyssal depths, triggered by increased salinity and winter cooling (Carney, 2005; Company and others, 2008). Such disturbances may increase OM transport to abyssal depths (Canals and others, 2006; Ulses and others, 2008; Palanques and others, 2011).

Similarly, heterogeneous sea-floor topography can modify the composition and abundance of species, as well as carbon remineralization rates. These abyssal hills likely play a significant role in Pacific deep-sea communities and OM cycling, given their large number and the limited continental sediment supply (Smith and Demopoulos, 2003).

3.2. Anthropogenic pressures

3.2.1. Climate change

Climate change will affect abyssal physical (salinity, temperature, etc.), biogeochemical (nutrients, CO_2, O_2, sedimentology) and biological processes and functions (Mora, and others, 2013; Sweetman and others, 2017). Abyssal temperatures could increase by 1° over the next 80 years, whereas abyssal sea-floor habitats beneath regions of deep-water formation may experience reductions in water-column oxygen concentrations by as much as 0.03 mL L^{-1} by 2100. Such changes could affect food supply and sediment transport (FAO, 2019; Cheung and Levin, 2019). Climate-induced changes in ocean circulation and hydrodynamics may affect abyssal connectivity by altering distributions of pelagic larvae of abyssal organisms (acknowledging that larvae of some abyssal taxa do not reach the upper ocean). Questions persist about how such changes impact deep-ocean communities but decadal studies in the northern Pacific demonstrate significant linkages (Ruhl and others, 2008). Assessments of climate change impacts, as well as synergistic or cumulative impacts with other anthropogenic activities, must therefore consider abyssal ecosystem responses (Smith and others, 2008; Levin and Le Bris, 2015; Sweetman and others, 2017).

The food-limited nature of abyssal ecosystems suggests high sensitivity of all biota, from microbes to megafauna, to changes in phytoplankton community structure and productivity and the quantity and quality of export flux (Billett and others, 2010; Ruhl and others, 2008; Ruhl and Smith, 2004; Smith and others, 2013). Climate warming will likely increase ocean stratification, reduce primary production, increase acidity, and shift dominant phytoplankton community structure, driving biotic changes over major regions of the abyss such as the equatorial Pacific (Levin and others, 2020; Smith and others, 2008). Predictions of significant decline OM flux to the deep seafloor in most oceans (Sweetman and others, 2017) contrast with predictions of increased production of water-column and seafloor biomass in polar seas (Jones and others, 2014). Threats to abyssopelagic environments also include the deepening of oxygen minimum zones.

3.2.2. Plastics and other forms of pollution

Pollution has long impacted abyssal depths (Chiba and others, 2018). High levels of plastic debris have been found, along with benthic organisms contaminated with organic pollutants, even at ocean depths of over 10,000 m (see Chapters 11 and 12 of the present Assessment). Few studies have documented interactions of abyssal life with debris and other pollutants but this research topic is rapidly gaining interest. Other examples of abyssal pollution include the dumping of nuclear waste prior to 1983, as described in Chapter 24, section 3, of WOA I (United Nations, 2017b).

3.2.3. Mining

In the last few decades, interest in mineral reserves at abyssal depths has grown considerably. Future extraction of seafloor minerals, in the form of polymetallic nodules, cobalt-rich crusts, and polymetallic sulfides, pose a significant potential threat to abyssopelagic and benthic communities, directly and indirectly (Christiansen et al. 2019). Chapter 19 of the present Assessment discusses the environmental, social, and economic aspects of seabed mining.

3.2.4. Anthropogenic pressures on abyssopelagic biodiversity

Although currently rare, bioprospecting and oil extraction activities on abyssal plains pose additional threats to the health of abyssopelagic and benthic habitats. Commercial fishing and fish farming on the high seas could threaten abyssopelagic diversity if poorly managed nationally and internationally. Poor management of both activities can reduce prey populations, affect food downflux, and undermine biodiversity, including targeted and non-targeted resources. Although currently rare, bioprospecting and oil extraction activities on abyssal plains pose additional threats to the abyssopelagic.

4. Consequences of the changes on human communities, economies and well-being

Despite its apparent remoteness and inhospitality, the deep ocean plays a crucial role in human social and economic well-being through its ecosystem functions and services on a regional to global scale (Armstrong and others, 2012; Thurber and others, 2014; van den Hove and Moreau, 2007) (Tables 1 and 2).

Table 1. Susceptibility of the abyssal seafloor and abyssopelagic zone to climate change-affected environmental drivers and pressures

	Abyssal seafloor impacts	**Abyssopelagic impacts**
Changes in temperature, acidity, salinity, and oxygen patterns	Medium to high	Low
Changes in sea level	Low (through terrestrial influence)	Low (through terrestrial influence)
Changes in severity of storms and intensity of extreme events	Low	Low
Changes in ultraviolet radiation	Low, indirect through bentho-pelagic coupling	Low, indirect through bentho-pelagic coupling
Changes in the physical and chemical aspects of the ocean	Low	Low
Food input	Medium to high	Medium to high

Table 2. Threats and pressures on abyssal ecosystem services and their importance in the abyss

	Abyssal plain threats	**Abyssopelagic zone threats**
Provisioning services		
Fisheries	currently none	currently none
Oil and gas	currently some; also indirect impact through dispersal from shelf and bathyal activity	not currently, but indirect impact through dispersal from shelf and bathyal activity
Methane reserves/potential for gas hydrate extraction	Gulf of Mexico, potentially other areas	not applicable
Hydrogen generation and sub-seabed storage for future carbon capture and disposal	presently unknown	not applicable
Mining (metal rich sediments, polymetallic nodules, rare earth metals, massive sulphides)	moderate to high in future (potential)	moderate to high in future (potential) through mining waste and processing water discharge
Waste disposal	high (widespread)	moderate to high (present)
Bioprospecting	Present, potentially high	high potential, unknown
Military activities and use	unknown	unknown
Other energy provision	not currently	not currently
Supporting services		
Habitat	low to moderate and high in the future	low to moderate and high in the future
Nutrient cycling	moderate	moderate
Water circulation and exchange	moderate	moderate
Chemosynthetic primary production	moderate	moderate
Resilience	High	high
Regulating services		
Gas and climate regulation	moderate	moderate
Waste absorption and detoxification	moderate	moderate
Biological regulation	moderate	moderate
Nutrient cycling	moderate	moderate
Cultural services		
Scientific knowledge	moderate	moderate
Educational value	moderate	moderate
Economic benefits	potentially high	potentially high
Aesthetic, inspirational, ethical, indigenous	High	high
Climatic record in deep-sea sediments	moderate	not applicable

4.1. Impacts on abyssal ecosystem services

Compared to other deep-sea habitats, abyssal plains provide ecosystem services limited in scope but important in magnitude and reach. Few abyssal services, such as mineral resources, could directly benefit humans, whereas most abyssal environments support the processes that drive deep-sea and global ecosystem and Earth climate system functioning on such vast scales that they influence the entire Earth system.

The "biological pump" provides the most important supporting and regulating ecosystem service of the abyssopelagic zone by accelerating transfer of carbon, nutrients, and other compounds from surface waters to the deep sea. Changes in fauna, trophic links, or community composition, or physical alterations in water masses (stratification, warming, deoxygenation, acidification, etc.), can disrupt associated biological processes, with abyssal impacts through benthic-pelagic coupling. Stress imposed by low oxygen, acidification, or elevated temperature can reduce species and ecosystem resilience through shifts in organism tolerance (Pörtner, 2010; Pörtner and Farrell, 2008), thus retarding recovery from disturbance caused by human activities such as seabed mining. Climate-change effects could exacerbate anthropogenic impacts and compromise deep-sea ecosystem structure and function, and ultimately their benefits for human welfare (Mora and others, 2013).

5. Outlook

Many unknowns remain regarding abyssal ecosystems but related research has increased significantly in the last decade with more anticipated, particularly given increasing interest in deep-sea mineral extraction. The United Nations Decade of Ocean Science for Sustainable Development (2021–2030) also includes plans for more deep-sea research.

The emergence of potential deep-seabed mining to exploit polymetallic nodules poses a risk to abyssal ecosystems. However, data collected during current exploration activities may increase deep-sea knowledge in several regions over the next ten years. Researchers frequently lament the substantial lack of taxonomic biodiversity data for most abyssal fauna. Work to collect such data is underway, but will require much more time and resources (Glover and others, 2018).

Studies demonstrate the sensitivity of the abyss to climate change. Despite the difficulties of predicting precise climate change effects over the next 10–20 years, we can expect rising temperatures, declining oxygen concentrations, shallowing of the aragonite saturation horizon, and changes in bentho-pelagic coupling (Rogers, 2015; Sweetman and others, 2017). Considering the slow growth rates of organisms and that they are well-adapted to abyssal conditions of cold, high pressure, stability, and food-poverty, impacts of predicted changes on abyssal communities will likely be more severe than those at shallower depths. Predictions of significant decreases in flux of organic material to the deep seafloor in most oceans may be especially problematic for abyssal areas. Future research will enhance abyssal biodiversity knowledge and increase our understanding of how climate change and anthropogenic activities will impact abyssal ecosystems.

Globally, the protection of abyssal-environments may increase. The Convention on Biological Diversity classification of Ecologically or Biologically Significant Areas (CBD, 2008) includes these environments and further efforts are underway through the International Seabed Authority's Regional Environmental Management Plans in connection with seabed mining, as well as legislative developments to manage Biodiversity Beyond National Jurisdiction.

6. Key remaining knowledge gaps

Despite recent advances in our knowledge of abyssal ecosystems, many gaps exist in understanding abyssal biodiversity, evolution, biogeography and distributions, connectivity, and responses to changing conditions and anthropogenic impacts.

The current poor state of taxonomic, natural history and biodiversity knowledge of the fauna on abyssal plains limits environmental impact monitoring and exposes the need for baseline studies that provide species lists and numbers. Given that more than 95 percent of species in planned mining areas are undescribed, current monitoring protocols are inadequate. Despite ongoing efforts to create the necessary faunal catalogues and taxonomic knowledge (Glover and others, 2016b; Dahlgren and others, 2016; Wiklund and others, 2017), future efficient monitoring requires sustained resources.

Very few studies have examined abyssal hard-bottom habitats and, although some megafauna information exists, we lack almost any information on associated microbes, protists, meiofauna, or macrofauna.

Vast areas of the abyssal seafloor remain completely unsampled. Records in international databases (e.g. OBIS), suggest particularly severe undersampling of the southern Pacific Ocean, as well as the deep Indian Ocean and Bay of Bengal.

We have limited knowledge about species geographic ranges, connectivity patterns, or resilience of assemblages to climate stressors or direct human disturbance in the abyss. Effective management of human activities to sustain deep-sea biodiversity hinges upon such information. In addition, poor characterization of abyssal contributions to ecosystem goods and services limits availability of appropriate tools to value human benefits adequately (Jobstvogt and others, 2014a, 2104b; Thurber and others, 2014).

The lack of documentation on and relating to management of human impacts on such a vast, dynamic space, almost all of which is located beyond national jurisdictions, may represent the single most important knowledge gap.

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Chapter 7P
Open Ocean

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Keynote points

- Global warming is already impacting the open ocean and marine heatwaves are likely to increase in frequency and strength in the future.
- Climate change induced changes in the open ocean biological pump will alter the ocean's ability to take up anthropogenic carbon.
- Deoxygenation of the open ocean is already leading to habitat compression for some pelagic species with subsequent impacts on fisheries.
- Increasing fluxes of plastic litter from the land are impacting open ocean ecosystems.
- A critical knowledge gap exists for deep pelagic (e.g. mesopelagic and bathypelagic) environments as they are poorly sampled and understood.

1. Introduction

1.1. Topic scope

Chapter 36F of the First World Ocean Assessment (WOA I) (United Nations, 2017a) included an assessment of both the open ocean (pelagic zone) and deep sea (benthic zone) ecosystems seaward of the continental shelf (200 m depth). In the present, updated Assessment, benthic ecosystems are treated separately, and this Chapter focuses solely on the pelagic realm throughout the full water column.

Previously, WOA I (United Nations, 2017b) found that the open ocean provided essential marine ecosystem goods and services, despite its relative inaccessibility. Furthermore, there was great potential for mineral, energy and living resources from these pelagic areas, although they were poorly studied spatially and temporally, which made conservation issues complicated as so little was known about biodiversity and ecosystem function.

1.2. Pelagic realm

The main physical drivers structuring pelagic ecosystems are depth/pressure, light, temperature, nutrient inputs (e.g. nitrogen, iron), dissolved oxygen and currents. The surface zone of the open ocean (epipelagic, down to 200 m) is defined by sufficient sunlight penetration to support primary production. Below this zone is the mesopelagic or "twilight" zone, generally extending from the bottom of the epipelagic zone to about 1,000 m - the maximum depth of sunlight penetration and the bottom of the permanent thermocline. The mesopelagic zone is important for active vertical migration and the microbial degradation of organic matter sinking from the surface - two key elements of the biological pump (Robinson et al., 2010). The daily vertical migration of deep-sea organisms from the mesopelagic to the epipelagic and back is increasingly appreciated as a driver of carbon flux due to increased estimation of mesopelagic nekton biomass (Irigoien and others, 2014).

The planet's largest ecosystem comprises the bathypelagic domain, a dark and cold (0–5° C) zone found between 1,000 and 4,000 m, comprising almost 75 per cent of ocean volume (Costello et al., 2010). The deep pelagic ocean is underobserved and undersampled due to a combination of factors: (i) limited access to open ocean sampling platforms for obtaining deep-water samples; (ii) the large ocean volume involved; and (iii) the widely dispersed populations. Data on mesopelagic ecosystems are improving, but still very little is known regarding organisms from the deeper zones, including the bathypelagic, abyssopelagic (4,000–6,000 m) and hadalpelagic (> 6,000 m) zones. Initial results indicate that the overall diversity of species may be less than in other ecosystems, although new microbial studies are revealing great diversity in the deep ocean. Surveys have shown that lateral connectivity also occurs between the deep zones of the open ocean and is not just limited to the mesopelagic and surface (Sutton, 2013).

Crustaceans (copepods, amphipods, ostracods, etc.) are important contributors to the abundance and species numbers of zooplankton in the deep ocean. Gelatinous animals, such as, inter alia, salps, jellyfishes and colonial siphonophores are also very important. Larger organisms present include many species of fishes, sharks, crustaceans (shrimps, krill, etc.) and cephalopods (squids, etc.). Biomass estimates based on acoustic measurements indicate that mesopelagic fishes may have been seriously underestimated in the past. They likely represent ~10,000 – 15,000 million tons and are responsible for respiring up to 10 per cent of primary productivity (Irigoien et al., 2014). Deep pelagic fish biomass is likely the overwhelming majority of fish biomass on the planet (Sutton, 2013). These species are also important prey for mammals (toothed whales and seals), tunas, seabirds and deep demersal fishes.

1.3. Pressures on the pelagic realm

The open ocean is impacted by multiple environmental stressors, most notably ocean warming, acidification and deoxygenation. These stressors are likely to promote shifts in the latitudinal and vertical distribution of open-ocean and deep-sea fisheries (Brander, 2010), whereas deoxygenation may result in habitat compression for aerobic organisms (Stramma et al., 2012) while expanding the volume of water supporting anaerobic processes. Changes in bottom-up or top-down forcing will likely result in complex and indirect effects on open ocean ecosystem services, most notably the biological carbon pump, though the overall impact is unclear as so little is known about microbial diversity, function and processes in the deep ocean.

1.4. Knowledge gaps identified in WOA I

It was noted in WOA I that key information about pelagic ecosystems was lacking, as data were available only from a few geographic areas and on a fraction of overall biodiversity. WOA I highlighted that information on ecosystem structure and processes are insufficient to assess the potential performance of conservation and management measures that have been developed for shelf and coastal marine ecosystems.

1.5. Scientific advances since WOA I

The ocean, including the open ocean, was the subject of a recent special report by the Intergovernmental Panel on Climate Change (IPCC, 2019). A key advance has been acknowledgement that the multi-stressor nature of climate change on the open ocean will require new tools for analysing the impacts of each stress on the ecosystem and the synergistic interactions among stressors as the response may be very non-linear (Boyd et al., 2015).

Diel vertical migrations have been inferred from space using a satellite-mounted light detection and ranging (LIDAR) instrument (Behrenfeld et al., 2019), providing new insights into this biogeochemically important process. Knowledge of the global distribution of trace elements and their isotopes in all ocean basins has been significantly advanced by the international GEOTRACES programme (Schlitzer et al., 2018). Our understanding of the physics and biogeochemistry of the open ocean has expanded both spatially and temporally through the increased use of Argo floats (Roemmich et al., 2019) and ocean gliders (Rudnick, 2016). These data, along with repeat hydrography surveys via GO-SHIP (Sloyan et al., 2019), have helped to inform new insights into the function of the biological pump with a further pathway discerned, namely, the particle injection pump (Boyd et al., 2019), which acts together with the traditional biological gravitation pump.

Over the last decade, rapid advances in omics have been quickly applied to open-ocean studies. This has allowed for near real time, at-sea sequencing of the microbial community (Bennke et al., 2016); the application of environmental DNA (eDNA) to detect white sharks in the open ocean (Truelove et al., 2019); or combining eDNA with autonomous underwater vehicles to examine biodiversity (Yamahara et al., 2019). The increasing use of smart tags and sensors attached to organisms (Harcourt et al., 2019), passive acoustic sensors (Delory et al., 2014) and new visualization tools for marine particles (Lombard et al., 2019) are providing new data on the biodiversity and function of open ocean ecosystems. In particular, our understanding of the mesopelagic zone has evolved to establish global biogeographic and biogeochemical provinces (Reygondeau et al., 2018).

2. Environmental changes in the open ocean since 2010

2.1. Changes in the overall status (including physical or biological state)

2.1.1. Ocean warming, marine heatwaves and wind patterns

The evidence is now clear that the ocean is warming over recent decades (Cheng et al., 2019) and, while the surface ocean has absorbed most of the extra heat, the warming signal is also observable in the intermediate and deep ocean (Cheng et al., 2017). Surface warming has been predicted to result in greater stratification of near-surface waters, although recent work indicates that, while sea surface temperatures are increasing at mid-latitudes, stratification is not increasing nor are mixed layer depths (MLDs) shoaling (Somavilla et al., 2017). In fact, winter MLDs have been increasing due to changes in Ekman pumping (Somavilla et al., 2017).

As global temperatures have increased, marine heatwaves (MHWs) (Hobday et al., 2016) have become longer and more frequent in recent years (Oliver et al., 2018). Modelling studies suggest that MHWs are also very likely to increase in the future under global warming (Frölicher et al., 2018). MHWs in the tropical Pacific and Indian oceans are driven by the El Niño-Southern Oscillation and related teleconnections (Holbrook et al., 2019) while, in higher latitudes, MHWs are associated with shifts in warm ocean currents, mesoscale eddy activity and atmosphere-ocean dynamics (Rodrigues et al., 2019). The thermohaline circulation, has been weakened in recent years due to global warming and its consequences on temperature and climate patterns in countries bordering the Atlantic and the equatorial zone around the globe and in the ecosystem services are increasingly profound (Ramshtorf et al., 2015).

Wind patterns have also changed over the open ocean over the last three decades, with small increases in the average wind speed and wave height. Larger increases were seen for extreme conditions (wind speed or wave height exceeding 90th percentiles) (Young and Ribal, 2019). Satellite observations from 1995-2018 showed the strongest increases in wind speed and wave height in the Southern Ocean.

2.1.2. Ocean acidification

Most recent estimates of the uptake of anthropogenic carbon by the open ocean (1994–2007) indicate that the uptake is increasing but with important regional deviations, for example, uptake was slower than expected in the North Atlantic, but faster in the South Atlantic (Gruber et al., 2019). Open-ocean time series studies, gathered through the inclusion of autonomous marine carbon sensors (e.g. pH and pCO_2), going back almost 20 years at some sites, show clearly observable trends in pH (decreasing) and pCO_2 (increasing) (Sutton et al., 2019).

2.1.3. Ocean deoxygenation

Oxygen loss from the open ocean is expected to increase in a warming world through a complex set of biogeochemical and physical processes (Levin, 2018). The capability to measure dissolved oxygen at nanomolar levels has indicated that anoxic (zero oxygen) regions may have been underestimated previously in the open ocean (Tiano et al., 2014). The impact of climate change on respiration is poorly understood at present, particularly for microbes (Robinson, 2019), where complex feedbacks may result in the redistribution of bacterial and archaeal species in the ocean (Beman and Carolan, 2013) as organisms align to specific niches within the different redox zones (Bertagnolli and Stewart, 2018). Despite being hypoxia-tolerant, some open-ocean zooplankton are already living close to their physiological limits and continued deoxygenation may cause unanticipated changes to ecosystem structure and function in the mesopelagic zone (Wishner et al., 2018).

2.1.4. Human impacts: Remaining wilderness areas and the rise of plastic pollution

The ocean has been strongly impacted by human activities, (Jones et al., 2018), most of the remaining wilderness areas identified lie outside of exclusive economic zones (i.e., areas beyond national jurisdiction). Despite being far from land-based sources, the abundance and extent of plastic litter in the open ocean is increasing (van Sebille et al., 2015). Open-ocean gyres are acting as zones of accumulation for plastic pollution, the so-called garbage patches, (Lebreton et al., 2018). The flux of microplastic litter to the open ocean is predicted to increase greatly in the future (Lebreton and Andrady, 2019).

2.2. Factors associated with the changes

2.2.1. Ocean warming and changes to the ocean carbon pump

Warming of the open ocean reduced marine fisheries production by up to an estimated 4.1 per cent between 1930 and 2010, based on hindcast models (Free et al., 2019). Ocean warming is suggested to have more of an impact than ocean acidification on global circumpolar fish stocks (Watson et al., 2018). Overall, the open ocean is likely to have a greater vulnerability to thermal stress compared to land (Pinsky et al., 2019), which may result in a higher sensitivity to warming and faster rates of colonization, resulting in faster species turnover. Warming has already promoted a poleward shift in the distribution of some species (Pinsky et al., 2020), including commercial species such as tuna (Monllor-Hurtado et al., 2017). While some seabird distributions appear to be insensitive to shifting ocean temperatures (Keogan et al., 2018), a MHW in the Northeast Pacific caused extreme mortality of common murres (Piatt et al., 2020). In this context, MHWs are likely to greatly impact biodiversity in the open ocean (Smale et al., 2019).

Large uncertainties remain as to whether a warming ocean will alter primary productivity (Behrenfeld et al., 2016), although modelling suggests small decreases with increasing temperatures in the tropical ocean (Kwiatkowski et al., 2017). However, the strong temperature dependence of metabolic rates in the upper ocean is likely to impact the biological carbon pump, particularly microbial species (Cavan et al., 2019), and may act as a positive feedback to climate by reducing the net sequestration of carbon by the ocean (Boscolo-Galazzo et al., 2018).

Global warming may also be impacting the timing (phenology) of phytoplankton blooms in the open ocean (Barton et al., 2016), although changes in insolation are the main driver for phytoplankton (Boyce et al., 2017) and may ultimately limit poleward migration of species (Sundby et al., 2016). Warming may be reducing the time lag between phytoplankton, protozoan production (Aberle et al., 2012) and zooplankton abundance, with implications for higher trophic levels (Sundby et al., 2016) and for the biological carbon pump and its resulting ecosystem services (Barange et al., 2017).

While changes in pH and carbonate concentration are likely to be less dramatic in the open ocean than in coastal waters (Duarte et al., 2013), biodiversity may be negatively impacted in regions where the uptake of anthropogenic CO_2 is greatest (e.g. North Atlantic) (Gehlen et al., 2014). Other biogeochemical processes will be impacted with decreasing pH (Gehlen et al., 2011) and, already, evidence exists for decreases in nitrification rates in the open ocean (Beman et al., 2011), which could alter the microbial community and nitrogen cycling in the future.

2.2.2. Deoxygenation - habitat compression

Ocean deoxygenation is resulting in the expansion, both vertically and horizontally, of oxygen minimum zones (Levin, 2018), which can lead to habitat compression of some pelagic organisms (Stramma et al., 2012) through metabolic constraints (Deutsch et al., 2015). Habitat compression may also lead to increases in the catchability of some billfishes in the Eastern Pacific, with potential for overexploitation unless managed carefully (Pohlot and Ehrhardt, 2017).

2.2.3. Direct human impacts

The cumulative impact of human activities on the open ocean is changing both temporally and spatially (Halpern et al., 2015), resulting in only a small proportion of marine wilderness areas of the open ocean remaining (Jones et al., 2018). Aside from the impacts of anthropogenic carbon emissions, other human activities also directly impact the open ocean.

Fishing activities. Marine foods are now sourced farther away from where they are consumed (Watson et al., 2015), thus expanding the global footprint of fisheries on the open ocean (Kroodsma et al., 2018). Ultimately, however, marine productivity limits the amount of fish that are available (Chassot et al., 2010) and currently global fisheries appear to have reached a plateau (see Chapter 15)..

Human-induced contaminant plumes in the open ocean. Industrial activities in the open ocean are impacting biodiversity through continuous emission of pollutants (Tournadre, 2014) as well as transient events. Oil spills such as the Deepwater Horizon disaster in 2010 in the Gulf of Mexico showed that the impact of such an event is felt across all trophic levels for many years (McClain et al., 2019). Modelling efforts suggest the impact on the ecosystem could last for decades (Ainsworth et al., 2018). Deep-sea mining and the marine disposal of mining wastes are also likely to impact the open ocean (Vare et al., 2018). The effects of dumping mine tailings in deep water (Ramirez-Llodra et al., 2015) are still poorly understood with regard to the impact on (meso)pelagic organisms.

2.3. Impacts of the changes on/interactions with other components of the marine system

2.3.1. Changes in ecosystem services

Currently there is a lack of information with regard to the ecosystem services of the mesopelagic and bathypelagic communities (Martinetto et al., 2020; St. John et al., 2016). Similarly, there are few examples of studies examining the extent of benthic-pelagic coupling in the ocean (Trueman et al., 2014).

2.3.2. Indirect climate change impacts on higher trophic levels

Changes in circulation due to climate warming in the North Atlantic have resulted in a northward shift of the copepod *Calanus finmarchicus*, the main food source for the endangered Northern Right Whale. These changes have led to the whales altering their seasonal foraging pattern to follow the copepods. Unfortunately, the redistribution of whales into regions where protections from ship strikes or entanglement with fishing gear are not yet in place results in a stall in the recovery of this species (Record et al., 2019).

3. Consequences of the changes on human communities, economies and well-being

3.1. Currently observed consequences

The open ocean is a special case when it comes to assessing the consequences of ecosystem change to humans, as there are no permanent human communities living in/on the open ocean at present. However, there are many coastal communities that depend on resources extracted from the open ocean and they will be impacted by the effects of climate change on ecosystems there. Some impacts are already starting to be observed, such as changes in species distributions resulting from poleward shifts in taxa (Barton et al., 2016) and habitat compression due to deoxygenation (Stramma et al., 2012).

Recent work suggests that the adoption of the Paris Agreement[122] has benefits for fisheries (Sumaila et al., 2019) and that improved fisheries management could offset some of the impacts of climate change to fisheries (Gaines et al., 2018).

3.2. Implications for achieving the Sustainable Development Goals (SDGs)[123]

3.2.1. Reducing marine pollution (SDG indicator 14.1.1)

The avalanche of plastic materials entering the oceans requires action by States to eliminate or reduce plastic use where possible. Recent initiatives in the European Union and elsewhere, to reduce plastic usage, increase recycling, to ultimately limit plastic waste entering the environment, in response to public pressure, are welcome but more needs to be done by all States if a significant reduction is to be achieved by 2025.

3.2.2. Assessing biogeochemical changes in the ocean (SDG indicators 14.2.1/14.3.1)

Modelling work has indicated the timescales required to assess and detect climate change-driven trends in the open ocean (Henson et al., 2016), referred to as a time of trend emergence (ToE). Continuous time series data are required for between 14 (pH) and 32 (primary productivity) years to distinguish climate change from natural variability. Similarly, pH and pCO_2 data collected at open ocean time series sites suggest 8 to 15 years to achieve ToE (Sutton et al., 2019). Developing new and extending existing time series sites in the open ocean will require investments in both technology and human capacity (Miloslavich et al., 2018).

3.2.3. Marine reserves (SDG indicators 14.5.1/14.c.1)

Increasingly large areas of the open ocean are being designated as marine reserves or marine protected areas (MPAs), most notably in the Pacific (e.g. Chile:Rapa Nui Marine Protected Area and USA:Papahānaumokuākea Marine National Monument) and managing these pelagic protected areas will be challenging (Norse, 2005). All of these MPAs will contribute to SDG 14, though more progress is still to be made (Lubchenco and Grorud-Colvert, 2015) as few existing MPAs are in areas beyond national jurisdiction. The outcome of the intergovernmental conference on an international legally binding instrument under the United Nations Convention on the Law of the Sea on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction will be a key step in establishing the legal framework for MPAs in the high seas (see also Chapter 30).

3.2.4. Fisheries (SDG indicator 14.4.1)

Achieving sustainable development of fisheries in the open ocean is complicated even with the existence of several legal frameworks in each region (see SDG indicators 14.5.1/14.c.1mentioned above, 14.6 (subsidies) also applies here), most probably due to insufficient knowledge on the overall structure and function of open ocean ecosystems. In particular, potential development of an industry based on mesopelagic fishes will require refinement of stock assessment methods and the inclusion of new technologies and modelling approaches (Hidalgo and Browman, 2019). Climate change will also impact open ocean

[122] See FCCC/CP/2015/10/Add.1, decision 1/CP.21, annex.
[123] See United Nations General Assembly resolutions 70/1, and 71/313, annex.

ecosystems and their related fisheries (Barange et al., 2018). Illegal, unreported and unregulated (IUU) fishing remains one of the greatest threats to sustainable fisheries and a global challenge.

3.2.5. Research resources for marine technology (SDG indicator 14.a.1)

More resources are needed for marine research and technology and building capacity, both technical and human, for collecting, interpreting and disseminating knowledge on the open ocean. This includes developing ocean basin-wide cooperation through the Global Ocean Observing System and related organizations. Activities within the United Nations Decade of Ocean Science for Sustainable Development (2021–2030)[124] should greatly benefit the achievement of this indicator.

4. Key region-specific changes and consequences

4.1. Arctic Ocean

The Arctic continues to warm rapidly, with subsequent loss of multi-year sea ice impacting ecosystems in the open ocean Arctic, combined with global warming and ocean acidification. This could lead to major changes in primary productivity, biodiversity and ecosystem function. Additionally, the poleward shift of many North Atlantic species (see below) is impinging increasingly into the polar Arctic.

4.2. North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean Sea and North Sea

Ocean warming is resulting in the poleward shift of many species with potential changes in ecosystem function. Regional seas are likely to be further impacted by pollution from microplastics unless the sources of these materials to the open ocean are not significantly reduced.

4.3. Tropical North Atlantic and Caribbean

Sargassum blooms are likely to further impact the Caribbean in years to come (Putman et al., 2018), and the impact there is likely to affect tourism negatively, though in other regions it might provide new opportunities (Milledge and Harvey, 2016). Large Sargassum blooms provide extensive physical structure at the surface while shading the waters below, possibly impacting phytoplankton productivity but also aggregating fishes in the shadows below the Sargassum rafts. The gyre structure of North Atlantic currents is concentrating macroplastics and microplastics into a “garbage patch” (Poulain, 2019). Intensification of hurricanes may be affecting meso- to large-scale mixing processes .

4.4. South Atlantic Ocean

MHWs are becoming more common in the South Atlantic with serious implications for climate patterns and hence for fisheries. Another adverse phenomenon involves increasing, frequency of South Atlantic Tropical Storms under climate change.

[124] See United Nations General Assembly resolution 72/73, para. 292.

4.5. Indian Ocean, Arabian Sea, Bay of Bengal, Gulf of Aden and the Persian Gulf

As the Indian Ocean warms in response to climate change, more MHWs are likely in the future, resulting in changes to ecosystem function and dynamics with subsequent impacts on the communities in the region that rely on fisheries.

4.6. North Pacific Ocean

The North Pacific gyre is likely to become more heavily impacted by microplastic pollution, with the potential impacts on the marine ecosystems not yet fully known or understood. Ocean warming, acidification and deoxygenation are also likely to cause changes in marine ecosystems and productivity. Increased MHWs are impacting ecosystems of the northeastern Pacific, inter alia, leading to pyrosome blooms and starvation of fish-eating birds (Piatt and others, 2020).

4.7. South Pacific Ocean

MHWs are likely to become more frequent and pronounced in the future. The oxygen minimum zone in the Eastern Tropical South Pacific is expected to expand both horizontally and vertically, impacting the distribution of pelagic fisheries. For ocean-dependent Pacific islands, climate change is likely to have a sizeable impact on livelihoods, health and culture.

4.8. Southern Ocean

The Southern Ocean is continuing to warm, and accounts for a largest proportion of the global increase in heat in the ocean (IPCC, 2019). A likely consequence of this is further contraction of the sea-ice habitat for krill southward, and a shift towards salp-dominated states, impacting higher trophic organisms (seals, whales and penguins) for which krill are a key prey species. The Southern Ocean will continue to remove CO_2 from the atmosphere, resulting in a lower pH, with potential for further decreasing calcification rates.

5. Outlook

5.1. The open ocean in the near future

Over the next decades, the open ocean will become warmer, deoxygenated and more acidic due to the impacts of climate change (IPCC, 2019). The different timescales of these multiple stressors and interactions among them will lead to changes in ecosystem function and structure on a variety of temporal and spatial scales. The time frame of these impacts will vary regionally and take longer to manifest at depth due to the volume and slow circulation of the deep ocean.

5.2. Ecosystem consequences of continued changes in the open ocean

Global change is impacting ecosystems services in the open ocean (blue economy), but it is difficult to predict future changes due to the overlapping effects from multiple stressors (Boyd et al., 2018). Habitat compression due to expanding oxygen minimum zones and continued poleward migration of some key taxa are expected to cause ongoing change in open ocean ecosystems. Changes in productivity and the biological pump will impact the sequestration of carbon into the deep sea.

5.3. Socioeconomic consequences of ongoing changes in the open ocean

Ongoing changes in the open ocean will have a wide-ranging socioeconomic impact over time as related activities will need to adapt (e.g. migration of fisheries due to warming and deoxygenation, increases in sargassum seaweed) and mitigate (e.g. microplastic pollution, maritime emissions) in response. The development of large-scale marine reserves and protected areas in the open ocean as actions to meet the SDGs will also require new international agreements regarding the establishment and monitoring of these areas. Increased demand for global observations of the open ocean (Levin et al., 2019; Miloslavich et al., 2018) will require greater investment in both equipment and human capacity to interpret data and provide informed assessments for advising and implementing policy.

6. Key remaining knowledge gaps

We still know very little about open ocean ecosystems and the impact of physical drivers on the biodiversity found there. Critically, the mesopelagic and deeper zones of the ocean are severely underexplored and poorly understood, including exchanges between the deeper and upper ocean, chiefly the daily vertical migration of organisms. There is also a need to ensure that basic information (e.g. traditional taxonomy) is collected about species that live in these environments, as omic data is only one of many strands that inform biodiversity (Boero, 2010).

7. Key remaining capacity-building gaps

Further development of deep-water Argo and associated sampling platforms (e.g. Underwater Video Profilers, eDNA samplers, biogeochemical sensors) for the mesopelagic (Martin et al., 2020) and deeper waters is critical to improving our understanding of this vast area of the ocean. Recent activities such as OceanObs19 have helped to identify capacity gaps on the ocean basin scale and efforts should therefore be targeted towards States working together to achieve adequate coverage for observational oceanography on such scales. Education and training of the next generation of researchers in all aspects of marine research is key to developing the human capacity to maximize the utilization of new technologies for this purpose (Levin et al., 2019).

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Chapter 7Q
Ridges, Plateaus and Trenches

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Keynote points

- Most recent studies of ridge biology address chemosynthetic environments (see Chapter 7R of the present Assessment).
- Climate change models show that bathyal environments will suffer a reduction in pH, which will affect benthic communities.
- Ridges, rises, plateaus and banks are under human pressure arising from existing and potential exploitation of resources, while evidence of pollution in trenches is accumulating.
- The vulnerability of those ecosystems to human pressures has triggered both increased societal awareness and new regulations.

1. Introduction and summary of the First World Ocean Assessment (WOA I)

Chapter 51 of the First World Ocean Assessment (WOA I) (United Nations, 2017a) was devoted to deep-sea features considered to be potentially threatened by human disturbance. These features, including seamounts, ridges and plateaus, submarine canyons and hadal trenches, are all topographically and hydrographically complex. Of these features, the present Assessment considers seamounts (Chapter 7N) and canyons (Chapter 7L) elsewhere, along with hydrothermal vents and other chemosynthetic ecosystems (Chapter 7R), which were also covered separately in WOA I (United Nations, 2017b). For each of the features considered, Chapter 51 provided detailed descriptions, including geology and physical oceanographic characteristics, extent (numbers of each feature as well as percentage of oceanic area) and ecological characteristics such as biodiversity and biogeography. It also documented anthropogenic impacts on these features, highlighting fishing (including removal of species and biomass, as well as the physical effects of fishing activities on structure-forming benthic communities), climate change (including acidification and deoxygenation, as well as rising temperatures), pollution, dumping, and mining. The present Chapter builds on this background by focusing on changes and new knowledge regarding ridges, plateaus and hadal trenches gained since 2010.

1.1. Ridges

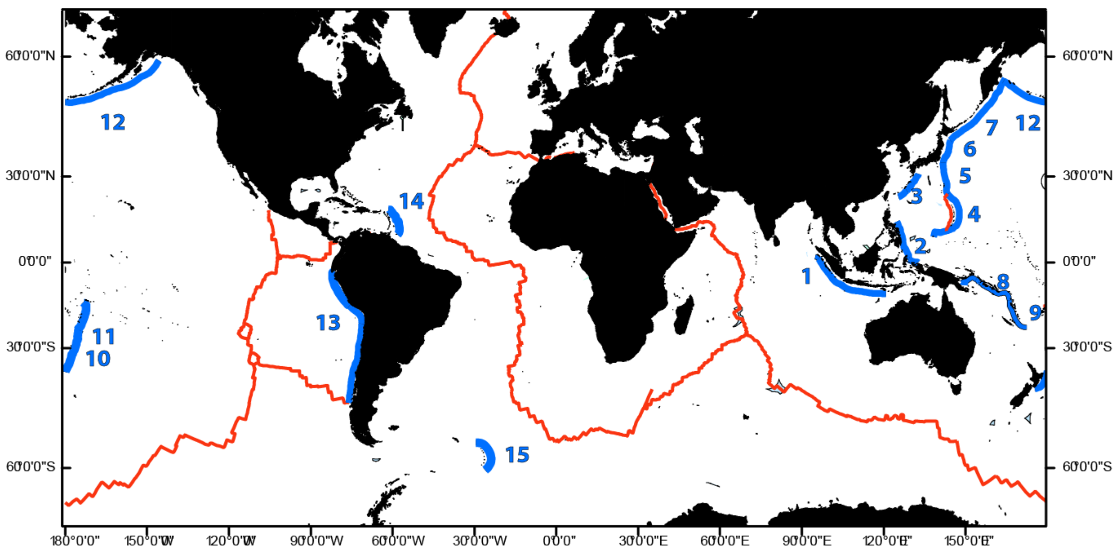
Mid-ocean ridges (MOR) subdivide the major ocean basins (Figure 1), but fracture zones at intervals permit movement of deep water and abyssal organisms (see Chapter 7O) between basins on the two sides of a ridge. Chapter 7R deals with active hydrothermal vents often associated with mid-ocean spreading ridges (Beaulieu and others, 2013), whereas Chapter 7N considers seamounts associated with ridges. Biogeographically, ridge faunas generally appear related to the faunas of adjacent basins or continental slopes (Alt and others, 2019; Watling and others, 2013). Ridges can host structure-forming benthic invertebrates such as cold water corals (Chapter 7F) and sponges, some of which are classified as indicator species of vulnerable marine ecosystems as defined by the Food and Agriculture

Organization (FAO, 2009). The island slopes and summits of seamounts (Chapter 7N) associated with ocean ridges are important areas for fisheries. Most ridges are in areas outside exclusive economic zones (EEZ) (Harris and Whiteway, 2009).

1.2. Hadal trenches

Hadal environments are relatively unknown because of the challenge of accessing extreme depths. However, because of their locations on the subduction edges of tectonic plates, the trenches are all close to land masses or islands and entirely or partly within EEZ. For example, the Mariana Trench, near territory claimed by the United States of America, lies almost entirely with the United States EEZ, while the Kermadec-Tonga Trench traverses the EEZ of New Zealand and the Kingdom of Tonga (Flanders Marine Institute, 2018). Thus, whilst trenches all potentially occur within the limits of national jurisdiction, some are shared by more than one State and the technical capacity of these different States to monitor and manage threats to hadal environments varies widely. The hadal zone, with depths below 6,000 m, occupies 45 per cent of the total ocean depth range, but only 0.404 per cent of total ocean area. Within this area, 95 distinct basins or trenches have maximum depths of 7,000 m or more, and are dominated by 15 recognized trenches (Priede, 2017) (Figure 1). For biological purposes, the United Nations Educational, Scientific and Cultural Organization redefined the upper boundary of the hadal zone as a depth of 6,500 m to reflect the boundary between the globally widespread abyssal fauna and the upper limit of the specialized hadal fauna (UNESCO, 2009). Except for higher pressure, the environment in hadal trenches is typical of much of the deep sea, with slow currents of 1 to 8 centimetres per second carrying water at approximately 2° C with sufficient oxygen (3.43 millilitres per litre) to support aerobic life, and a slow rain of particulate organic matter from the surface providing food (Jamieson and others, 2010).

Figure 1. World map with hadal trenches (depths greater than 6,000 m below sea level – blue segments): 1–Java, 2–Philippines, 3– Ryukyu, 4–Marianas, 5–Izu-Bonin, 6–Japan, 7–Kuril-Kamchatka, 8–New Britain, 9–South Solomon, 10–Kermadec, 11–Tonga, 12– Aleutian, 13–Ecuador to Chile, 14–Puerto Rico, 15–South Sandwich/Islas Sándwich del Sur. (Red) World's ocean-ridge system. (Adapted from Bird, 2003)



1.3. Plateaus, rises and banks

These are large and relatively flat topographic features, identified as continental fragments or micro-continents and often separated from major continents by deep-water channels. Currently, 184 plateaus have been mapped (Harris and others 2014), covering approximately 5 per cent of the world's oceans. Although found in all the world's oceans, plateaus are most prevalent in the Indian Ocean (e.g. Kerguelen and Mascarene plateaus) and the South Pacific (Challenger and Campbell plateaus), which reflects their recently recognized origin from tectonic break-up of the Gondwana supercontinent (Mortimer and others, 2017). Faunal diversity and composition can closely resemble that of nearby continental shelves, slopes and banks (Narayanaswamy and others, 2013). However, topographic and oceanographic complexity, combined with food availability, can have a major influence on community composition and diversity (Compton and others, 2013; Knox and others, 2012). Compton and others (2013), investigating amphipod communities around New Zealand, reported higher abundance and diversity on the more complex Chatham Rise compared to the western end of the Challenger Plateau, with its comparatively lower food supply. However, Leduc and others (2012) rejected food availability as a primary driver of nematode community composition.

Deep-water fisheries target the slopes of plateaus, rises and banks (e.g., Johnson and others, 2019). Emerging activities such as mining also pose threats to these environments (e.g. Leduc and others, 2015).

2. Description of the environmental changes (between 2010 and 2020)

2.1. New knowledge acquired since 2010 and how it can be used to evaluate changes

Changes due to human pressures have been observed and, consequently, some measures of protection for bottom habitats (ridges, trenches and plateaus) are being applied (Table 1).[125] A huge advance in knowledge resulted from the Census of Marine Life that ended in 2010 but for which publication has continued well into the current decade. Many of those publications (2010–2014) were reviewed for WOA I. We summarize other advances below.

2.1.1. Ridges: biodiversity and ecosystem function

Substantial progress in the study of ridges has been reported over the past decade. Mid-ocean ridges increase environmental heterogeneity and influence biological communities (Alt and others, 2019). On the Indian Ocean ridges, the first detailed investigation of megafaunal assemblages (Sautya and others, 2017) showed that abundances were higher at the upper bathyal zone but lower at deeper zones in rift valley walls and floors. Recent seabed mapping in the southern Indian Ocean has improved the resolution of large-scale features and has revealed an unknown diversity and complexity of seabed morphology that will likely be reflected in biodiversity of benthic communities (Picard and others,

[125] See http://www.mpatlas.org/map/high-seas/.

2018).

Further discoveries of deep ocean seabed complexity will be made as mapping continues, particularly through global initiatives such as the GEBCO-Nippon Foundation Seabed 2030 Project."

Large portions of the MOR system fit the criteria of the Food and Agriculture Organization of the United Nations for defining vulnerable marine ecosystems (VME) (Morato and others, 2018) while others are considered priority habitats in need of protection by regional conventions such as the Convention for the Protection of the Marine Environment of the North-East Atlantic.[126] Recent ridge studies have showed the importance of VME indicator species. Both cold water coral communities and sponge grounds are important for global biogeochemical cycles and the ocean's benthic pelagic coupling loop, responsible for nearly 30 per cent of the transfer of organic matter produced at the ocean surface, and the seafloor (Cathalot and others, 2015).

The diverse benthic communities along the northern Mid-Atlantic Ridge (MAR) provide a complex three-dimensional structural habitat that provides refuge, feeding opportunities and spawning and nursery areas for a wide range of associated sessile and mobile species, including commercially important fish and crustacean species (Beazley and others, 2013; Pham and others, 2015; Gomes-Pereira and others, 2017). For example, deep-water sharks were found to lay eggs among cold water corals (Henry and others, 2013). The presence of large black coral colonies with high longevity (several millenniums) in the MAR is also indicative of well-preserved environments.

Large fracture zones not only allow communication of water masses between basins separated by the MAR but also can act as a conduit for larval dispersal. Along the Vema Fracture Zone, macrofauna abundances were generally higher on the eastern than the western side (Brandt and others, 2018). Much new knowledge of ridges in the last ten years has been acquired in relation to interest in finding polymetallic sulphide (PMS) and cobalt-rich manganese crusts enriched in valuable metals for mining. However, because most of these data relate to hydrothermal vents, they are not dealt with here (see Chapter 7R). Geological, geochemical and geophysical studies conducted for submission to the Commission on the Limits of the Continental Shelf provide another major source of new information about ridges. Although these data are not directly collected for environmental understanding, they may address this need in the future. For example, these data may be used to model the distribution of suitable habitat for fauna, which may provide valuable input for management (Lecours, 2017). Some work on habitat suitability models already show that, together with the margins, MOR contain important and suitable habitats for seven suborders of Octocorallia (Yesson and others, 2012) and scleractinian corals (Davies and Guinotte, 2011), with the north MAR being particularly important to these taxa.

2.1.2. Deep-sea fishing on MOR

Deep-sea trawling has direct impacts on deep-sea benthic communities where the gear touches the seafloor, whereas bottom longlines have a much smaller impact but still affect some of the oldest continuously living organisms on the northern MAR (Pham and others, 2014).

[126] United Nations, *Treaty Series*, vol. 2354, No. 42279.

2.1.3. Climate

Climate change projections for the deep sea indicate substantial effects in bathyal habitats (200–3000 m depths), including ridges, and their communities (Levin and others, 2019a). Recent model projections by Sweetman and others (2017) indicate that bathyal depths worldwide will experience significant reductions in pH (0.29 to 0.37 pH units) in all oceans by 2100, and oxygen concentrations will decline by as much as 3.7 per cent in the bathyal Northeast Pacific and Southern Oceans. The flux of particulate organic matter (marine snow) to the sea floor will decline significantly in most oceans, most notably in the bathyal Indian Ocean with a predicted decrease of 40–55 per cent by the end of the century. Models also predict a decreased calcium carbonate saturation rate throughout the world's oceans (Zheng and Cao, 2014). Marine calcifying organisms inhabiting cold waters and deep areas may be particularly sensitive to projected changes in carbonate chemistry (Levin and others, 2019a). Where ridges occur at bathyal depths, ridge fauna will likely experience all of the aforementioned climate-related effects (Levin and others, 2019a).

2.1.4. Hadal trenches

The last decade has seen a great increase in sampling and research at hadal depths driven by renewed interest and new technologies (Jamieson, 2015; Jamieson and others, 2018). New low-cost lander vehicles can be deployed from small ships, without full ocean-depth winches (Jamieson and others, 2019). A major effort was the international KuramBio II expedition to the Kuril-Kamchatka Trench (Brandt and others, 2016, 2018). A parallel development has been research and expeditions sponsored by private individuals such as the descent to the bottom of the Mariana Trench by the Deepsea Challenger in 2015 or the Five Deeps expedition (Five Deeps, 2019; Stewart and Jamieson, 2019).

This activity has given new insight into the environment and life in hadal trenches. These findings include evidence that no fish can survive at depths greater than 8,400 m (Yancey and others, 2014), which confines trench-endemic fishes to the slopes around the edges of the deepest trenches. At depths greater than 6,800 m, the only fishes present are snailfishes of the family Liparidae. New species in several taxa have been discovered in the Mariana Trench (Gerringer and others, 2017), Atacama Trench (Priede, 2017), and more await description.

Generally, biodiversity decreases with increasing depth in the trenches (Jamieson, 2015). For invertebrates, no fixed maximum depth exists. Nematodes, polychaetes, molluscs, crustaceans and echinoderms all occur at the bottom of the deepest trenches. A funnelling effect concentrates organic matter along the trench axis (Ichino and others, 2015; Luo and others, 2017), potentially resulting in highest abundances and biomass at the maximum depth. Leduc and others (2016) reported six times more infaunal nematodes at the bottom of the Tonga Trench (10,800 m depth) than at the trench edge. Jamieson and others (2009) found the largest numbers of mobile scavenging lysianassoid amphipods at the greatest depths. In the Kuril-Kamchatka Trench, bivalves and holothurians dominated hadal depths (Brandt and others, 2018).

In contrast to the endemicity of hadal snail fishes, the same species of invertebrates tend to occur in different trenches (Ritchie and others, 2017), although new evidence indicates genetic differentiation between species in some trenches (Zhang and others, 2019) and discoveries of new species (Eustace and others, 2016).

Hadal trenches can act as faunal barriers between different parts of the deep sea. In the Kuril-

Kamchatka Trench, the hadal fauna differs from the abyssal fauna of the Northwest Pacific and its marginal seas (Brandt and others, 2016). The Trench isolates species of the marginal seas from the Northwest Pacific Ocean. It also hampers faunal dispersal for some species of desmosomatid, nannoniscid and ischnomesid isopods (Bober and others, 2018; Jennings and others, in press). However, for some species, there is no evidence of a strict biogeographic barrier between the Sea of Okhotsk and the open Northwest Pacific. Jamieson and others (2011) recognized a transition zone between abyssal and hadal fauna in the Kermadec Trench and there is evidence for community structure within the trenches (Jamieson and others, 2013; Fujii and others, 2013; Gallo and others, 2015; Lacey and others, 2016; Leduc and others, 2018)

Trenches are in seismically active zones and the giant Tohoku-Oki earthquake in 2011 resulted in almost instantaneous slumping of 0.2 cubic km of sediment, containing over 1Tg of organic carbon, into the Japan Trench (Kioka and others, 2019; Oguri and others, 2013). This input of carbon changed the composition and distribution of meiofauna on the landward slope of the trench (Kitahashi and others, 2014) and altered the sediment and sub-sea floor hydrogeologic structure (Kawagucci, and others, 2012). In addition, radioactive isotopes from the Fukushima Daiichi nuclear power plant disaster were transferred to a depth of 4,800 m about a month after the earthquake (Honda and others, 2013), and deposited on the sea floor below 7,000 m in depth within four months (Oguri and others, 2013).

Proximity to land and human habitation increases hadal trench vulnerability to anthropogenic impacts, a situation magnified by the funneling effect that concentrates sedimentation into the trench axis. Pollen from terrestrial trees occurs in significant quantities in Southwest Pacific trenches, providing a potential food source for hadal organisms (Leduc and Rowden, 2018). Jamieson and others (2017) found extraordinarily high levels of polychlorinated biphenyls (PCB) and polybrominated diphenyl ethers (PBDE) in amphipods at the most extreme depths in the Mariana and Kermadec trenches. Concentrations were much higher than those observed in areas of high industrialization, indicating long-term bioaccumulation at these depths. Chiba and others (2018) also observed plastic debris down to the bottom of the Mariana Trench, and microplastic particles have been reported in the hind guts of amphipods from six Pacific Ocean trenches at depths from 7,000 to 10,890 m (Jamieson and others, 2019).

2.1.5. Plateaus, rises and banks

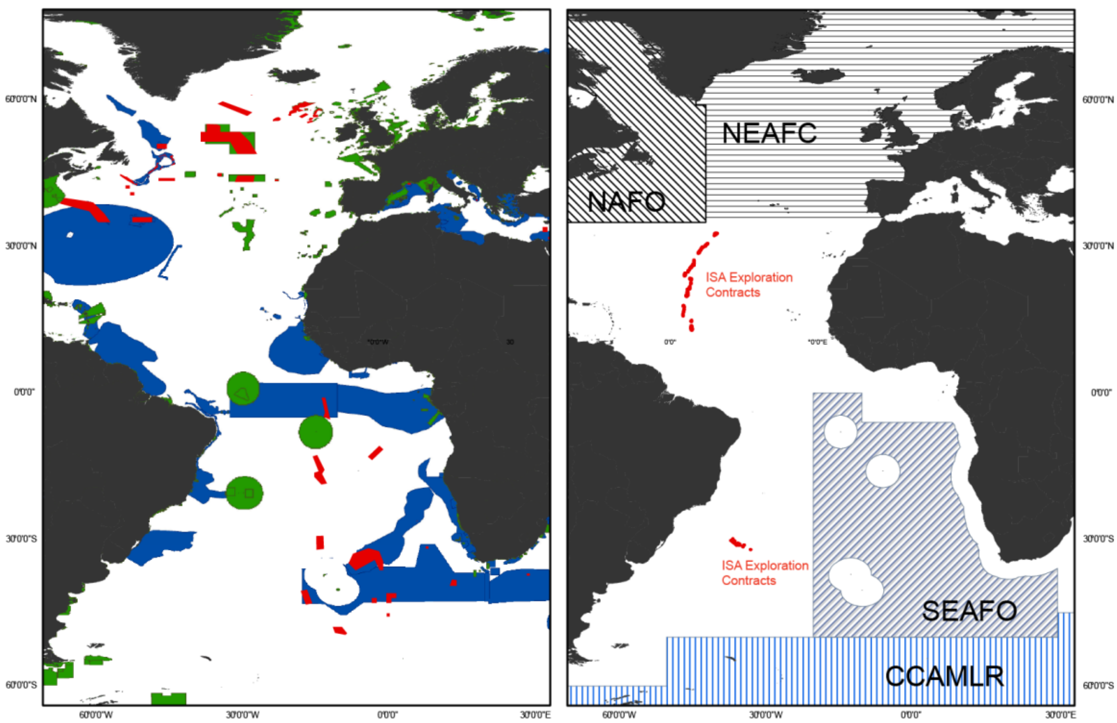
Pre-2010, a dedicated Global Census of Marine Life project studied seamounts (CenSeam), but it targeted very few banks and plateaus. In the Northeast Atlantic, a national strategic environmental assessment of the region investigated George Bligh, Hatton, and Rockall Banks. George Bligh Bank community composition resembled that observed on hard substrata elsewhere in the Northeast Atlantic (Narayanaswamy and others, 2013). Recent studies of the Kerguelen Plateau indicate potentially contrasting benthic faunal distribution shifts (poleward shift, latitudinal reduction and local extinction) of, for example, the echinoids *Abatus cordatus, Brisaster antarcticus, Ctenocidaris nutrix* and *Sterechinus diadema* in response to environmental change (Guillaumot and others, 2018). However, interpreting and predicting future response to climate change requires careful consideration. Predictions regarding changes in water temperature and salinity typically span large spatial scales that may not reflect local scales such as the Kerguelen Plateau, where differences in the location of fronts and heat flux (Vivier and others, 2015) may lead to changes in species distributions in this location in the future (Guillaumot and others, 2018).

Investigating the smaller macrofauna along the Chatham Rise in the Southwest Pacific, Leduc and others (2015) linked community structure most strongly to the density of phosphorite nodules, sometimes forming a nodule-specific community. These nodules are likely to be mined in the future (Leduc and others, 2015) In the absence of nodules an alternate community will develop and the nodule-specific community will be lost where mining has taken place (Bluhm, 2001).

3. Description of economic and social changes (between 2010 and 2020)

Vulnerability of deep-sea ecosystems to anthropogenic pressures and related impacts has increased during the past decade because of the increasing economic value of oceanic resources. Such pressures have triggered both an increased societal awareness and new regulations (Figure 2). These regulations tackle issues such as illegal, unreported and unregulated fishing, exploration for deep-sea mining, bioprospecting and exploitation of genetic resources, the definition of Marine Protected Areas (MPA), and the distribution and protection of VME or other ecologically and biologically significant areas (EBSA).

Figure 2. Left: close up for the Atlantic area. Areas identified as Ecological and Biologically Significant (EBSA) and areas with protection measures at the bottom in the Atlantic. Marine Protected Areas in both areas of national or beyond national jurisdiction and the high seas (Green) are from UNEP-WCMC. EBSA (Blue) and areas of closures to bottom fisheries (Red). Right: boundaries of CCAMLR - Convention for the Conservation of Antarctic Marine Living Resources within the Antarctic Treaty system and Regional Fisheries Management Organizations (RFMO). NEAFC- Northeast Atlantic Fisheries Commission; NAFO – Northwest Atlantic Fisheries Organization; SEAFO – South East Atlantic Fisheries Organization. The red Polygons represent ISA exploration contracts in the Area.



These new regulations are contributing to Sustainable Development Goal 14: i) to conserve and sustainably use the oceans, seas and marine resources for sustainable development[127] and related targets such as the ones to prevent and significantly reduce marine pollution of all kinds, as it relates to

[127] See United Nations General Assembly resolution 70/1.

hadal trenches; ii) to sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts; iii) to minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels; iv) to effectively regulate harvesting and end overfishing, illegal, unreported and unregulated fishing and destructive fishing practices and implement science-based management plans;v) to conserve at least 10 per cent of coastal and marine areas, consistent with national and international law and based on the best available scientific information; vi) also to increase scientific knowledge, develop research capacity and transfer marine technology; and vii) to enhance the conservation and sustainable use of oceans and their resources by implementing international law as reflected in the United Nations Convention on the Law of the Sea[128] for all the other environments considered here.

In the last ten years, these initiatives have led, inter alia, to the establishment of Marine Protected Areas that specifically include features discussed in the present Chapter (Table 1). Good international marine spatial planning (within countries' EEZ and in areas beyond national jurisdiction (ABNJ) will be needed to manage potential conflicts between exploration/exploitation and preservation/conservation (e.g. massive sulphides, EBSA and MPA in the Mid-Atlantic Ridge (MAR); see Figure 2).

Hadal trenches contain no resources currently considered for direct human exploitation. Biomass is too low and remote from the surface to sustain any fisheries and their sediment-draped sides lack any known mineral resources. Bioprospecting could target microbes adapted to life at high pressure (piezophiles) that may have special industrial applications. Peoples and others (2019) describe a large diversity of bacteria and archaea in sediments from the Mariana and Kermadec Trenches but few could be isolated and cultured. Important differences in the microbial communities between the two trenches could link to differences in organic matter supply from the surface; the Kermadec Trench, with high organic matter input, supported more taxa associated with organic matter degradation. However, taxa were not trench-specific and those that were isolated were related to previously identified piezophiles from other environments.

[128] United Nations, *Treaty Series*, vol. 1833, No. 31363.

4. Key region-specific changes and consequences

Table 1.

Region	**Observed climate changes**	**Human pressures**	**Areas identified as Ecological and Biologically Significant (EBSA) and areas with protection measures at the bottom (ridges, trenches and plateaus) (http://www.mpatlas.org/map/high-seas/)**
Arctic Ocean	**Climate:** Reduced oxygenation, acidification and warming of deep waters; change in export flux of organic carbon (Sweetman and others, 2017)	**Ridges and rises, plateaus, banks:** exploration for mineral resources (Chapter 19); expansion of fisheries (Chapter 15)	
North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean Sea and North Sea	**Climate:** Reduced oxygenation, acidification and warming of deep waters; change in export flux of organic carbon (Sweetman and others, 2017); potential effects on larval dispersal in the water column, affecting population connectivity (Levin and others, 2019a); warming, deoxygenation of intermediate and deep Mediterranean waters (Stendardo and others., 2015), reduction of Mediterranean abyssal waters ventilation with consequences on vent and seep taxa and ecosystem functions	**Ridges and rises, plateaus, banks:** exploration for mineral resources (Chapter 19); offshore hydrocarbons (Chapter 20); expansion of fisheries (Chapter 15) **Trenches:** pollution	**EBSA: Northwest Atlantic hydrothermal vent fields; Atlantic Equatorial Fracture Zone and high productivity system.** **MPA:** Azores Marine Park **OSPAR:** Charlie-Gibbs North High Seas MPA; Charlie-Gibbs South High Seas MPA; MAR North of the Azores High Seas MPA. **Bottom Fishing Closure:** North East Atlantic Fisheries Commission (NEAFC) bottom fishing closures
South Atlantic Ocean and Wider Caribbean	**Not enough knowledge to observe change**	**Ridges and rises, plateaus, banks:** Exploration for mineral resources (Chapter 19); Offshore hydrocarbons (Chapter 20);	**EBSA:** Subtropical Convergence Zone (STCZ)

		expansion of fisheries (Chapter 15) **Trenches:** pollution	**Bottom Fishing Closure:** South East Atlantic Fisheries Organisation (SEAFO) bottom fishing closure
Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf	**Not enough knowledge to observe change**	**Ridges and rises, plateaus, banks:** Exploration for mineral resources (Chapter 19); Offshore hydrocarbons (Chapter 20); expansion of fisheries (Chapter 15) **Trenches:** pollution	**EBSA:** East Broken Ridge Guyot
North Pacific Ocean	**Climate:** Warming trend in the Northeast Pacific .	**Ridges and rises, plateaus, banks:** Exploration for mineral resources (Chapter 19); expansion of fisheries (Chapter 15) **Trenches:** pollution	**EBSA**: Kyushu Palau Ridge, West Kuril Trench, Japan Trench, Izu-Ogasawara Trench and North of Mariana Trench; Ryukyu Trench area
South Pacific Ocean	**Not enough knowledge to observe change**	**Ridges and rises, plateaus, banks:** Exploration for mineral resource (Chapter 19); expansion of fisheries (Chapter 15) **Trenches:** pollution	**EBSA: Salas y Gómez and Nazca Ridges, Kermadec-Tonga-Louisville Junction**
Southern Ocean	**Climate:** Warming, change in the circulation and particulate organic carbon fluxes. (East Scotia Ridge), species distribution shifts. Purkey and Johnson, 2010	**Ridges and rises, plateaus, banks:** expansion of fisheries (Chapter 15) **Trenches:** pollution	Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR)-Conservation Measure 22-06 (2019)[1,2] Bottom fishing in the Convention Area

5. Outlook

Many unknowns remain regarding deep-sea environments and ecosystems, but significant research has occurred in the last decade, with more anticipated in the next decade. The United Nations proclaimed the Decade of Ocean Science for Sustainable Development (2021–2030)[129] to support efforts to reverse the cycle of decline in ocean health and to gather ocean stakeholders worldwide behind a common framework that will ensure that ocean science can fully support countries in creating improved conditions for sustainable development of the ocean. The Intergovernmental Oceanographic Commission will coordinate this effort. The European Commission has created five European Research and Innovation Missions, including one dedicated to the oceans and seas.

Recently, the high media profile of some private initiatives has increased interest in ridge and trench exploration, potentially boosting interest in these ecosystems for a wide audience.

Ridges and plateaus support numerous VME (with benthic communities dominated by corals and sponges and hydrothermal vents) which receive protection under regulations of the Food and Agriculture Organization of the United Nations. However, the emergence of potential deep-sea mining on ridges and rises to exploit polymetallic sulphides and cobalt-rich manganese crusts poses new threats to these ecosystems. Presently, the International Seabed Authority is developing regulations for exploitation, including impact assessment and protections. Final recommendations are expected by 2020 (Chapter 19).

The Convention on Biological Diversity (CBD)[130] has promoted the development of representative networks of MPAs and other effective area-based conservation measures (OECMs) with a 2020 target of 10 per cent of the total marine area (CBD, 2010). It has also initiated a programme to identify EBSA (CBD, 2009).

Marine genetic resources (MGR) in areas beyond national jurisdiction, the High Seas and the Area (the seabed, ocean floor and subsoil thereof beyond the limits of national jurisdiction), are unregulated, which is a particularly significant issue given 1) the unknown economic potential in fields such as pharmaceuticals, bioremediation, cosmetics, nutraceutical or biomedical innovation, and 2) the uneven capacity worldwide to use MGR. Since access to MGR mostly begins with marine scientific research which, as a conditional freedom of the high seas, is subject to the relevant provisions of the United Nations Convention on the Law of the Sea Part XIII (for example, sharing information and knowledge), which offer a partial basis for the development of new legal regimes for the management of MGR in areas beyond national jurisdiction (Broggiato and others, 2014)

An international legally binding instrument on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction is currently being negotiated under the United Nations Convention on the Law of Sea, focusing on a package of issues composed of area-based management tools, including MPAs, environmental-impact assessment, capacity building and transfer of marine technologies, and MGR, including questions on the sharing of benefits (Rabone and others, 2019).[131] However, even with all of this and planned reductions in single-use plastic and marine disposal, the deep sea ultimately becomes a sink. Dumping and pollution are of special concern in the hadal trenches because of the tendency for concentration of such material along the trench axis affecting the organisms living there. (Jamieson and others, 2017) .

[129] See United Nations General Assembly resolution 72/73.
[130] United Nations, *Treaty Series*, vol. 1760, No. 30619.
[131] See United Nations General Assembly resolution 72/249.

6. Key remaining knowledge gaps

In the last decade most research on ridges has been associated to studies on hydrothermal vents and individual seamounts (Chapters 7R and 7N), which cover a small portion of the global ridge system. For ridges, plateaus and trenches, major gaps will remain in scientific understanding of biodiversity patterns and spatial scales, species composition and abundance.

As with most of the deep-ocean, knowledge on the pelagic realm is particularly limited, including basic aspects of biodiversity such as species composition and abundance as well as spatial and temporal variations, but certain aspects of the benthic ecosystems are also still poorly understood. Ecological and environmental data, such as life-history patterns, substrate topography and mesoscale ocean dynamics, are needed to inform particle flux, food web and habitat suitability models that can address ecosystem response to disturbance. Our lack of knowledge means that the deep-sea remains the ‘black box’ in global model simulations.

Further, science has barely begun to understand how human impacts will affect deep-sea ecosystem functions and consequently the services these ecosystems provide to society (Thurber and others, 2014). Such knowledge is critical to effective ocean management. Recently, the deep-sea biology community, through several initiatives (e.g. Deep-Ocean Stewardship Initiative, Deep-Ocean Observing Strategy) has identified the four key questions to be answered in order to achieve sustainable management of the deep sea (DOSI, 2019), namely, (i) what is the diversity of life in the deep ocean? (ii) How are populations and habitats connected? (iii) What is the role of living organisms in ecosystem function and service provision? and (iv) How do species, communities and ecosystems respond to disturbance? Although presented as general questions in the deep sea, these questions are well suited to be posed in the specific context of ridges, plateaus and trenches and should be considered priority in future research.

7. Key remaining capacity-building gaps

Access to the deep ocean is constrained to a few developed countries, even though a vast portion of it is within the EEZs of developing nations and the high seas. Availability of technology, such as deep-sea vehicles, is the most limiting factor for exploration. Probably this gap is the most difficult to overcome due to financial and technical reason, but collaborative and interdisciplinary research networks have been suggested as an effective way to optimize time at sea (Levin and others, 2019b). A multidisciplinary approach is also necessary to develop new ways to create easy-access modelling to forecast changes and vulnerability for a better environmental assessment.

Another major gap is also in the field of expertise, especially in developing countries. Training is needed for a new generation of scientists, including on best practices, taxonomic abilities, the ecosystem approach, and how to explore, manage and conserve the deep-sea using the latest tools.

International collaborations through existing programs like those offered by the UNESCO/IOC IODE or the WMO Learn Education and Training Programme, or newly formed initiatives, dedicated to deep-sea research, can contribute to facilitate access to technology and training materials, including dedicated courses, participation in research cruises, training internships on field research, instrumentation development and data analysis.

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Chapter 7R
Hydrothermal Vents and Cold Seeps

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Keynote points

- Hydrothermal vents and cold seeps have uniquely complex habitats and communities, diverse endemic species, high biomass and productivity supported by chemosynthesis.
- These ecosystems are sources of biotechnological and biomedical innovation.
- They have a significant role in global ocean processes, sequestering carbon dioxide (CO_2) and methane, and contributing to surface ocean productivity through iron export.
- In the last five years, explorations using new tools to detect water column signals located tens to thousands of vent fields and cold seeps.
- Resource exploration (polymetallic sulphides and methane hydrates) and the need to map and protect vulnerable habitats and species support recent investigations.
- The International Seabed Authority has issued seven polymetallic sulphides exploration contracts since 2011, encompassing vent fields from the Indian and Atlantic mid-Ocean ridges.
- Vulnerable marine ecosystems (VME) and marine protected areas (MPA) in exclusive economic zones (EEZ) and in areas beyond national jurisdiction (ABNJ) protect some vents and seeps.
- Conservation status of vents or seeps identified eight areas protected under national law within the exclusive economic zones
- Knowledge gaps include spatial and temporal patterns, impacts from direct disturbance, changes to deep-water circulation, deoxygenation, warming and acidification.
- Ocean warming triggering gas hydrate dissociation is a major stressing factor to cold seepage activity and ecosystems.
- Capacity-building is a priority, particularly in island States.

1. Introduction

1.1. Scope and summary of the baseline state from the First World Ocean Assessment (WOA I)

Hydrothermal vents occur wherever a heat source drives seawater circulation through the sub-sea floor. Cold seeps refer to hydrocarbon-rich fluids emanating from buried organic matter, fossil fuel reservoirs or methane hydrates. Both environments encompass a wide range of fluid compositions and habitat types (Cordes and others, 2009; Watanabe and others, 2010; Levin and Sibuet 2012; Le Bris and others, 2019).

The present Chapter focuses on marine life and seafloor habitats influenced by fluid emissions, including shallow seeps and vents, important to local biodiversity and biogeography and to the flux of greenhouse gases to the atmosphere, with long-distance effects on both the seabed and water column. Chapter 45 of the First World Ocean Assessment (WOA I) (United Nations, 2017a) noted accelerating exploration of hydrothermal vents (Beaulieu and others, 2015), notably in relation to mineral resource exploration, and reported on the development of conservation status of vents or seeps within the exclusive economic zones and beyond national jurisdictions.

1.2. How the topic is affected by and affects other marine components

High local biomass of chemosynthetic microbial primary producers and associated fauna are sustained by fluxes of methane, hydrogen sulphide, hydrogen, or reduced iron and manganese. Many specialist taxa host bacterial symbionts (Dubilier and others, 2008) and act as ecosystem foundation species (Govenar, 2010). Global communities are similar at the family level, forming 11 biogeographic regions by endemic species (Rogers and others, 2012; Moalic and others, 2012). Peripheral habitats benefit from chemosynthetic resources (Levin and others, 2016). Hydrothermal plumes export metals and organic material and contribute to regional and global iron budgets (Resing et al. 2015; German and others, 2016; Tagliabue and Resing, 2016).

1.3. How the topic is relevant to human communities and well-being

1.3.1. Fishing grounds

Sessile organisms, including habitat-forming species (sponges, soft and hard corals), benefit from hard substrata formed at vents and seeps, contributing to essential habitats for groundfishes (US Pacific Fishery Management Council, 2019). Chemosynthetic primary production can contribute to commercial fisheries stocks productivity, e.g. exploited crabs off British Columbia (Canada) that assimilate carbon from chemosynthetic sources (Seabrook and others, 2019). Off California (United States of America) seep population densities of species targeted by fisheries increase (Grupe and others, 2015).

1.3.2. Greenhouse gas flux regulation

Vents are natural sources of CO_2 and methane issuing from magma degassing, mantle serpentinization and diagenetic organic matter degradation in buried sediments. Chemoautotrophy and methanotrophy contribute to trap these emissions at the sea floor (Orcutt and others, 2011; Wankel and others, 2011; Römer and others, 2014a; Ruppel and others, 2017). Anaerobic methane oxidation by archaea is a key sequestration pathway (Boetius and Wenzhöffer, 2013). Hydrothermal iron can locally fertilize the surface waters (Guieu and others, 2018; Ardyna and others, 2019) and globally supports the oceanic phytoplankton-driven CO_2 sink.

1.3.3. Ecological models for adaptation and resilience

Hydrothermal vents and cold seeps provide models to study animal stress responses in high CO_2/low pH conditions, extreme temperature, hypoxia, exposure to sulphides, toxic metals and metalloids and help to understand biochemical, physiological and behavioural adaptations (e.g. Hall-Spencer and others, 2008; Tunnicliffe and others, 2009; Childress and Girguis 2011; Di Carlo and others, 2017; Rossi and Tunnicliffe, 2017). Colonization patterns provide insights into larval dispersal capacities, species dependencies and resilience to disturbances (Gollner and others, 2017; Mullineaux and others, 2018). Functional traits approaches address the contributions of common and rare species (Chapman and others, 2018).

1.3.4. Biotechnological and biomedical innovation

Biotechnical discoveries reflecting unique microbe-animal interaction and extreme habitat conditions include: antibiotic molecules in hydrothermal worms (Tasiemski and others, 2014; Papot and others, 2017); metal resistance genes in vent microbes implicating enzymatic detoxication pathways in polluted environments (Vetriani and others, 2005; Colaço and others, 2006); and chemoautotrophic C-fixation pathways relevant to CO_2 emissions sequestration (Scott and others, 2018; Rubin-Blum and others, 2019).

1.3.5. Public engagement with the ocean

The discoveries and imagery of these iconic ecosystems reach large, global audiences, supplemented by telepresence cruises, books, films, theatre, games and toys inspiring citizen science projects. These ecosystems showcase diverse adaptations of deep ocean taxa, the roles of microbes and life origin on Earth.

1.4. Advances in knowledge and capacity

1.4.1. Exploration and mapping

Systematic mapping with autonomous underwater vehicles tracking anomalies in the water column (e.g. temperature, redox potential or methane, gas bubbles or particles) improved capacity to locate seeps or vents (Baker and others, 2016; James and others, 2016; Andreassen and others, 2017; Baumberger and others, 2018).

Exploration of vent and seep systems has extended in subduction zones of the Northwest Pacific (e.g. Baker and others, 2017) and on Arctic ridges (Marques and others, 2020), in the Southern Ocean (Linse and others, 2019), the Central, Western and Eastern Indian Ridges (Copley and others, 2016; Zhou and others, 2018; Gerdes and others, 2019) (Figure 1). Identified methane seepage areas have increased since WOA I (United Nations, 2017b) along the coasts of the United States of America (Quattrini and others, 2015; Baumberger and others, 2018), in the South China Sea (Feng and others, 2018), in Brazil (South West Atlantic, Ketzer and others, 2019), in Caribbean (Digby and others, 2016), and in India (Bay of Bengal, Mazumdar and others, 2019). Improved seabed mapping resolution produced detailed baselines of faunal assemblage distributions that can be used for assessing responses to human activities (Thornton and others, 2016; Gerdes and others, 2019).

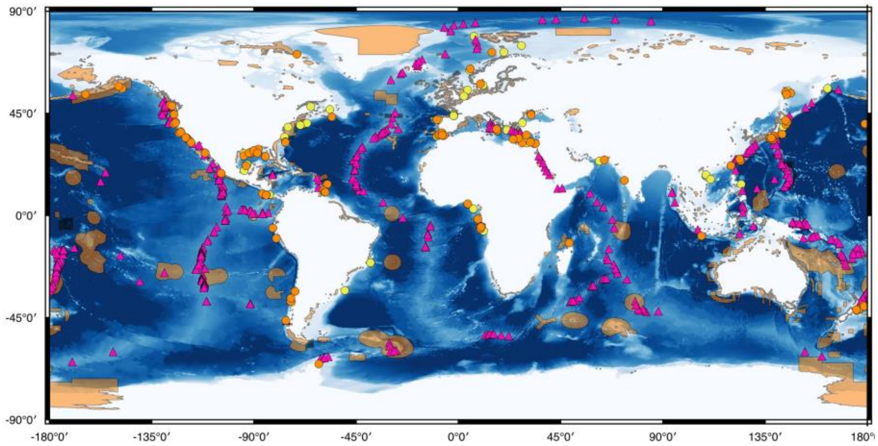

Figure 1: Active vent sites from the InterRidge Vent Database (pink triangles) (Beaulieu and Szafrański, 2020) and seep areas from the Biogeography of Deep-Water Chemosynthetic Ecosystems Database (orange circles) (ChEssBase, 2019) and more recent inventories (yellow circles) (Olu and others, 2010; Quattrini and others, 2015; Baumberger and others, 2018; Feng and others, 2018; Etiope and others, 2019; McDonald and others, 2020). Polygons are currently designed MPAs (United Nations Environment Programme World Conservation Monitoring Centre database [UNEP-WCMC(WDPA)]). Bathymetry from https://www.gebco.net/data_and_products/gridded_bathymetry_data/. Map created using Q-GIS version 2.18.20 (QGIS Development Team, 2018).

1.4.2. Variability in space and time

Repeated surveys show that communities can be stable over decades on slow spreading ridges (Cuvelier and others, 2011) and some back-arc basins (Du Preez and Fisher, 2018). This challenges the paradigm, based on fast-spreading ridges, that vent communities are dynamic and resilient to disturbance. Variable geothermal and geochemical energy sources fuel both ecosystems, including hybrid systems on sedimented margins (Goffredi and others, 2017). Genetic and hydrodynamic models reveal population connectivity patterns that are critical in context of managing seabed resource development (Mullineaux and others, 2018; Suzuki and others, 2018).

2. Environmental changes since WOA I

2.1. Changes in the overall status

2.1.1. Drivers and pressures

Vent and seep drivers of change include growing economic demands for energy, strategic metals and food (Figure 2). Fossil fuel demand is driving offshore oil and gas exploitation at depths > 1500 metres (Cordes and others, 2016) (Table 1). Deep-sea fisheries are expanding on seamounts, island slopes, mid-ocean ridges and continental margins where vent and seep ecosystems occur. Seep ecosystems on continental margins are exposed to deep water warming with concomitant enhancement of methane hydrate dissociation (James and others, 2016; Ruppel and Kessler, 2017), expanding hypoxia (Breitburg and others, 2018) and ocean acidification (IPCC, 2019) (Table 1). Vulnerabilities include chemosynthetic holobiont species with particularly high oxygen demand (Childress and Girguis, 2011), and fauna dependent on carbonate substrata (Ramirez-Llodra and others, 2011; Levin and Le Bris, 2015; Sweetman and others, 2017) (Figure 2, Table 1).

Exploration for seafloor massive sulphides (SMS) (Petersen and others, 2016) and extractive technology testing (Okamoto and others, 2019) are developing (Table 1). By 2018, the International Seabed Authority had issued seven polymetallic sulphide exploration contracts in ABNJ, in areas of the Atlantic and Indian mid-ocean ridges hosting active and inactive vents (WOA II Chapter 19). Vent ecosystems are also reported in area of exclusive economic zones covered by SMS exploration licenses. While resource exploitation may target inactive SMS (WOA II Chapter 19), the definition of "inactive" is still unconstrained and their biological and ecological characteristic remains understudied (Van Dover and others, 2019), particularly at sites with only diffuse fluid vents that may escape water-column detection.

2.1.2. State of changes associated with pressures and potential impacts

Substratum changes, vent emissions and faunal recruitment were reported near drilling holes (Nakajima and others, 2015), contrasting with another impact study (Copley and others, 1999). Destruction by trawling damage has been predicted (Bowden and others, 2013) and the impact of ore-processing waste dumping on seeps has been documented (Samadi and others, 2015). Increasing plastic debris at seeps has been reported (Miyake and others, 2011; Chiba and others, 2018) and hypoxia expansion, acidification and warming have been documented in regions hosting seeps and vents (IPCC, 2019).

3. Economic and social consequences

3.1. Area-based management tools (ABMT)

Eight vent or seep areas are protected under national law within the exclusive economic zones of Canada, Mexico, the United States of America, France and Portugal (Table 1). Beyond national jurisdictions, the Convention for the Protection of the Marine Environment of the North-East Atlantic ("OSPAR Convention")[132] recommended "Oceanic ridges with hydrothermal vents/fields" as threatened and/or endangered habitats to be protected by its MPA network in Region V of the maritime area (Arctic and North Atlantic) (OSPAR, 2014; 2018) (Table 1).

Several vent fields have been described as ecologically and biologically significant areas (EBSA) under the CBD process (Dunn and others, 2014; Bax and others, 2016) (Table 1). EBSAs are not area-based management tools (ABMT) but provide information that may play a role in decision-making processes. Seeps have been recommended as EBSA, but few have specific status (Table 1).

Habitats hosting chemosynthetic ecosystems are identified as Specially Protected Areas under the 1995 Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean[133] (United Nations Environment Programme, MAP, 2017) (Table 1). Another approach to biodiversity conservation is the International Union for Conservation of Nature Red List assessment as recently executed for Indian Ocean vents (Sigwart and others, 2019).

United Nations General Assembly resolution 71/123 of 7 December 2016 on sustainable fisheries called for protection from destructive fishing practices, and the number of protected vents increased (Menini and Van Dover, 2019) (Figure 1, Table 1). Following the International Guidelines for the Management of Deep-sea Fisheries in the High Seas (Food

[132] United Nations, *Treaty Series*, vol. 2354, No. 42279.
[133] Ibid., vol.1102, No. 16908.

and Agriculture Organization of the United Nations, 2009), regional fisheries management organizations recognize hydrothermal vents as vulnerable marine ecosystems (VME) (Food and Agriculture Organization of the United Nations, 2016). Developing International Seabed Authority Regional Environmental Management Plans may ensure protection of active vents as areas of particular environmental interest (APEI), but the paucity of data renders this task difficult (Dunn and others, 2018) (Chapter 30).

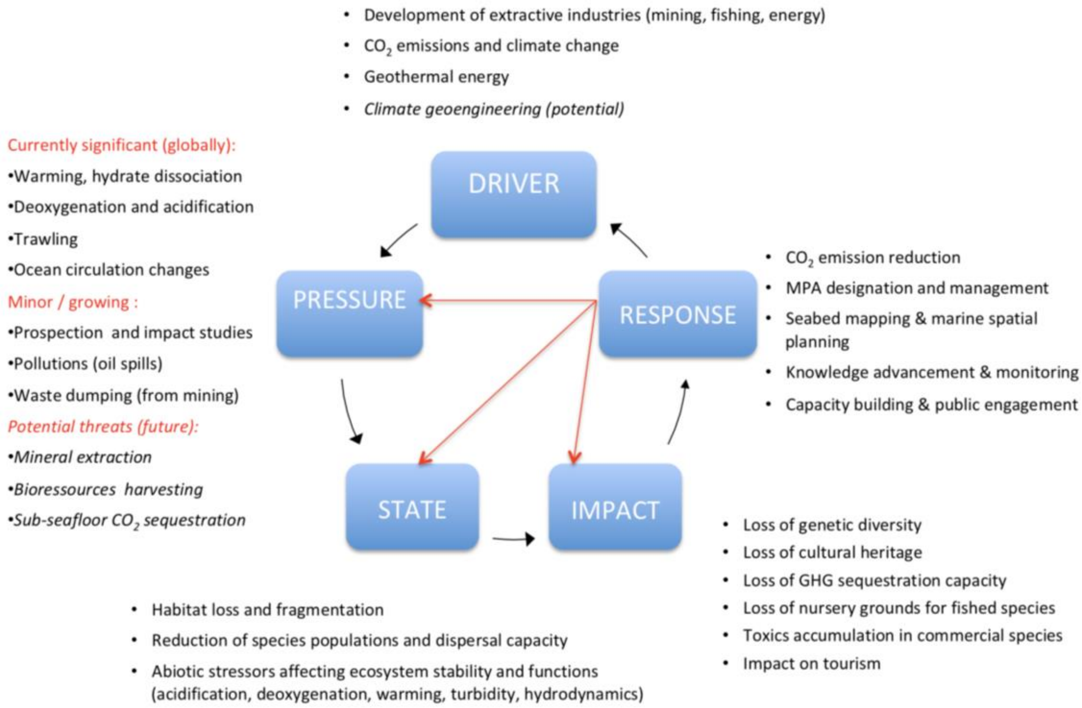

Figure 2: Synthesis of the DPSIR approach applied to vents and seeps, summarizing the information developed in sections 2 and 3.

3.2. Implications for achieving the Sustainable Development Goals (SDGs)

Sustainable Development Goal (SDG) 14[134] calls for enhancing the conservation and sustainable use of oceans and their resources by implementing international law as reflected in the United Nations Convention on the Law of the Sea.[135] Achieving this goal requires assessment of the cumulative pressures of climate change and human activities at vents and seeps (Levin and Le Bris, 2015), involving strong iinvestments in capacity building, technology transfer and development for deep-sea investigations (SDG 4, with 4B related to developing countries). Ocean literacy societies promote ocean conservation and sustainable use by supporting multi-stakeholder partnerships and public understanding of vent and seep ecosystems (SDGs 17.16 and 17.17), through telepresence research expeditions, citizen science initiatives, policy briefs (e.g. from the Deep-Ocean Stewardship Initiative) and education.

[134] See United Nations General Assembly resolution 70/1.
[135] United Nations, *Treaty Series*, vol. 1833, No. 31363.

Chemosynthetic ecosystems provide “regulatory ecosystem services” for climate change impact mitigation by acting as filters for natural methane and CO_2 emissions (Thurber and others, 2014, James and others, 2016) (SDG 7). Renewable energy industry development contributes to the projected deficit of secure supplies of certain metals and has stimulated exploration of deep-sea mineral resources. If SMS mining occurs at vents, it will imply trade-offs with SDG 14 with introduction of pollutants in the trophic chain and essential habitat degradation, incompatible with sustainable fishing activities. Costs to biodiversity, biotechnological innovations and cultural values may arise (see Chapter 19 of the present Assessment; see also 2.1.1 above).

4. Key region-specific changes and consequences

Table 1. Emerging threats, risks and conservation assessments and efforts at vents and seeps since 2014.

Basin	Resource exploration and exploitation	Increased cumulative pressures risks (including climate change)	Conservation assessment and efforts
Arctic	Mineral resource exploration on Arctic ridges Gas exploitation extension Fisheries expansion	Accelerated exploitation with sea-ice retreat combined with warming (Sweetman and others, 2017) through methane hydrate destabilization (James and others, 2016)	Iceland: Eyjafjörður Hydrothermal Vents 1 and 2 nominated components to OSPAR MPA Network (OSPAR, 2018).
North Atlantic	Three ISA exploration contracts signed for northern mid-Atlantic ridge in area hosting active vent fields (Russia-2012, France-2014, Poland-2018).	North Atlantic abyssal /intermediate water warming and acidification (Gehlen and others, 2014) Water column larval dispersal effects on connectivity (FAO, 2018)	Portugal EEZ: Menez Gwen, Lucky Strike and Rainbow vent fields protected, Natura 2000 sites, Azores Marine Park. Mid-Atlantic Ridge north Azores High Seas MPA: OSPAR water column protection; seabed and subsoil protection by Portugal (OSPAR 2018). Spain: Gulf of Cadiz Mud volcanoes Site of Community Importance (EU Habitats Directive) (2014). UNEP/CBD: Lost City, Broken Spur and TAG vent fields as EBSAs
Mediterranean	Natural gas extraction extension, Eastern and Southwest Mediterranean	Intermediate /deep water warming, deoxygenation; abyssal waters ventilation reduction (Adloff and others, 2015)	United Nations, General Fisheries Commission for the Mediterranean (2018): ‘Nile delta cold hydrocarbon seeps’ VME fishery closure
Black Sea		Salinity change enhances methane hydrate destabilization (Riboulot and others, 2018) Anoxia expansion, seep ecosystem threats	
South Atlantic	Deep oil and gas exploration and exploitation development off Brazil (Almada and Bernardino, 2017)	Continental margin extensive oil production off Brazil, seep exploration limited (Bernardino and Sumida, 2017)	
Gulf of Mexico, Caribbean	Deep oil and gas exploration and exploitation in Gulf and off Guyana	Climate change and eutrophication-driven extension of dead zones with impacts on seeps at intermediate depths (Johnson and Purkey 2009; Breitburg et al. 2018). Oil exploration in course with seep exploration limited in Southwestern Caribbean (Digby and others, 2016)	

Indian	Four exploration contracts issued by ISA in areas hosting active vent fields of the South-West Indian Ridge (China in 2011) and Central Indian Ridges (Korea-2104, Germany-2015, India-2016)	Sensitivity of seep ecosystems to regional oxygen decrease on Pakistan margins (Fischer and others, 2012)	IUCN Red list: Scaly foot gastropod listed as endangered, draft assessments completed for endemic species to regional vents (Sigwart and others, 2019)

North Pacific	Japan Oil, Gas and Metals National Corporation (JOGMEC) tests SMS extraction in Okinawa Trough (Okamoto and others, 2019). South China Sea: Production test of seep gas hydrate extraction (Li and others, 2018)	Trawling pressures increase combined with ocean warming trend in the Northeast Pacific Increasing risk of methane hydrate dissociation (Ruppel and Wessler 2017; Hautala and others, 2014)	Canada: EEZ Pacific vents offshore Pacific 'Area of Interest'. Canadian Pacific cold seeps are EBSAs (DFO, 2018) Mexico: EEZ MPA system Guaymas Basin & Eastern Pacific Rise Sanctuary (decreted in 2009, Management plan published in 2014 EBSA: Guaymas Basin Hydrothermal Vents Sanctuary (in 2016). Deep Pacific Mexican Biosphere Reserve (in 2018). United States of America Pacific Fishery Management Council (2019) designated seeps Essential Fish Habitat. EBSA: Cold seeps in southwest Taiwan Basin.
South Pacific	Vent SMS exploration licenses in EEZs of South-West Pacific	Landmine tailings vent / seeps impact (Samadi and others, 2015)	New Zealand EEZ: 88% active hydrothermal vents are MPAs. France - New Caledonia EEZ (2014): shallow vents and unexplored ridge systems in the MPA Parc Marin de la Mer de Corail Mining regulation and environmental policies in several island nations
Southern Ocean		East Scotia Ridge vents and Antarctic seeps influenced by warming, circulation and carbon flux changes (Römer and others, 2014b)	Vent and seep species identified in the CCAMLR VME Taxa Classification Guide (2009)

5. Outlook

Vent and seep biota and habitat conditions remain poorly documented, including vent areas where mineral exploration is under way (e.g. Indian Ocean). Seeps biogeography is not described (Olu and others, 2010). SMS extraction effects on active vent ecosystems and periphery are unclear. Expected impacts include sediment plumes, toxic compound release, habitat loss and metapopulation connectivity disruption (Dunn and others, 2018). Models of larval dispersal start to be developed and highlighted limited inter-regional connectivity in areas such as the western Pacific (Mitarai and others, 2016). The great longevity of foundation species of seep ecosystems (up to 200 years) further suggests slow disturbance recovery (Fisher and others, 2016). Both trawling (see 2.1.2 above) and fossil fuel exploitation could also have long-term impacts (Amon and others, 2017). Lack of seep baseline data still limits prediction of resilience capacity of these communities (Cordes and others, 2016).

Oxygen depletion, methane flux and hydrodynamic condition changes resulting of climate disturbance, as well as acidification, affect large regions hosting vent and seep ecosystems and likely interact with key biological processes, although specific impacts have not been reported yet A direct impact from warming to seeps is expected to be methane hydrate dissociation (Ruppel and others, 2017). Changes in the upper water column may also affect the vent and seep propagule dispersal (Yahagi and others, 2017; Mullineaux and others, 2018).

6. Key remaining knowledge gaps

Vent species discovery rates remain high, suggesting species richness under-sampling (Thaler and Amon 2019). Chemosynthetic fauna databases (ChEssBase, 2019; Chapman and others, 2019) will enable global scale analyses and the use of new techniques, such as eDNA high-throughput sequencing, and metacommunity models will help resolving connectivity patterns (Chen and others, 2015; Breusing and others, 2016; Mullineaux et al. 2018).

Long-term ecosystem research is essential to elucidate processes linking vent and seep communities to climate-change stressors (IPCC, 2019). In situ measures of physiological responses and changes in ecosystem function are required to assess climate-change vulnerability. Tolerance thresholds to climate stressors are largely unknown, particularly for species thriving at the periphery hypoxic areas (Fischer and others, 2012).

Carbon storage in vents and seeps lacks quantitative estimates, including ranges and controlling factors for vent and seep productivity (Marlow and others, 2014; Le Bris and others, 2019) and the role of viruses as mediators of prokaryote ecology (Corinaldesi and others, 2012; Ortmann and others, 2005). Vent effluents in ocean biogeochemical cycles require integrated assessments to evaluate impacts on surface water productivity from iron injection (Guieu and others, 2018; Ardyna and others, 2019).

7. Key remaining capacity-building gaps

Capacity gap is larger in less developed nations - particularly Small Island Developing States that host vent and seep derived resources. Training new deep-sea scientists in environment-related disciplines is a challenge recognized by Intergovernmental Oceanographic Commission programmes (IOC, 2016). Ecological assessments require faunal knowledge, while molecular tools need field validation of results. Oceanographic data and species inventories underpin ecosystem function models helping to predict vulnerability and recovery. Knowledge transfer includes taxonomic capacity and development of low-cost technologies for deep-sea research and monitoring (Levin and others, 2019) and mapping, exploring and developing monitoring strategies involves the training of scientists, young students and in particular, women.

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Chapter 7S
Sargasso Sea

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Keynote points

- The Sargasso Sea is a high seas area, internationally recognized as a fundamentally important part of the global ocean because of its role in climate regulation and its unique ecosystems.
- The Bermuda Atlantic Time-series Study (BATS) continues to collect observations enabling inferences on the impact of climate change in the ocean and increased understanding of ocean processes. Continuation of this fundamental long-term research is essential.
- Mass blooms and strandings of *Sargassum* since 2011 are due to a previously rare form of *Sargassum natans*. These are causing major socioeconomic problems for the region and may also adversely impact unique oceanic *Sargassum* communities.
- The importance of the Sargasso Sea as a spawning area for both the European and American eels has been emphasized by satellite tracking of adults and widespread larval surveys. Increased understanding of the ecology of commercial tuna and tuna-like species and awareness of the use of the area by endangered and threatened species is increasing the need for ecosystem-based fishery management.
- Most changes and threats, including climate change, overfishing of eels, plastic pollution and mass blooms of *Sargassum* are externally driven. These increasing threats will adversely impact the contribution of the Sargasso Sea to Sustainable Development Goal (SDG) 14 to conserve and sustainably use the oceans, seas and marine resources for sustainable development and, therefore, other SDGs.[136]
- The increasing activity in the Sargasso Sea demonstrates the importance of addressing cumulative impacts of human activities on the high seas.

1. Introduction

The present Chapter builds on developments and knowledge of the previous baseline state reported in Chapter 50 of the First World Ocean Assessment (WOA I) (United Nations, 2017). Continuing research around the ocean time series hosted by the Bermuda Institute of Ocean Sciences (BIOS) underpins understanding of fundamental ocean processes, including the importance of microbes and the effects of climate change. Progress in understanding the broader ecology of the Sargasso Sea is described, in particular: *Sargassum* weed, its distribution, associated fauna and the real and potential impact of recent blooms on coastal communities; ongoing research into the life cycle of European and American eels (*Anguilla anguilla* and *Anguilla rostrata*); increased awareness of the biology of some commercial fish species and ongoing developments in ecosystem modelling; and increased threats from plastic pollution. Ongoing and recent international developments pertaining to the Sargasso Sea are outlined in the light of the on-going intergovernmental conference on an international legally binding instrument under the United Nations Convention on the Law of the Sea[137] on the

[136] See United Nations General Assembly resolution 70/1.
[137] United Nations, *Treaty Series*, vol. 1833, No. 31363.

conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction (BBNJ process).

The 2016 baseline case described the background oceanography of the Sargasso Sea, the unique surface ecosystem and communities based upon floating aggregations of two species of *Sargassum* and their role as feeding and nursery areas for fishes, juvenile turtles and seabirds. Many animals migrate through the Sargasso Sea and many migrate to it to breed. It is the only known spawning area for European and American eels. Many of the species inhabiting the Sargasso Sea are endangered or threatened and are listed as such in the International Union for Conservation of Nature (IUCN) red list, the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES),[138] and the 1990 Specially Protected Areas and Wildlife Protocol to the Convention for the Protection and Development of the Marine Environment of the Wider Caribbean Region (Cartagena Convention)[139] (Laffoley and others, 2011). Threats, economic values and conservation responses were summarized.

There have been changes and developments to this baseline case, but the Sargasso Sea remains a fundamentally important part of the global ocean due to an interdependent mix of physical oceanography, its ecosystems and its role in global-scale ocean and earth-system processes. It contributes significantly to local as well as global economies both directly from fisheries for highly migratory species (including European and American eels), coral reefs, whale watching and “turtle tourism”, and indirectly from its role in climate regulation, conservation of genetic diversity and nutrient cycling (Laffoley and others, 2011; Pendleton and others, 2015). On the other hand, it is also threatened by climate change, pollution, increased fishing activities and increased shipping

2. Change of state

2.1. Ocean time series

The continuing importance of long-term ocean time series in understanding variability in the ocean and ocean processes has been reinforced both locally by the results from Hydrostation S and BATS, and globally via numerous reviews (Neuer and others, 2017; O’Brien and others, 2017). The BATS programme is one of the few ocean time series with long enough records to enable anthropogenic change to be distinguished from natural variability (Henson and others, 2016). The breadth of research utilizing these data is summarized on the BATS website.[140]

2.2. Sargassum

The baseline case described the role of two species, namely, *Sargassum natans* and *Sargassum fluitans*, primarily for their role in hosting specialized communities of animals and acting as nursery and feeding areas. Advances in our knowledge of these communities have implications for future conservation measures. These communities vary in both time and space. Considerable variability over a 40-year period, and also between samples taken a year apart, was found by Huffard and others (2014). The reasons are unknown but increasing ocean acidity may be the cause of the reduction in calcareous epibionts such as bryozoans.

[138] Ibid., vol. 993, No. 14537.
[139] Ibid., vol. 1506, No.25974.
[140] Available at www//bats.bios.edu.

Variability at molecular level within species occurs in the widely dispersed slender Sargassum shrimp and it is suggested that conservation measures for such species should cover large areas or have networks of protected areas (Sehein and others, 2014).

Since the mass stranding of thousands of tons of *Sargassum* on beaches within the Caribbean, Gulf of Mexico and the coasts of West Africa and South America in 2011, there have been considerable efforts to identify the blooms, their causes and their movements using satellite tracking, modelling, direct sampling at sea and a combination of different techniques (Schell and others, 2015; Franks and others, 2016; Djakouré and others, 2017; Brooks and others, 2018; Putnam and others, 2018). The blooms were identified as a previously rare form of *Sargassum* (*S. natans* VIII) by Schell and others, (2015). This identification was subsequently confirmed by genetic studies (Amaral-Zettler and others, 2017). *S. natans* VIII was described from the Caribbean by Parr (1939) but it was then largely forgotten. It differs morphologically from both *S. fluitans* and *S. natans* and hosts reduced communities of animals which in turn make it less attractive to fish, turtles and seabirds which feed on or beneath the *Sargassum* mats (Martin, 2016). Consequently, changes in *Sargassum* type or distribution could impact species diversity and abundance. The distributions of the different species and forms of *Sargassum* differ both spatially and temporally and *S. natans* VIII is believed to be limited by temperature, since it is most abundant in warm water to the south of the Sargasso Sea and the Caribbean. It is rare further north but it has been found off Bermuda since 2016 (Clover, 2017). So far, these blooms have not impacted the Sargasso Sea directly but they have the potential to do so via reduced *Sargassum* communities and because they are preventing successful nesting of turtles on the affected beaches around the Caribbean.

These blooms originate in the North Equatorial Recirculation Region (NERR) south of the Sargasso Sea and, from there, are carried into the Caribbean (Johnson and others, 2013; Franks and others, 2016,Djakoure and others 2017,Putnam and others,2018) Such blooms have been an annual event since first observed in 2011. High levels of dead *Sargassum* that has sunk from the surface have also been reported on the sea floor in the Vema Fracture Zone beneath the NERR, potentially providing a food source to deep-sea benthic ecosystems (Baker and others, 2018). The causes of the blooms are the subject of ongoing research but may include modifications induced by climate change, such as increased temperature and changes in ocean currents, enhanced nutrient levels originating from the rivers Congo, Orinoco and especially the Amazon, equatorial upwelling, and dust from the Sahara (Djakauré and others, 2017). The question is whether this regime shift in the tropical and sub-tropical Atlantic is primarily caused by human activity. Various monitoring satellites, which feed information to the Sargassum Watch System, for example, inform communities on the location of blooms and warn them of potential beaching events (Hu and others, 2016).

2.3. Fishes

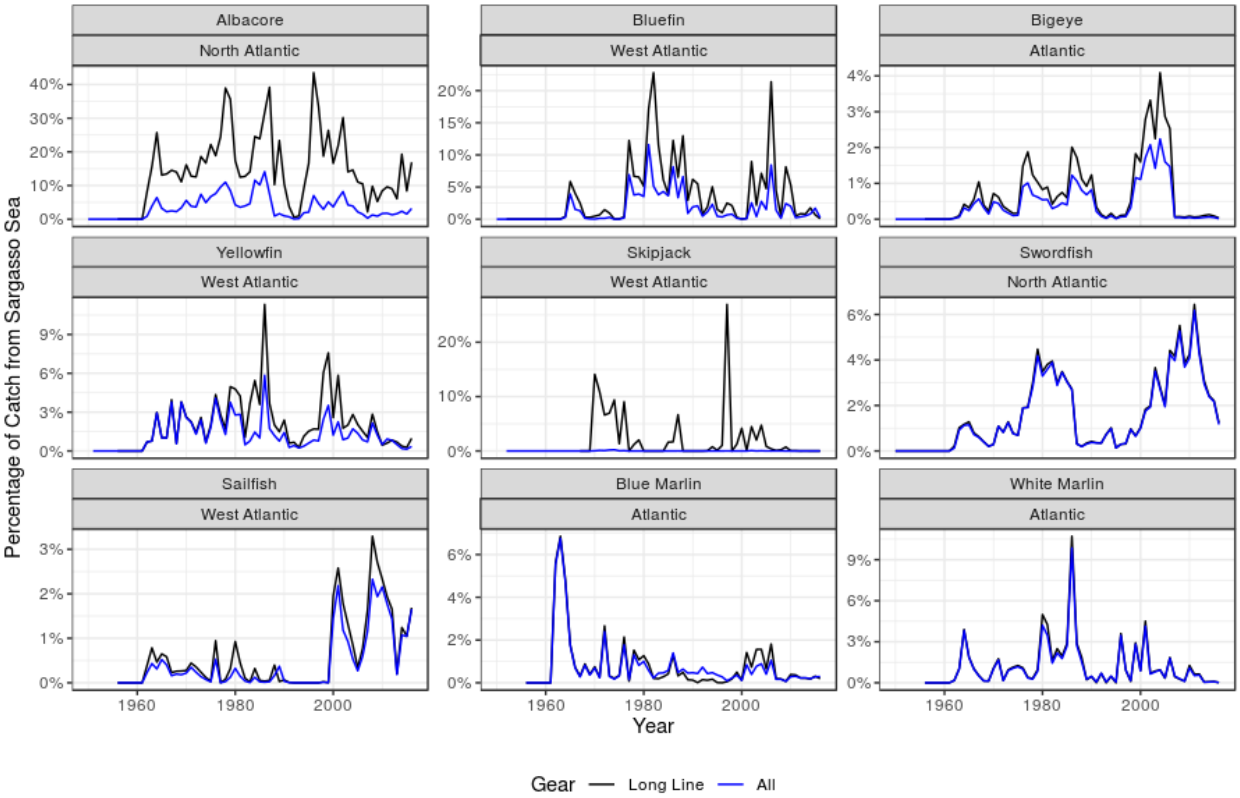
The importance of the Sargasso Sea to the European and American eels has been reinforced. The larvae of both species were known to occur in the south-west of the Sargasso Sea in the vicinity of the seasonal subtropical convergence (Munk and others, 2010; Miller and others, 2015). Satellite tagging tracked migrating European eels from European rivers as far as the Azores (Righton and others, 2016). Similar tagging of American eels showed migration from Canada to the Sargasso Sea (Béguer-Pons and others, 2015). More recently, it has been shown that European eels spawn across a 2,000 km swathe of the southern Sargasso Sea in an area bounded by temperature fronts (Miller and others, 2019). This wide spawning area may reflect different starting times of migrations, different swimming abilities or larval drift in ocean currents. Recruitment levels to fisheries for both species have collapsed and this reduction is matched by declines in numbers of eel larvae in the Sargasso Sea (Hanel and others, 2014). Climate change, rising sea temperatures, changes in ocean currents and the North Atlantic Oscillation all potentially adversely impact the marine life cycle of eels (Miller and others, 2016).

New information on food webs and spawning sites of tuna and tuna-like species managed by the International Commission for the Conservation of Atlantic Tuna (ICCAT) has reinforced the importance of the Sargasso Sea in providing habitat, foraging and spawning grounds and migratory corridors for these species (Luckhurst, 2015a; Luckhurst and Arocha, 2016; Anon, 2016). The Northwest Atlantic Fisheries Organization (NAFO) has acted to protect seamounts in the northern Sargasso Sea by closing the area to bottom trawling until 2020 (NAFO, 2015).

Despite decreases in catches worldwide and in the relative abundance of the main commercial pelagic species, the capacity of the global fishing fleet has continued to increase (Rousseau and others, 2019). Spatial estimates of fishing effort are not available from ICCAT for the Sargasso Sea. In their absence we have plotted the percentage of the catches of the main ICCAT species (stock boundaries defined by ICCAT) as an indicator of the level of fishing in the Sargasso Sea over time.

Figure 1 updates the analysis of Luckhurst (2015b), which provided catch analyses from 1992 to 2011 for the principal ICCAT species, with the latest catches reported by ICCAT (https://www.iccat.int/en/accesingdb.html), These latest catches are up to and including 2017; more recent data are not available due to delays in reporting to and processing by ICCAT. This shows the proportion of the total catch (black) and the longline catch (blue) of highly migratory species taken from the Sargasso Sea region. Up to a maximum of 12 per cent of North Atlantic albacore and 10 per cent of West Atlantic bluefin catches are taken in the region. Catches of tropical tunas (bigeye, yellowfin and skipjack) and billfish (swordfish, sailfish, blue marlin and white marlin) are smaller but still significant. The proportion of the catches taken from the Sargasso Sea show considerable variability over time, potentially due to changes in targeting by the long-line fleets, but effort data to evaluate this are not available from ICCAT. The longline fleet is shown because of the ecological importance of by-catch species such as billfishes, sharks, seabirds and sea turtles. To move towards ecosystem-based fisheries management in the Sargasso Sea, understanding the spatial overlap between fishing effort and the behaviour of non-target species will be important, including migration routes, aggregating behaviour and habitat use of all species that use it (Kell and Luckhurst, 2018; Boerder and others, 2019).

Figure 1. Time series showing the percentage of the total (black) and long line catches (blue) coming from the Sargasso Sea region; data are from the ICCAT Catch-at-size database CATDIS.



2.4. Plastic pollution

Plastic pollution in the Sargasso Sea was first observed in 1972 (Carpenter and Smith, 1972).

Concentrations of microplastics in the surface of the Sea were found to be orders of magnitude greater than previously recorded, with the greatest concentration in the subtropical convergence zone (Law and others, 2010). Accumulation of surface particles in this zone was forecast by models used to guide sampling by the "7th Continent" expedition, 2014. It was estimated that the North Atlantic subtropical gyre, that is, the Sargasso Sea, had about 56,000 tons of floating plastic in 2014 (Eriksen and others, 2014). Presumably more is present today. There have been extensive reviews of plastic pollution and its effects in the global ocean and in ocean gyres (GESAMP, 2014; GESAMP, 2016; Law, 2017; Eriksen and others, 2016). More recently, laboratory experiments have found adverse effects of plastic leachates on the photosynthetic bacterium *Prochlorococcus* (Tetu and others, 2019). *Prochlorococcus* produces up to 20 per cent of atmospheric oxygen. If these results are confirmed in situ, plastic pollution poses a threat to global oxygen production by marine bacteria. The adverse impacts described in these various reviews will apply to the Sargasso Sea and, the concentrating effects of the ocean gyre and the subtropical convergence trap plastic within mats of *Sargassum*, which makes the Sargasso Sea particularly vulnerable.

3. Institutional arrangements

One of the major challenges facing the Sargasso Sea is a legal one. The Sargasso Sea falls within the high seas - the 50 per cent of the planet outside national jurisdiction (Freestone, 2015). To address this challenge, five Governments came together in 2014 to sign the Hamilton Declaration on Collaboration for the Conservation of the Sargasso Sea and to establish the Sargasso Sea Commission to act as steward for this extraordinary area (Freestone and Morrison, 2014). Five more Governments have since joined and others may follow (Sargasso Sea Commission, 2018).

The Sargasso Sea Commission is based on a new paradigm for the conservation of areas beyond national jurisdiction, convening stakeholders from multiple countries and organizations to address issues that fall outside national agendas. Parties to the Convention on Biological Diversity[141] have agreed that the Sargasso Sea be included on a list of ecologically or biologically significant areas (ESBA) (CBD, 2012). Using this as a basis, in 2015, NAFO agreed conservation measures by declaring a moratorium on bottom trawling on Sargasso Sea seamounts in the NAFO area, together with gear restrictions on midwater trawling (NAFO 2015; Diz, 2016).

The Commission is working to protect the Sargasso Sea alongside a number of Governments and partners. In collaboration with the Convention on the Conservation of Migratory Species of Wild Animals,[142] it is working to protect the migratory range of the European eel through the Sargasso Sea. It is also exploring ways to regulate impacts of vessel activities and to work with ICCAT to use the Sargasso Sea as a pilot project on the ecosystem approach to fisheries management (Kell and Luckhurst, 2018), and is working with the United States National Aeronautics and Space Administration (NASA) which is developing comprehensive satellite imagery of the Sargasso Sea area.

4. Consequences of changes

The changes outlined above are mostly driven externally. On a global scale, climate change

[141] United Nations, *Treaty Series*, vol. 1760, No. 30619.
[142] Ibid., vol. 1651, No. 28395.

affects ocean temperature, ocean acidity and ocean circulation, which causes ecosystem changes in both *Sargassum* and its dependent communities and in deeper living pelagic and benthic communities. These effects have the potential to adversely affect spawning, larval feeding and migrations of eels and other fishes. Concurrent with overall warming of the global ocean is an increase in frequency of global marine heatwaves which adversely impact biodiversity and threaten to disrupt ecosystem services in certain areas of the ocean (Smale and others, 2019). The southern Sargasso Sea has been identified as an area that has been significantly affected. Most of the pollution, including plastic, comes from land and is concentrated by ocean currents in the Sargasso Sea. Eel populations are impacted by overfishing in exclusive economic zones (EEZ) and national waters. In addition, they are exposed to various threats during their freshwater stage, including pollutants and obstructions caused by dams and hydropower plants (Hanel and others, 2019).

The impacts of global environmental changes on the oceans, future predictions for fisheries and governance issues are summarized in the Nippon Foundation-Nereus Programme (2015), and ocean issues related to the SDGs[136] are summarized in the Nippon Foundation-Nereus Programme (2017). Monitoring changes in ocean temperature and chemistry and understanding the impact of these changes on ecosystems relate directly to SDG 13 on climate action and SDG 14. The ongoing time series stations off Bermuda are central to this global monitoring (Neuer and others, 2017). Mass strandings of *Sargassum* on beaches cause widespread socioeconomic problems to local communities, adversely impacting tourism, fishing and health, and killing biota, including turtles and fish. The costs of cleaning up beaches run into millions of dollars and affected countries are developing management plans and technologies to minimize impacts and seek potential uses for the *Sargassum* (Milledge and Harvey, 2016; Wabnitz and others, 2019). Because of the widespread impacts to both humans and to local and ocean ecology, these blooms impact directly all SDGs. American and European eels support valuable fisheries in many countries on both sides of the Atlantic as well as lucrative aquaculture operations in Asia, but the populations of both species have crashed in recent years (Hanel and others, 2019; Atlantic States Marine Fisheries Commission, 2018). The causes are many and varied and these ecological and socioeconomic changes will also impact all SDGs.

Changes in trophic webs brought on by a warming ocean and increased acidity may significantly impact populations of top predators such as highly migratory tunas and swordfish (*Fernandes and others, 2013)*. Changes caused by weakening of the Atlantic ocean's overturning circulation may result in shifts in species distributions (Caesar and others, 2018). Ocean warming, ocean acidification and deoxygenation, combined with other stresses, could change primary productivity, growth and distribution of fish populations (Barange and others, 2018). This, in turn, will result in changes in the potential yield of exploited marine species and the associated economic and social benefits that they provide (*Gattuso, and others,* 2015). These impacts will in turn impact all SDGs. Finally, the impacts and potential impacts of the rising amounts of plastic in the oceans are well documented, (e.g. Beaumont and others, 2019) and will affect all SDGs.

5. Outlook

The outlook for the Sargasso Sea, both in the short and long term, depends upon international decisions, priorities, and cooperation. The importance of the Sargasso Sea is recognized internationally, and because it is in the high seas, its protection falls within the competence of a number of organizations. The remoteness and size of the Sea mean that, in open ocean terms, it remains relatively pristine despite the concentrating effects of its rotating currents. However, its integrity is threatened both by the changes outlined previously and by others, including the potential for increased fishing activity over the last three years by some 28 countries as estimated using automatic identification system data (Sargasso Sea Commission, 2019), and by increased shipping activities through the region. The development of deep-sea mining in areas adjacent to the Sargasso Sea poses new threats (Dunn and others, (2018). The Sargasso Sea demonstrates the challenges faced by existing sectoral bodies to govern high seas ecosystem in a holistic manner.

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Chapter 8B
Human Health as Affected by the Ocean

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Keynote points

- There are both health benefits and risks to living near the sea. The advantages can include enhanced air quality, exercise opportunities, novel marine-derived pharmaceuticals and ready access to food from the sea, which itself has health benefits (as a source of protein and essential micronutrients), although seafood is also traded inland; as well as sources and renewable energy.
- The ocean presents health risks from tsunamis, storms and tropical cyclones. Humans are also at enhanced risks from contaminated food from the sea, sea level rise and increased risks of storms and cyclones from climate change.
- Chemical contaminants (including air pollution particulates), harmful or toxic algal blooms and pathogens pose health risks, particularly in estuarine and coastal waters where there is adjacent urbanization and/or recreational usage.
- Novel pollutants, such as antibiotics, hormones, nanomaterials (e.g., fullerenes, carbon nanotubes, metallic nanoparticles and nanaoplastics) and microplastics, are a cause for concern. Combustion nanoparticles (e.g., $PM_{2.5}$) as a major component of air pollution, are well established as contributing to cardiovascular disease (CVD) and lung cancer.

1. Introduction

In the First World Ocean Assessment (WOA I) (United Nations, 2017), various adverse impacts on human health were noted from sewage discharge, disease vectors linked to seawater (especially from sewage discharge), nanomaterials and microplastics, especially from plastic waste. Nanomaterials include both materials intentionally manufactured, for use in cosmetics, for example, and those resulting from the breakdown of plastic waste. Some benefits to human health were also noted, especially from fish and seaweed as food elements, marine pharmaceuticals and marine nutraceuticals, as well as from the recreational effects of time spent by the seaside. There was no comprehensive discussion on the relationship between human health and the ocean. The present Chapter, therefore, seeks to give an overview of all aspects of the relationship between human health and the ocean.

2. General aspects of the relationship between human health and the ocean

The marine environment brings both benefits and risks to human health, especially for people who live near to it (Figure 1; Depledge and others, 2013; Moore and others, 2013, 2014). Health has been defined as a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity (WHO, 1984). However, people live in an interdependent existence with the totality of the living world, hence, human health cannot be separated from the health of our total planetary biodiversity and has now been redefined as the ability of a body to adapt to new threats and infirmities (Lancet - Editorial, 2009). The complex interactions between the seas and oceans and human health and well-being have been viewed primarily within a risk framework, for example, adverse impacts of extreme weather, chemical pollution (from domestic and industrial effluents, aquaculture, offshore industries, air pollutants and road dust runoff, black carbon in the Arctic) and, increasingly, climate change (Borja and others, 2020; Depledge and others, 2017, 2019; Fleming and others, 2019; Pleijel and others, 2013; Tomero and Hanke, 2016; Valotto and others, 2015; Walker and others, 2019; Winiger and others, 2019). However, new research is expanding our concept of the "health" of the "Global Ocean", with a broader recognition of its essential and beneficial contribution to the current and future health and well-being of humankind (Borja and others, 2020; Depledge and others, 2019; Ercolano and others, 2019; Lindequist, 2016; Table 1).

The marine environment contributes significantly to human health through the provision and quality of the air we breathe, the food we eat and the water we drink, and marine–derived pharmaceuticals, as well as providing health-enhancing economic and recreational opportunities (see Chapters 5 and 8C of the present Assessment; Ercolano and others, 2019; Lindequist, 2016). The coastal environment can also have a calming effect (White and others, 2013) and provide important cultural benefits (see Chapter 31, section 1.4). However, at the same time, the marine environment is under pressure from human activities such as transport, industrial processes, fishing, agricultural and waste management practices, climate-change related impacts associated with rising sea levels and coastal erosion, and biological invasions. Figure 1 summarizes the links between the degradation of the marine environment and human health.

Assessment and management of the impacts on marine ecosystems and on human health resulting from the pressures on those ecosystems have largely been undertaken separately under the umbrella of different disciplines and, frequently, with little or no obvious collaborative interaction (Depledge and others, 2013; Moore and others, 2013, 2014). Consequently, many of our perceptions of the interactions between the marine environment and human health are limited and still relatively unchallenged, leaving an opportunity to address critical knowledge gaps to further inform science-based policies for the sustainable use of marine resources and environmental and human health protection (Figure 1; Moore and others, 2014).

The complex nature of the interactions between the marine environment and human health was reviewed by the European Marine Board (Moore and others, 2013, 2014) and others (Borja and others, 2020; Depledge and others, 2013, 2017, 2019; Fleming and others, 2014, 2019). These reviews have emphasized the need for an interdisciplinary approach to address all levels of organization, from genes to ecosystems.

There are five key scientific challenges to improving our understanding of the linkages between the marine environment and human health (Galloway and others, 2017; Moore and others, 2014), which are:

(a) To improve measurement and monitoring of the distribution of marine pollutants including algal toxins, nanoparticles as contributing factors to CVD and lung cancer (Chang and others, 2020; Liu and others, 2016; Moore, 2020; Mossman and others, 2007; Numan and others, 2015; Stapleton, 2020), microparticles and plastic marine litter as a vector), pathogens and non-indigenous species (NIS) as potential health hazards at required time and spatial scales (Galil, 2018; Vezzulli and others, 2016);

(b) To improve knowledge of processes and models of the dynamics of transport and transformation of marine pollutants, pathogens and NIS health hazards in the environment;

(c) To improve assessment of marine pollutant, pathogen and NIS health hazard exposure and risk to humans (Galil, 2018; Moore and others, 2013, 2014; Vezzulli and others, 2016);

(d) To understand the impacts of waste management activities on the marine environment and human health;

(e) To find explanations for the association between the marine environment and observed human health benefits, described as the "Blue Gym" effect (Depledge and Bird, 2009; Robinson and others, 2020; White and others, 2013; Wyles and others, 2019), including socioeconomic influences (Li and Zhu, 2006; Sachs and others, 2001).

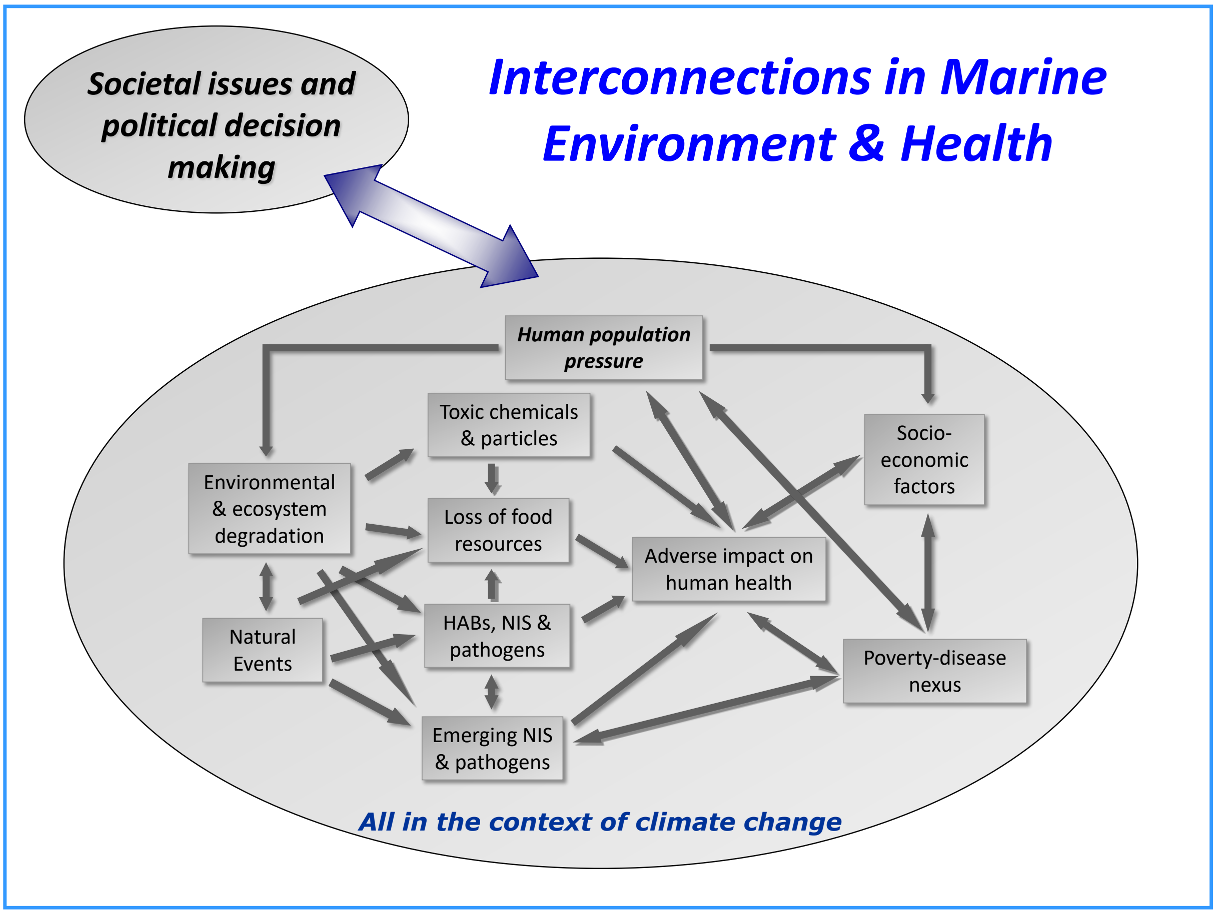

Figure 1. A summary of the interconnectivity of the key adverse processes between the marine environment and human health. Toxic chemicals and particles includes air pollution particulates, nanoparticles and microplastics. (HABs – toxic or harmful algal blooms; NIS – (poisonous and venomous) non-indigenous species). (*Source: Original diagram partly adapted from Moore and others, 2014*).

The potential benefits for human health such as novel pharmaceuticals (e.g., antimicrobial, antitumor, antidiabetic, anticoagulant, antioxidant, anti-inflammatory, antiviral, antimalarial, antitubercular, anti-aging and antiprotozoal) derived from marine organisms, essential micronutrients in seafood, and from living in proximity to the sea (Table 1) have often been overlooked in the past (Table 1; Borja and others, 2020; Depledge and others, 2019; Ercolano and others, 2019; Fleming and others, 2019; Gascon and others, 2017; Hosomi and others, 2012; Lindequist, 2016; Wheeler and others, 2012; White and others, 2014; Wyles and others, 2019). However, it is becoming well established that there are various health benefits to be gained from living by the sea (Giles, 2013). The reason why this should be is less clear, and has so far eluded an overall scientific explanation. However, several hypotheses have been proposed: psychological stress reduction due to pleasant surroundings (Gascon and others, 2017; White and others, 2014); improved immunoregulation from exposure to bacteria and parasites with which we co-evolved (Rook, 2013); and exposure to bioactive natural products (biogenics) such as harmful or toxic algal toxins (Berdalet and others, 2016; 2017). This third (biogenic) hypothesis has proposed that inhalation and ingestion (with upper respiratory tract mucus) of certain natural products, such as low concentrations of aerosolized algal toxins, have direct effects on the body's molecular regulatory systems, resulting in health benefits, including anti-inflammatory, anti-cancer and anti-ageing effects (Asselman and others, 2019; Moore, 2015; Van Acker and others, 2020; Table 1). Coastal areas have higher ultraviolet (UV) levels and, consequently, inhabitants may benefit from increased vitamin D (Cherrie and others, 2015; Table 1).

Table 1. Summary of benefits and hazards/risks associated with living in proximity to the sea.

Benefits	Hazards and risks

Improvements in the length and quality of life (Gascon and others, 2017)	**Chemical and radionuclide pollutants, including toxic airborne particulates (both land-derived and from shipping) and coastal ozone (Moore and others, 2014; Pleijel and others, 2013; Valotto and others, 2015; vom Saal and others, 2007; Walker and others 2019; Wan and others, 2016)**
Improved physical and mental health (Gascon and others, 2017; White and others, 2014; Wyles and others, 2019)	**Nanomaterials and microplastics (Chang and others, 2020; Galloway and others, 2017; Moore and others, 2014; Mossman and others, 2007; Numan and others, 2015)**
Increased vitamin D (Cherrie and others, 2015)	**Pathogens and public health consequences from sewage, agricultural runoff and flooding (Leonard and others, 2018a; Moore and others, 2013, 2014; Vezzulli and others, 2016)**
Reduced behavioural problems in children (Gascon and others, 2017)	**Environmental impacts on food security and safety, such as collapse of fisheries and contamination of food resources (Moore and others, 2014)**
Low concentrations of airborne aerosolized algal toxins may have beneficial hormetic effects on health (anti-inflammatory and anti-cancer effects) (Asselman and others, 2019; Moore, 2015; Van Acker and others, 2020)	**Harmful or toxic algal blooms and algal toxins (Berdalet and others, 2016)**
Benefits from consumption of seafood that is high in protein and essential micronutrients (Hosomi and others, 2012)	**Poisonous or venomous indigenous and non-indigenous species (NIS) such as silverstripe blaasop (produces tetrodotoxin), nomadic jellyfish and lionfish (Galil, 2018)**
Marine–derived pharmaceuticals (Ercolano and others, 2019; Lindequist, 2016)	**Adverse natural events (volcanic eruptions, earthquakes, tsunamis, tropical cyclones and flooding) (Moore and others, 2014; Powell and others, 2019; Ruskin and others, 2018)**
	Transmission of antimicrobial resistance and pathogens via natural bacterial ecosystems (Leonard and others, 2018b; Imran and others, 2019)
	Plastic marine litter as an emerging potential vector for pathogens and their possible global transport (Vethaak and Leslie, 2016; Keswani and others, 2016); as well as possible collisions with large plastic litter at sea.
	Increased risks from overcrowding as coastal population increases (Moore and others, 2014)

With regard to the potential hazards and risks for human health (Table 1), which are more comprehensively documented than the benefits (Borja and others, 2020; Depledge and others, 2013, 2017, 2019; Fleming and others, 2014, 2019; Moore and others, 2013, 2014), the European Environment and Health Process, coordinated by the World Health Organization (WHO), has identified five general “key environment and health challenges of our time”. Their particular focus in relation to the marine environment includes:

(a) Health and environmental impacts of climate change (for example, tropical cyclones);
(b) Health risks to children and other vulnerable groups posed by poor environmental, working and living conditions, especially the lack of water and sanitation (for example, contaminated food from the sea);
(c) Socioeconomic and gender inequalities in the human environment and health (for example, the poor injury record of fishers and seafarers and culturally-related limited access to healthcare for females);
(d) The burden of non-communicable diseases, in particular to the extent that the burden can be reduced through adequate policies in areas such as urban development, transport, food safety and nutrition, and living and working environments (for example, the role of fish protein in providing essential nutrients);
(e) Persistent, endocrine-disrupting and bio-accumulating harmful chemicals and nanomaterials; and novel and emerging chemical problems (for example, the impacts of such substances on the health of the marine environment and thus on the humans depending on it) (WHO-Europe, 2010).

The marine aspects of these policy priorities reflect to some extent the scientific challenges specifically identified above in relation to human health and the marine environment. They focus largely on the risks, and tend to leave out and, therefore, do not take into account the benefits deriving from the marine environment. Furthermore, both gender differences and gender inequalities can give rise to inequities between men and women in health status and access to health care. However, gender norms and values are not fixed and can evolve over time, can vary substantially from place to place, and are subject to change (WHO, 2014). Nevertheless, there are a number of threats to human health arising from the marine environment that have now been identified:

- Increase in spread of pathogens related to climate warming here (e.g., *Vibrio*). Also there is some evidence related to an increase in some HAB species related to climate warming is some regions (Hinder and others, 2012; Vezzulli and others).
- Recently, non-indigenous species (NIS), sometimes called invasive alien species, have started to be considered as one of the major threats to global marine ecosystems through impacts on these ecosystems’ structure, function and services (Galil, 2018). A small number of poisonous or venomous marine NIS represent potential threats to human health. Intensification of anthropogenic activities, coupled with rapidly increasing coastal urbanization, drive complex and fundamental changes in coastal waters, including increases in alien species. Some of these alien venomous and poisonous species have attracted the attention of scientists, managers, the media and the public for their conspicuous human health impacts. In the Mediterranean Sea alone, 10 NIS are considered human health hazards, running the gamut from nuisance to lethal (Galil, 2018). Human health hazards of NIS are expected to worsen as a result of climate change. The poleward influx of warm water biota enables them to spread to regions as yet uncolonized.
- A further, recently identified health threat is the potential role of plastic marine litter as a vector for opportunistic human pathogens and antibiotic resistant microorganisms (Barboza and others, 2018; Harrison and others, 2018, Imran and others, 2019). Various pathogenic bacteria bind, particularly and strongly, to plastic litter (for example, *Vibrio cholerae* and some strains of *Escherichia coli*). Such human pathogens can colonize plastic surfaces in stable biofilms. The scientific and medical understanding of this health threat of plastic pollution is inadequate but the threat is dealt with as a further aspect of the problem of marine litter discussed in Chapter 12 of the present Assessment. A severe problem could arise in areas that are highly polluted as a result of natural disasters, climate crises or occurring epidemics, or in conflict zones (Vethaak and Leslie, 2016; Keswani and others, 2016; Galloway, and others, 2017; Leonard and others, 2018a, 2018b; Moore and others, 2014).

In a general context, some new multinational, interdisciplinary projects are now addressing some of these issues, including:

(a) The Seas, Oceans and Public Health in Europe (SOPHIE) Project funded by the European Union (European Union, 2020)) which has developed a "research road map", to help scientists to gather evidence and inform policies which enhance and protect both human health and the health of the marine environment;

(b) The Blue Communities programme (https://www.blue-communities.org/Home), a research capacity-building programme for marine planning in East and South-East Asia, which includes a project to assess the benefits and risks of coastal living associated with environmental, demographic and climate change.[143]

3. Health of coastal communities relative to inland communities

Studies comparing the health of coastal communities to that of inland communities have, so far, largely been confined to developed countries. The evidence differs between physical health and mental health. For physical health, there is evidence from Australia (Ball and others, 2007), New Zealand (Witten and others, 2008), the United States of America (Gilmer and others, 2003) and the United Kingdom of Great Britain and Northern Ireland (White and others, 2013) that living in a coastal setting encourages greater levels of recreational physical activity. Although there is some evidence that this extra activity may translate into healthier weight, for the most part, even among children living at the coast (Wood and others, 2016), the evidence is equivocal (Bell and others, 2019). A re-examination of responses to a question in the 2001 Census of England and Wales showed that a significantly higher proportion of people in coastal areas said that they enjoyed good health. This effect may be greater for more socioeconomically deprived groups (Wheeler and others, 2012). In Belgium, a recent survey concluded that people living less than 5 km from the coast report themselves as enjoying better general health than do those living 50–100 km from the coast (Hooyberg and others, 2020).

As regards mental health, an increasing amount of evidence suggests that living in coastal settings, visiting them frequently or simply having a coastal view from home is associated with increased life satisfaction (Brereton and others, 2008) and a decreased risk of anxiety and depression (Nutsford and others, 2016; White and others, 2013; Wyles and others, 2019).

Differences in human health between coastal and inland areas can be due to causes other than the proximity of the sea. Socioeconomic status has a major effect on health generally (Marmot and Wilkinson, 2005); and where there are differences in economic prosperity between coastal areas and inland areas, differences in human health between those areas may be due in part to those economic differences, rather than to direct health benefits of being close to the ocean (Li and Zhu, 2006). However, interpreting this very complicated relationship between economic prosperity and health is often difficult due to the plethora of potential interacting factors (Sachs and others, 2001).

A key challenge is to determine how each coastal community can improve its resilience to sociodemographic change and the increasing number of extreme weather events and environmental threats. Evidence shows that there are advantages to policies that offer a range of co-benefits to both the environment and health. However, any policy response is complicated by the fact that the diversity of coastal communities means that there is unlikely to be any "one size fits all" solution (Depledge and others, 2017; Li and Zhu, 2006; Sachs and others, 2001).

4. Effects of exposure to contaminated seawater

Many of the main activities related to coastal tourism and recreation involve contact with seawater,

[143] See http://www.blue-communities.org/About_the_programme.

with paddling, swimming, boating, surfing, recreational fishing and diving being among the most common. Fishers and seafarers also come into contact with seawater as part of their work. Such contact brings with it the risk of exposure to pathogens including algal toxins in the water or in marine aerosols. For a long period after disposal of municipal wastewater into the sea became common, there was little concern about the effect of pathogens in the wastewater on human health – the scale of dispersal of the wastewater into the much greater volumes of seawater was thought to minimize risk through dilution (Sullivan, 1971). However, eventually, concern did grow and led to the adoption of measures, in Europe, for example, such as the Bathing Waters Directive (EEC, 1975).

Studies in many places have quantified the scale of the risk to human health from contact with seawater containing pathogens, such as some strains of *Escherichia coli* – bacteria commonly found in the gut of warm-blooded animals (Zmirou and others, 2003; Wade and others, 2006). For example, in Hong Kong, China, a major epidemiological study was conducted in 1992 in which 25,000 beachgoers were interviewed in order to establish the health effects of exposure to bathing water. The results indicated that the total incidence of swimming-related illness symptoms was 4l per 1,000 interviewees, higher than the 30 per 1,000 found earlier in 1987. Eye, skin and respiratory symptoms were 2–20 times more prevalent in swimmers than in non-swimmers (Kueh, 1995).

Likewise, in Santander, Spain, a study over the main holiday season in 1998 showed that 7.5 per cent of the 1,858 bathers studied reported fever or respiratory, gastrointestinal, eye or ear symptoms within seven days – and this was in waters which met the regulatory standards in force (Prieto, 2001). A similar study of 654 surfers was carried out in the winter seasons from 2013 to 2015 in San Diego, California, United States of America, where the quality of coastal waters was adversely affected after heavy rainfall (which usually leads to increased run-off or discharge of contaminants). The study examined the incidence of gastrointestinal illness, sinus infections, ear infections and infected wounds within three days of over 10,000 surfing sessions. It found that the incidence of those conditions rose by between 26 and 105 per cent (varying among types of complaint) after surfing sessions in dry weather, as compared with periods when the persons studied were not surfing. After heavy rainfall, and a consequent increase in surface run-off, the incidence of post-surfing diseases rose by a further 26 to 102 percentage points as compared with non-surfing periods (Arnold and others, 2017). Sewage-contaminated seawater contains a range of microbial pathogens, and exposed individuals may experience various disease symptoms such as skin rashes, conjunctivitis, sinus infections and, in particular, gastroenteritis (Harder-Lauridsen and others, 2013). With a predicted increasing frequency of heavy rainfall associated with climate change in some regions, the future implications for human health worldwide could be considerable, particularly in those areas without well-functioning sewage systems or where current sewage systems are unable to contain the excess run-off and raw sewage is discharged (Harder-Lauridsen and others, 2013). Climate-change related increases in the frequency and severity of riverine and coastal flooding leading to the release of raw sewage and runoff of vector animal faeces, may also represent a health problem with the transmission of emerging infectious microbial agents, such as in the Covid-19 virus pandemic (SARS-CoV2) (Seneviratne and others, 2012).

The global impact of poor water quality was examined in a study by the Joint Group of Experts on the Scientific Aspects of Marine Environment Protection (GESAMP) and WHO. Based on global estimates of the number of tourists who go swimming, and WHO estimates of the relative risks at various levels of contamination, this study estimated that bathing in polluted seas causes some 250 million cases of gastroenteritis and upper respiratory disease every year and that some of those people affected would be disabled over the longer term. Measured by adding up the total years of healthy life that are lost through disease, disability and death, the worldwide burden of disease incurred by bathing in contaminated seawater is some 400,000 disability-adjusted life-years (a standard measure of time lost due to premature death and time spent disabled by disease), comparable to the global impacts of diphtheria and leprosy. GESAMP/WHO estimated that the cost to society, worldwide, amounted to about 1.6 billion United States dollars a year (GESAMP, 2001). Furthermore, harmful/toxic algal blooms can induce serious neurological disease and also have major financial impacts (Bechard, 2020; Diaz and others, 2019).

The most common pollutants tend to come from one of two places: humans and animals. Human fecal matter in water bodies constitutes the greatest public health threat because humans are reservoirs for many bacteria, parasites and viruses that are dangerous to other humans and can lead to a variety of illnesses. The cause of many problems can often be traced back to sewage overflows or leaky residential septic systems. Run-off from agricultural land can also represent a serious health concern, as fecal waste from farmed animals can contain pathogens including various viruses, cryptosporidium, *Escherichia coli* and salmonella, while pet waste on beaches can also pose health threats to humans (FAO, 2017; Moore and others, 2014; WHOI, 2020).

Exposure to contaminated seawater thus impacts on the health of those enjoying recreation by the sea and adversely affects coastal tourism and recreation. Drawing together the scientific work in this field, in 2003 WHO published *Guidelines for Safe Recreational Water Environments: Coastal and Fresh Waters* (WHO, 2003). More recently, WHO, with the support of the European Union, prepared recommendations on scientific, analytical and epidemiological developments relevant to the parameters for bathing water quality, with special reference to Europe (WHO, 2018). WHO has indicated that these recommendations will inform the revision of the 2003 Guidelines (WHO, 2020). However, achievement of such standards requires adequate planning and infrastructure. Even where, as in some parts of India, strenuous efforts are being made to install properly operating sewage treatment systems, problems persist. For example, in Goa, a major tourist location, fecal coliform bacteria exceeded the relevant standards at all ten of the beaches monitored (GSPCB, 2019).

The monitoring of bathing water will not achieve its end of improving public health without improvements in the readily understandable communication to the public of the findings. The current European Union legislation on bathing water (EU, 2006) provides for standardized ways of publicizing the results of the monitoring that is required. Similar systems are found in various Australian States (NSW-DPIE, 2020; SA-EPA, 2020) and in the United States of America (WHOI, 2020).

Climate change may be influencing the prevalence of microbial infections (Deeb and others, 2018; Konrad and others, 2017). For example, increases of *Vibrio* (*V. vulnificus and V. parahaemolyticus*), both topical infections and seafood ingestion borne infections (oysters), have been described in relation to climate change, with rises in cases overall as well as new cases found in high latitude areas that were previously not impacted as they are having more days over the minimum temperature threshold (Vezzulli and others, 2016).

5. Problems for human health posed by food from the sea

Human health can be affected by many aspects of food from the sea. Some problems are the result of pollutants (such as mercury) or pathogens (often from sewage and ballast water) discharged into the sea and taken up by plants, fish and shellfish that are harvested for human consumption (Takehashi and others, 2008). Others are the result of toxins generated by, or viruses found in, various biota in the sea and taken up by some fish and shellfish (see Chapters 10 and 11 of the present Assessment).

According to WHO, mercury is one of the ten most poisonous substances to human health (WHO, 2013). A principal form of mercury to which humans are exposed is organic methyl mercury (MeHg). The principal source of inorganic mercury in the sea is the burning of fossil fuels (see Chapter 11). This is converted into MeHg by microbes in the aquatic environment, where it bioaccumulates in food webs. In humans, MeHg exposure occurs predominantly through the consumption of seafood. MeHg is a neurotoxin and is particularly harmful to fetal brain development. A large body of research has demonstrated a link between exposure to MeHg in the womb and developmental neurotoxicity (e.g. deficits in fine motor skills, language and memory) among populations that consume seafood regularly. A review of studies in 43 countries showed that pooled average biomarkers suggested an intake of MeHg that was:

(a) Several times above the FAO/WHO reference level for consumption in fish-consuming inhabitants of coasts and river banks living near small-scale gold-mining installations;[144]
(b) Well over the reference level in consumers of marine mammals in Arctic regions;
(c) Approaching the reference level in coastal regions in South-East Asia, the western Pacific and the Mediterranean.

Although the two former groups have a higher risk of neurotoxicity than the latter, the coastal regions of South-East Asia are home to very large populations. In all three areas, many of the samples showed levels of MeHg intake in excess of the reference value (Sheehan and others, 2014). Other experts, while recognizing the threat from MeHg, argue that it is important also to balance the benefits from fish-derived lipids with possible risks when considering fish as part of the diet of mothers and their children (Myers and others, 2015). Certain fish species have been identified (e.g., MeHg biomagnifies in the aquatic food chain and larger predatory fish such as shark, swordfish, king mackerel, and certain species of tuna) as at greater risk for MeHg exposure than others, so making appropriate choices in fish consumption can lead to increasing the benefits of eating seafood while decreasing the potential risk (Siblenagel and others, 2011).

Contamination of seafood by the presence of hormones, antibiotics, and persistent organic pollutants (POPs) such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) continues to represent a hazard for human health (Binelli and Provini, 2003; Chen and others, 2015; Lu and others, 2018; EU Persistent, endocrine-disrupting and bio-accumulating harmful chemicals: https://ec.europa.eu/environment/archives/docum/pdf/ bkh_main.pdf). The recently recognized contamination of the ocean by nanomaterials and microplastics is of emerging concern, not only because of the potential ecological impacts, but also the potential to compromise food security, food safety and consequently human health. The presence of nanomaterials and microplastics in marine animals used for human food is now an emergent global phenomenon that require further research to determine whether there is human health risk (Chang and others, 2020; Galloway and others, 2017; Mossman and others, 2007; Numan and others, 2015; Sforzini and others, 2020; Stapleton, 2019; Stern and others, 2012; Smith and others, 2018; Vethaak and Leslie, 2016; Von Moos and others, 2012). Combustion nanoparticles are taken up into cells by endocytosis and accumulate in lysosomes, where overloading of the lysosomes results in membrane permabilisation, with resultant release of intralysosomal iron that causes oxidative cell injury leading to oxidative stress with subsequent tissue and organ damage (Moore, 2020; Numan and others, 2015; Stern and others, 2012; Sforzini and others, 2020; Von Moos and others, 2012). There are now concerns that other nanoparticles including nano- and microplastics may behave in a similar way (Boverhof and others, 2015; Von Moos and others, 2012).

Shellfish are the major vector of illnesses caused by pathogens discharged to the sea. Oysters, for example, can concentrate such pathogens up to 99 times the level in their surrounding water (Burkhardt and Calci, 2000; Morris and Acheson, 2003; Motes and others, 1994; Vezulli and others, 2016). The most common viral pathogens involved were norovirus (83.7 per cent) and the hepatitis A virus (12.8 per cent) (Bellou and others, 2013). No global database exists on outbreaks of illness of this kind. However, a survey of outbreaks reported between 1980 and 2012 found records of about 368 shellfish-borne viral outbreaks. The majority were located in East Asia, with more than half in Japan, followed by Europe, America, Oceania and Africa. In addition to sewage-borne pathogens, toxins (e.g., yessotoxins, brevetoxins and ciguatoxins) can be produced by toxic algae (e.g., dinoflagellates), often at relatively low concentrations (e.g., 200 cell/L of *Alexandrium* spp.) and not necessarily restricted to algal blooms (see Chapter 10 of the present Assessment for causes of such blooms; and US Centers for Disease Control databases)). Algal toxins can enter the food web and are often present in shellfish and fish where they can cause illness as a result of their consumption as human food. The health impacts of algal toxins are not limited to illnesses and deaths caused by poisoning, but also include health impacts from the loss of shellfish and other fisheries that have to be

[144] The FAO/WHO reference level is 2.0 microgrammes per gramme, which is not considered as posing an appreciable risk (WHO, 2008).

closed to protect people from poisoning, and the disruption of ecosystems caused by deaths of fish and top predators that ingest the algae or the toxins that they produce. Many toxic algal bloom events are reported annually, from all parts of the world, and the number is growing. The increased numbers are, in part, due to improved observation and recording but there is reliable evidence demonstrating a real increase in the incidence of these problem blooms as a result of the interaction of many factors, including rising sea temperatures, increased inputs of nutrients to the ocean, the transfer of non-indigenous species by shipping, and changes in the balance of nutrients in the sea (Hinder and others, 2012). Health warning systems could be implemented in higher risk areas by involving not just the public health authorities, but also community planners, utility managers and designers.

Effective monitoring and management programmes are, however, in place in some "at risk" regions to prevent these toxins from commercial seafood (Anderson, 2009; Anderson and others, 2001; see Chapter 10). Such monitoring and management programs are based on rigorous research on method development and validation as well as understanding of temporal and spatial patterns of toxic algae and knowledge of their transfer to humans.

Toxic algal blooms are complex phenomena and many different disciplines need to be involved in finding a way to address the problems they cause, ranging from molecular and cell biology to large-scale field surveys, numerical modelling and remote sensing (IOC, 2017). Other biogenic toxins of health concern, which are not produced by algal blooms, include cyanotoxins produced by cyanobacteria, tetrodotoxins produced by symbiotic bacteria are used by metazoans as a defensive biotoxin to ward off predation, or as both a defensive and predatory venom while palytoxins are intense vasoconstrictors that pose risks to humans primarily through exposure to coral (Bane and others, 2014; Ramos and Vasconcelos, 2010; Zanchett and Oliveira-Filho, 2013). Humans who consume shellfish contaminated with brevetoxins, which are produced by some species of plankton, are at high risk of developing neurotoxic shellfish poisoning. There are also reports of skin ailments resulting from contact with brevetoxin-contaminated water and of respiratory illness from brevetoxin aerosols, particularly in vulnerable people with asthma (Hoagland and others, 2009). Shellfish metabolites of brevetoxin can also show different patterns of toxicity (Turner and others, 2015). Tetrodotoxins, produced by some species of bacteria, and ciguatoxins produced by some species of plankton, can accumulate in fish and other seafood and are poisonous when consumed. These types of biogenic toxin were previously associated with tropical waters, but are now being found in temperate zones (Rodriguez and others, 2008; Silva and others, 2015a, 2015b). The social costs of all these illnesses can be huge, and the estimated costs related to illnesses from toxic algal blooms in just one single county in Florida, United States of America, amounted to between 0.5 and 4 million United States dollars (Hoagland and others, 2009).

6. Key remaining knowledge and capacity-building gaps

Knowledge gaps mainly relate to:

(a) The ways in which, and the extent to which the ocean can produce health benefits through proximity to it, delivery of marine-derived pharmaceuticals, and the development of novel seafoods;

(b) The extent to which health threats from the ocean affect human health in different parts of the world: for example, the ways in which marine vectors can deliver pathogens to humans; the scale and location of illness from swimming in contaminated water and from seafood; the extent of contamination of fish and shellfish;

(c) Socioeconomic and gender inequalities in the human environment and health, including health risks to children and other vulnerable groups posed by poor environmental, working and living conditions (especially the lack of water and sanitation) (Moore and others, 2013, 2014; WHO, 2014);

(d) Burden of non-communicable diseases, in particular to the extent that it can be reduced through adequate policies in areas such as urban development, transport, food safety and nutrition, and living and working environments (Moore and others, 2013, 2014); (e) The mechanisms by which novel health threats may arise from the ocean: for example, the role of nanomaterials (including combustion particulates) and nano- and microplastics and the extent of human exposure to them (Galloway and others, 2017; Mossman and others, 2007; Numan and others, 2015; Sforzini and others, 2020; Stapleton, 2019; Stern and others, 2012; Vethaak and Leslie, 2016; Von Moos and others, 2012; Wright and Kelly, 2017); and the conditions under which algal blooms can become toxic (see Chapter 10);

(f) Empirical assessment of socio-economical and health effects of Marine Protected Areas (MPAs) is sparse. Ban and others (2019) reveal that most studies on well-being outcomes of MPAs focused on economic and governance aspects, whereas social, health and cultural aspects received only a cursory mention. Furthermore, the largest MPAs are situated far from human habitation (e.g., Marae Moana (Cook Islands) Ross Sea marine reserve (Antarctica), Papahānaumokuākea Marine National Monument (Hawaiian Archipelago), Pacific Remote Islands Marine National Monument, Coral Sea Marine Park), whereas in the densely inhabited Mediterranean fully protected MPAs, that conceivably may provide health benefits, constitute only 0.06% of the countries' Exclusive Economic Zone (Kersting and others, 2020).

(g) Health and environmental impacts of climate change (WHO, 2014).

Efforts to address these issues must include interdisciplinary research which, in turn, requires the building of capacities to carry it out and apply the results. This necessitates both the training and retention of expert staff and the provision and financing of the necessary infrastructure. Efforts to tackle the causes of ill health linked to the ocean must also include the provision of adequate infrastructures and skilled personnel, particularly with regard to environmentally sound management of chemicals and all wastes throughout their life cycle, integrated water resources management and the testing of harvested food UN/SDG 12: https://sustainabledevelopment.un.org/sdg12).

7. Outlook

Increased knowledge of the linkages between the ocean and human health will help to improve interventions to protect human health from threats, and to increase the health benefits derived by humans from the sea. Improved capacities around the world, including effectively managed Marine Protected Areas (OECD, 2017), will enable the challenges posed by the sea to human health to be addressed more universally. including Marine Protected Areas".

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Chapter 8C
Coastal Communities and Maritime Industries

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Keynote points

- About 40 per cent of the world's population lives in the coastal zone, that is, within 100 km of the coast. This proportion is increasing.
- Coastal communities play a key role in supporting all components of the ocean economy, as well as a range of social and cultural values, and all forms of coastal and marine management and governance. While coastal communities often have to deal with physical and social vulnerabilities, they are crucial contributors to conservation, to marine hazard responses and to climate mitigation and adaptation.
- The ocean supports a wide range of economic activities, including the harvesting of food, shipping, seabed mining, offshore hydrocarbon exploration and exploitation, tourism and recreation, use of marine genetic resources, production of freshwater by desalinization and production of salt. These various economic activities are steadily growing in scale. Separate Chapters in Part 5 of the present Assessment, on trends in pressures on the marine environment, give more detail on areas not discussed in depth here.
- Shipping carries about 90 per cent by volume of international trade, which makes it fundamental to the global economy. It is still recovering from the economic crisis of 2008–2011.
- Globally, tourism continues to grow at about 6 per cent a year. Coastal tourism represents a substantial proportion of overall economic activity for many countries, especially small island developing and archipelagic States.
- Shipping and tourism have been seriously dislocated by the COVID-19 pandemic.
- Desalinization continues to grow in importance, particularly in the Middle East, North Africa and small island and archipelagic States. Sea salt production also continues at a generally steady level, but accounts for only about one-eighth of total salt production.

1. Introduction

The present Chapter gives an overview of the relationship between humans, their economic activities and the ocean. It starts with a description of the way in which the human population is concentrated to a growing extent around the coasts. It then provides an overview of the communities in which these costal populations live, followed by an overview of the main economic activities that involve the ocean: harvesting food from the ocean; shipping; tourism and recreation; seabed mining; offshore hydrocarbon exploration and exploitation; use of marine genetic resources; production of freshwater by desalinization; and the production of salt. It aims to give, as far as possible, information on levels of economic activity, levels of employment, gender perspectives and the safety aspects of the activities. Some of these industries are discussed in detail in Part 5 in addressing the pressures they impose. So the present Chapter contains cross references to Chapters in Part V in order to avoid duplication. For shipping and tourism, however, more detail is given in the present Chapter. The pressures from shipping are dealt with in Chapter 10 on nutrient pollution, Chapter 11 on liquid and atmospheric inputs, and Chapter 12 on solid waste. Tourism infrastructure is considered in Chapter 14 on marine infrastructure, and the effects of tourism on species and habitats are considered in Chapter 6 and Chapter 7 on the state of species and habitats. Where appropriate, pressures from these industries are noted in the present Chapter to the extent that they are not covered elsewhere.

Coastal communities are crucial components of economic activity on the coast, as home to the people who work or are involved in all kinds of maritime industries, but also in terms of the social and cultural aspects of the coast, with a range of artistic endeavours, traditional practices and communal involvement with the sea. Coastal communities also play a key role in supporting the many decision-making, management and governance activities on the coast and for the sea. In view of this link, the present Chapter also provides an overview of coastal communities.

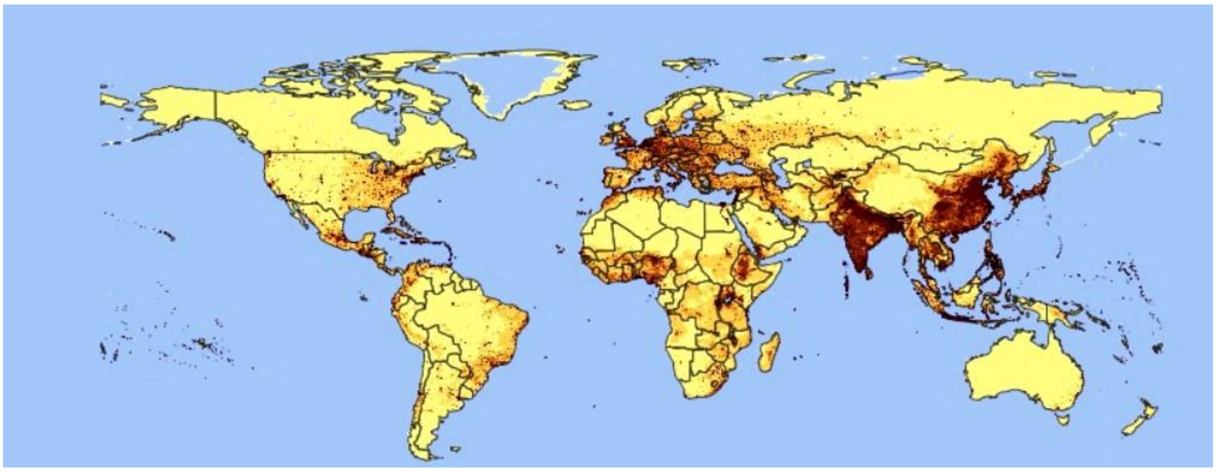
2. Coastal communities

The First World Ocean Assessment (WOA I) in its Chapter 1 (United Nations, 2017a) noted that 38 per cent of the world's population lives within 100 km of the shore, 44 per cent lives within 150 km, 50 per cent within 200 km, and 67 per cent within 400 km (Small and others, 2004). A more detailed analysis was carried out in Chapter 18 of WOA I (United Nations, 2017b) on the location and level of activity of the world's ports, but a more general analysis of the status of coastal communities was not carried out, since the focus of discussion on human activities was sectoral.

2.1. Coastal population and size of coastal communities

Although there have been calls for regular monitoring and assessment of the process of change in coastal areas (see, for example, Shi and Singh, 2003), this has largely been done at the national or regional levels. Little, if anything, has been published about the total global coastal population since the early 2000s. Because of the significance of the impacts of sea level rise, studies since then have concentrated particularly on low elevation coastal zones, which have a narrower scope (for example, Neumann and others, 2015).

Studies in the early 2000s showed that, globally, there is a major concentration of population in the coastal zones. Figure 1 is based on the Global Rural-Urban Mapping Project (GRUMP) population count grids for 2010. This project uses night-time satellite data of observed light sources to identify urban areas, and reallocates census count data within administrative boundaries. The resulting map (Figure 1) shows that the global coastal population is concentrated particularly in East, South-East and South Asia. The evidence suggests that concentration in the coastal zone is increasing as a proportion of the total global population (Merkens and others, 2016). Nevertheless, access to the ocean, particularly for maritime transport, remains important for land-locked States.



The boundaries and names shown on this map and the designations used do not imply official recognition or acceptance by the United Nations.

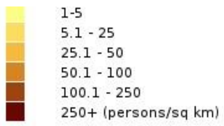


Figure 1. Global Population Density 2010. Source: GRUMP, 2011.

Urban areas near the coast reinforce this concentration: 40 per cent of the population within 100 km of the coast live in 4 per cent of the land area within that distance (Small and Nicholls, 2003). Much of this concentration (about 90 per cent) is in coastal cities with populations of over one million. An analysis of such cities as recorded in *The World's Cities in 2018* (United Nations, 2018) is shown in Table 1.

Table 1. Coastal cities with populations of over 1,000,000 in 2018. Source: United Nations, DESA, 2018.

Region	Number of coastal cities of over one million population in 2018	Total population of those cities in 2018 (Millions)	Range of annual average growth rates of those cities 2000 – 2018
Sub-Saharan Africa	21	54.6	6.6 – 0.4
North Africa	6	16.1	3.5 – 0.7
East Asia	60	258.7	6.3 – 0.1
South Asia	12	86.3	5.6 – 1.2
South-East Asia	20	74.4	6.8 – 0.6
West Asia	14	44.8	5.2 – 1.3
Europe	19	48.1	1.5 – (-0.1)
Latin America and the Caribbean	28	94.2	2.7 – (-0.1)
North America	15	66.5	2.7 – 0.2
Oceania	5	16.8	2.1 – 0.9
Total	**200**	**760.5**	

This analysis thus shows that the main concentrations of urban coastal population are in East, South and South-East Asia, and that the most rapid rates of growth of such populations are in those regions and sub-Saharan Africa.

At the other end of the scale are tens of thousands of smaller coastal communities around the world. The number of, and populations in, such communities are unknown. It seems likely, however, that the number of such communities along the coasts of the world is high, and that official local government units often contain many more than one community. For example, in Nova Scotia, Canada, a recent assessment indicates that, while there are about 50 official municipalities, there are approximately 1,000 separate coastal communities (Charles, 2020). Accordingly, the diversity of coastal communities arises globally, notably in differences between the big cities noted above, and rural communities, where such economic activities as fishing, aquaculture, shipping and tourism are typically prominent.

Whatever the size of the community, they often play a role in stewardship of the coast. Indeed, the role of coastal communities in conservation is being increasingly recognized and valued, in terms of many local initiatives in ocean conservation, around the world, that often succeed both in improving livelihoods and protecting communities (Charles, 2017; Charles and others, 2020).

The role of coastal communities in conservation is being increasingly valued. Many coastal communities around the world and their small-scale fishers have undertaken a large number of local initiatives in ocean conservation, often with considerable success. The successes of these communities are often based on local knowledge, structures and cooperation (Charles, 2017).

The vulnerability of coastal communities to the impacts of climate change is of increasing concern. This vulnerability is relevant to the planning of tourism development (especially in small island developing States with economies dependant on tourism) and fisheries management. The Intergovernmental Panel on Climate Change (IPCC) concludes that, under current trends of increasing exposure and vulnerability of coastal communities, risks, such as erosion and land loss, flooding, salinization and cascading impacts due to mean sea level rise and extreme events are projected to increase significantly throughout the present century (IPCC, 2019). Coastal communities located in the Arctic, in low-lying (often deltaic) States like Guyana and Bangladesh, in paths frequented by cyclones or hurricanes, and in densely populated megacities are especially vulnerable. On the other hand, there appear to be health benefits from living in the coastal zone (see Chapter 8B on human health as affected by the ocean).

Small coastal communities are not just physically vulnerable to climate change impacts, they are also socially vulnerable, particularly in rural areas (Charles and others, 2019). Rural coastal communities are vulnerable to weather events and flooding as a result of geographic location, and also limited access to health care, goods, transportation and other services. Sensitivity to market fluctuations from their dependence on natural resources, and poverty, limited economic opportunities and losses of populations, create problems when trying to adapt (Armitage and Tam, 2007; Amundsen, 2015; Bennett and others, 2016; Metcalf and others, 2015; May, 2019c). Such factors strain material assets, as well as the social and moral foundations that facilitate collective problem solving (Amundsen, 2015; May, 2019a). Communities are more likely to mobilize collective resources in response to threats when people actively care about each other and the place they live (Amundsen, 2015; May, 2019b; Wilkinson, 1991). This may be a function of attachment to the history, culture or environmental context of a place and/or the people in a place. These attachments can become potential sources of resistance to change in contexts of low social diversity and slow population change, or the basis for conflict in contexts of high social diversity and fast population change (Graham and others 2018; May, 2019b, 2019c). The combined effect of physical and social vulnerability on community capacities is particularly challenging at a time when collective action efforts for mitigation and adaptation are more important than ever (May, 2019b, 2019c).

The IPCC warns that for our most vulnerable communities, many of which are coastal, transformative mitigation and adaptation is necessary to assuage the worst impacts of climate change. Incremental change is no longer seen as a possibility by most States: more radical action is thought to be needed to reduce impacts from and adapt to a changing climate. Response to threats from climate change is varied and includes a mix of hard and soft coastal defences. Built infrastructure, such as seawalls or dikes, is widely used but tends to be more costly and maintenance-dependent than ecosystem-based measures, such as marshes, mangroves, reefs or seagrass (see also section 7.3). Limited data inhibits estimates of the cost effectiveness of both hard and soft measures, especially across geographies and scales (Oppenheimer and others, 2019), although State-level estimates exist (see, for example, Environment Agency, 2015). The World Bank estimated that, without concrete climate and development action, over 143 million people could be forced to move within their own countries to escape the slow-onset impacts of climate change by 2050 in just three regions: sub-Saharan Africa, South Asia and Latin America (Rigaud and others, 2018). To address these problems, in coastal areas, integrated coastal zone management is widely regarded as an effective approach to climate change and other drivers (Nicholls and Klein, 2005; Nicholls and others, 2007; see also Chapter 30 on management approaches).

3. Capture fisheries, shellfish harvesting and aquaculture

Food from the sea represents the largest maritime industry in terms of the numbers of people involved. In 2017, the total first sale value of total production was estimated at 221 billion United States dollars, of which 95 billion dollars was from marine aquaculture production (including fish, shellfish and seaweed). These figures include small proportions of production not used for food (FAO, 2019). Further details are given in Chapter 15 on capture fisheries, Chapter16 on aquaculture and Chapter 17 on seaweed harvesting.

The world fishing fleet consisted of about 4.5 million vessels in 2017, a number which has been relatively stable since 2008. Globally, just under one third of the fishing fleet is still composed of unpowered vessels, which reflects the large proportion of small-scale and subsistence fisheries. Only 2 per cent of the total fleet consists of vessels of 24 or more metres length overall, and around 36 per cent of vessels are less than 12 metres in length overall (FAO, 2019).

In 2017, an estimated 135 million people were involved in capture fisheries and marine aquaculture: some 120 million in capture fisheries and some 15 million in marine aquaculture. Employment in capture fisheries (as opposed to subsistence fishing) amounts to about 40.4 million, and employment in marine aquaculture is about 15.6 million. In addition, there is a slightly smaller workforce engaged in post-harvest processing. About 13 per cent of this employed workforce are women. Including subsistence fishing, about 50 per cent of those engaged in this group of activities are women (FAO, 2019; World Bank and others, 2012). There have been no recent surveys of death and injuries in the fishing industry. However, the most recent survey shows that those engaged in the industry suffer much higher levels of death and injury at work than in other industries: around 18 – 40 times higher than the average in a range of developed countries for which statistics were available (Petursdottir and others, 2001).

Apart from subsistence fisheries, fisheries and aquaculture depend on substantive supply chains from producer to consumer. The problems caused by the COVID-19 pandemic are challenging fishing industries (especially in relation to international trade of products) and disrupting these supply chains. Fishing operations have also been affected, with effort reduced by an estimated 6.5 per cent during the March and April 2020. In some areas (e.g. the Mediterranean and the Black Seas) small-scale fisheries have been halted. For the future, COVID-19-compliant practices will bring restrictions on working practices both on the water and in post-harvest handling (FAO, 2020).

Further information on capture fisheries, aquaculture and seaweed harvesting can be found in Chapters 15, 16 and 17, respectively.

4. Shipping

4.1. Situation as shown in the First World Ocean Assessment (WOA I)

When WOA I was written, international shipping was still recovering from the financial crisis from 2008 to 2011. Shipping is conventionally reckoned to represent 90 per cent of international trade, although one estimate in WOA I put it nearer to 75 per cent by volume and around 60 per cent by value (United Nations, 2017f).

4.2. Cargo traffic

Up to 2020, recovery of the world's economy post 2011 has been reflected in the growth of world trade, and consequently in the tonnage of cargo carried by international shipping (Figure 2). When the distances over which the cargoes were carried are taken into account, the growth in ton-miles is even larger (UNCTAD, 2019). Recovery is still in progress, and will have been seriously affected by the massive drop in world trade caused by the COVID-19 crisis.

Such growth, however, has occurred against a weak competitive background for the international shipping industry. The economic crisis from 2008 to 2011 occurred during a time when world shipping had commissioned a large increase in tonnage to meet the increased freight demand of the preceding years. This additional tonnage was delivered at a time when demand had started to reduce, with the result that during the 2010s, the shipping industry was operating against a background of oversupply. This had the consequence of depressing freight rates. As measures to control further the pollutant emissions from ships take effect (from 2020), further pressures associated with implementing modifications to fleets will be placed on the shipping industry. To meet the new requirements (as detailed in Chapter 11), ships must either purchase bunkers with a lower sulphur content (which may have a higher price, since the traditional ships' bunkers have been the high-sulphur oils for which there was less demand) or retrofit scrubbers to clean the ships' exhausts. The further economic pressures of this kind are described in Chapter 11. The combined effect of continuing overcapacity and higher operating costs remains unclear (UNCTAD, 2019).

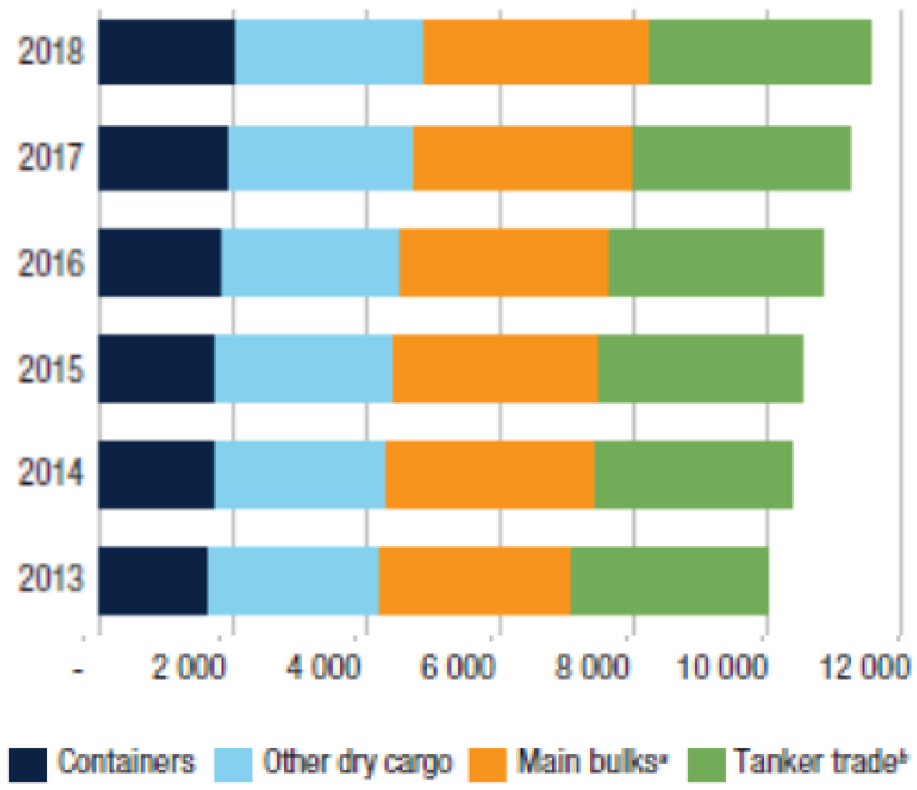


Figure 2. International seaborne trade by commodity type, 2013–2018 - Million tons loaded; (a) "Main bulks" are iron ore, grain and coal; (b) "Tanker trade" covers crude oil, refined petroleum products, gas and chemicals. Source: UNCTAD, 2019.

For many years, the quantities of cargo loaded in ports in developing countries were smaller than those unloaded in those countries, marking an imbalance in seaborne trade. By the time of WOA I, the quantities, on average, were nearly in balance, and since WOA I, the quantities loaded in developing countries now exceed those unloaded. Even excluding China, as the single largest developing-country importer/exporter, there is still an excess of unloadings in developing countries (UNCTAD, 2019).

Container traffic continues to be focused on the main East-West arteries across the Northern Hemisphere (Asia-Europe, Trans-Pacific and Trans-Atlantic) which account for 40 per cent of all container shipping. Of the remaining 60 per cent, 27 per cent is intra-regional, 13 per cent occurs across the other East-West routes in the Northern Hemisphere, 12 per cent is associated with traffic between Southern Hemisphere countries, and 8 per cent is associated with North-South traffic (UNCTAD, 2019). At the same time, there is a growing tendency to consolidate container shipping, and so the combined market share of the top ten container shipping lines increased from 68 per cent in 2014 to 90 per cent in 2019. This is combined with a returning interest in container shipping lines integrating their operations with traffic between originators and ports and between ports and the ultimate destinations. These developments have the ability to undermine competition and thus to result in higher transit costs (UNCTAD, 2019).

The total world fleet of ships carrying all this cargo amounted to 96, 295 ships in early 2019, accounting for 1.97 billion dead-weight tons (dwt) of capacity. Bulk carriers and oil tankers maintained the largest market shares of vessels that dominated the world fleet, at 42.6 per cent of all vessels and 28.7 per cent of dwt, respectively. A large proportion of the world's tonnage continues to be registered in a relatively small number of registries. Nearly 70 per cent of the world's tonnage is registered in seven registries: Panama (17 per cent), Marshall Islands (12 per cent), Liberia (12 per cent), Hong Kong Special Administrative Region of China (10 per cent), Singapore (7 per cent), Malta (6 per cent) and China (5 per cent). No other registry is responsible for more than 4 per cent of the world's tonnage (UNCTAD, 2019).

Likewise, ownership/control of shipping continues to be concentrated in the hands of firms in a relatively small number of countries. In 2019, five economies accounted for more than 50 per cent of the world tonnage: Greece, Japan, China, Singapore and Hong Kong, China. Over the previous five years, Greece, Singapore, China and Hong Kong, China have increased the proportion that they own/control (UNCTAD, 2019).

The construction of new ships still remains very concentrated in China, Japan and the Republic of Korea, together representing 90 per cent of all cargo ship construction activity. The demolition of ships that have reached the end of their useful life likewise continues to be concentrated in the same countries as reported in WOA I. In 2018, 47.2 per cent of the total reported tonnage of propelled seagoing vessels of 100 gross tons and above sold for demolition were demolished in Bangladesh, 25.6 per cent in India, 21.5 per cent in Pakistan, 2.3 per cent in Turkey and 2 per cent in China, leaving 1.4 per cent for the rest of the world. The share of this market held by China, India and Turkey has been declining (UNCTAD, 2019).

In 2020, the COVID-19 pandemic is disrupting global trade extensively. Demand for the transport of raw materials and finished goods has dropped significantly, while demand for the transport of health-related goods has risen (UNCCSA, 2020). Overall, cargo shipping activity has dropped significantly: for example, trade from the European Union to China and the United States of America has dropped in the first 31 weeks of 2020 by 47 per cent and 25 per cent, respectively, compared to 2019; trade in the reverse directions has dropped by 26 per cent and 38 per cent, respectively (EMSA, 2020).

4.3. Passenger traffic

Passenger traffic is almost entirely carried on local ferries or on cruise ships. The pattern of ferry traffic remains as described in WOA I, but the level of traffic has grown steadily (ISL, 2017).

The activities of cruise ships have also continued to grow steadily with the increased global market for cruising: the number of passengers is increasing at around an average of 5 per cent a year (Figure 3). The size of individual cruise ships is also growing steadily (Figure 4). The overall market remains dominated by passengers from the United States of America (around 50 per cent of the total market) and the global distribution of cruising remains largely as described in WOA I, with the major focuses being the Caribbean and the Mediterranean, which together accounted for a little over half of all traffic in 2017 (CLIA, 2018).

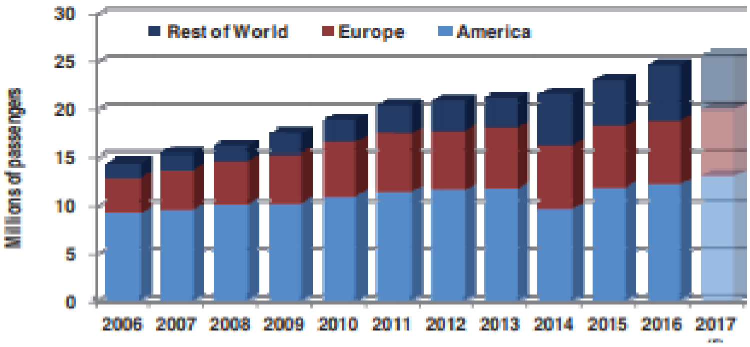


Figure 3. Numbers of passengers on cruise ships, 2006–2017 (2017 statistic estimated). Source: ISL, 2017.

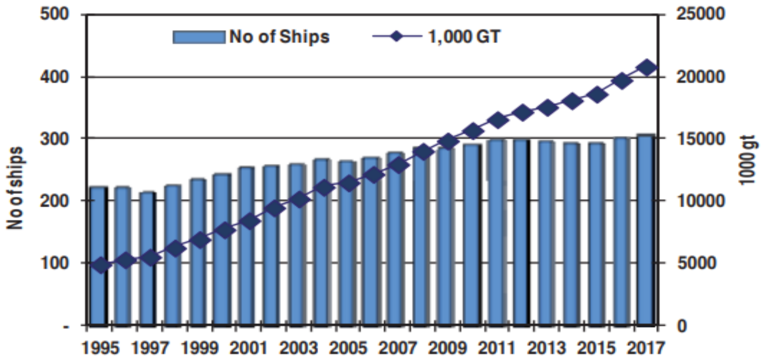


Figure 4. Numbers of cruise ships and their gross tonnage. Source: ISL, 2017.

WOA I noted the relatively recent, but rapid, growth of tourism to Antarctica, particularly as regards cruise ships - from 27,324 cruise-ship passengers in the 2003-2004 season to 37,044 in the 2013-2014 season, which is an increase of 35 per cent. This growth has continued, reaching 51,700 in the 2017-2018 season (an increase of a further 40 per cent), with a forecast of further growth to 55,750 in the 2018-2019 season. Over 80 per cent of the tourists land on Antarctica (IAATO, 2018). Passenger landings and marine traffic are highly concentrated at a few specific locations, particularly along the Antarctic Peninsula's south-western coast. Growth in Antarctic tourism is closely correlated with in the economies of the countries sending most visitors to the region: 60 per cent of the tourists come from the United States of America (33 per cent), China (16 per cent) and Australia (11 per cent). The proportion of tourists from China increased significantly between 2013 and 2014 and 2017 and 2018. Markets for Antarctic travel are probably far from saturated, and demand is therefore likely to continue to grow (Bender and others, 2016). Apart from some categories such as private yachts, this shipping traffic is covered by the new mandatory Polar Code (IMO, 2015).

Tourism is also increasing rapidly in the Arctic: summer tourism quadrupled and winter tourism increased by over 600% between 2006 and 2016, although large areas remain unaffected. This increase is likely impact on Arctic ecosystems and communities, especially as new parts of the Arctic open up with less sea ice, new airports and continued promotion of the area (Runge and others (2020).

In 2020, passenger traffic on ferries dropped significantly in the early year as a result of the COVID-19 pandemic but by August 2020 is beginning to recover (e.g. EMSA, 2020). Cruise-ship activity has plummeted for the same reason: in August 2019, there were 1.8 million persons on board cruise ships; in August 2020, there were only a small number of crew (EMSA, 2020).

4.4. Seafarers

The number of seafarers serving on international merchant ships was estimated in 2015 at 1,647,500, of which 774,000 were officers and 873,500 ratings. A new survey will be carried out in 2020. China, the Philippines, Indonesia, the Russian Federation and Ukraine were estimated to be the five largest supply countries for all seafarers. For officers, China was reported to be the largest supplier, followed by the Philippines, India, Indonesia and the Russian Federation. For ratings, the Philippines was the largest supplier, followed by China, Indonesia, the Russian Federation and Ukraine. In 2015, there was thought to be a shortage of about 16,500 officers and a surplus of around 119,000 ratings. While the global supply of officers is forecast to increase steadily, this trend is expected to be outpaced by increasing demand (BIMCO/ICS, 2016). The important international instruments for the protection of seafarers were described in WOA I.

The best estimate of the proportion of seafarers who are women remains at about 2 per cent, mainly in the cruise-ship sector (ITF, 2019).

Travel and border restrictions imposed in 2020 to control the spread of the SARS-CoV-2 virus, has created a major crisis for seafarers. In July 2020, there were estimated to be 600,000 seafarers affected: approximately 300,000 seafarers kept working aboard ships due to the problems of changing crews, and an equal number of unemployed seafarers waiting ashore to join their ships (ITF, 2020).

4.5. Piracy and armed robbery against ships

There was a slight decline in the total number of attempted and actual cases of piracy and armed robbery against ships between 2015 and 2019 (Table 2). The most significant areas in which piracy and armed robbery occur remain those in South-East Asia and West Africa.

Table 2. Attempted and actual cases of piracy and armed robbery against ships, 2015–2019. Source: IMB, 2020.

Region	2015	2016	2017	2018	2019
East Asia	31	16	4	7	5
South-East Asia	147	68	76	60	53
South Asia	24	17	15	18	4
East Africa, the Red Sea and the Gulf of Aden	3	6	13	5	4
West Africa and the Mediterranean	32	57	45	82	67
South America	8	22	24	25	24
Rest of the world	1				
Total	**246**	**191**	**180**	**201**	**162**

4.6. Environmental impacts

Discharges and emissions from ships and sewage are discussed along with other liquid and atmospheric pollution in Chapter 11, with garbage derived from ships considered in Chapter 12, and noise inputs to the ocean from ships covered in Chapter 21.

Environmental impacts associated with the growth of shipping in the Arctic Ocean are considered in Chapter 7M. Steps are being taken to prepare sustainably for such traffic, with the International Maritime Organization (IMO) adopting the International Code for Ships Operating in Polar Waters (Polar Code)[145] which is mandatory under both the International Convention for the Safety of Life at Sea (SOLAS)[146] and the International Convention for the Prevention of Pollution from Ships (MARPOL)[147] (IMO, 2015). The Arctic Council has also set up arrangements for emergency prevention, preparedness and response for shipping incidents, and adopted in 2011 a legally binding Agreement on Cooperation on Aeronautical and Maritime Search and Rescue in the Arctic (Arctic Council, 2011).

[145] See International Maritime Organization, document MEPC 68/21/Add.1, Annex 10.
[146] United Nations, *Treaty Series*, vol. 1184, No. 18961.
[147] International Maritime Organization, document MEPC 62/24/Add.1, annex 19, resolution MEPC.203(62).

5. Seabed mining

There are two distinct aspects to the seabed mining industry. One is the long-established mining of relatively shallow deposits by a number of countries within their own waters. The other is the potential development of deep seabed mining for which commercial operations have not yet commenced. The established mining undertakings include, among others, aggregates (sand and gravel) in many western European countries; placer diamond mining in Namibia; placer tin mining in several South-East Asian countries; and, most recently, iron sand mining in New Zealand. There are also projects related to mining for phosphorite under development in Mexico, Namibia and New Zealand. Details of both established and potential activities are given in Chapter 19 on seabed mining.

The established mining activities are disparate, since they involve very different countries and situations. No overview of the economics of these activities is available, and there have been no surveys of employment, of the occurrence of death and injury to workers or of pay across this field.

6. Offshore hydrocarbons

In 2016, approximately 27 per cent of the global production of oil, and 30 per cent of that of natural gas, was offshore. Offshore oil is produced in more than 50 different countries, including Brazil, Mexico, Norway, Saudi Arabia and the United States of America (IEA, 2018). For natural gas, Australia, Iran, Norway and Qatar were the main offshore producers in 2017. The offshore industry had an estimated annual global investment capital expenditure of 155 billion United States dollars in 2018, which is projected to reach 200 billion dollars by 2021. Further details are given in Chapter 20 on hydrocarbon exploration and extraction.

Chapter 21 of WOA I (United Nations, 2017c) provided a survey of the social aspects of the offshore hydrocarbon industry. In general, this description remains accurate. Employment numbers inevitably fluctuate significantly, depending on the international price of crude oil and the planned capital expenditure by oil and gas companies. The workforce draws heavily from a global talent pool.

7. Tourism and recreation

7.1. Situation as shown in the First World Ocean Assessment (WOA I)

Chapter 27 of WOA I (United Nations, 2017d) assessed the full range of aspects of tourism and recreational activities affecting the ocean. These included the scale, showing rapid growth over several decades; the social and economic aspects, showing the economic importance for many countries (especially small island developing States); the demands for built environments; and the many pressures that tourists and their activities impose on the marine environment. Exceptionally, cruising was treated as part of Chapter 17 on shipping.

In the present Assessment, tourism-related infrastructure and development is considered in Chapter 14, and the problems associated with atmospheric, liquid and solid wastes resulting from tourist activities are considered in Chapters 10 and 12. The present section, therefore, deals with the social and economic aspects of tourism.

The picture has recently changed substantially because of the COVID-19 pandemic. The World Tourism Organization projects that the number of international tourist arrivals in 2020 is likely to drop by between 58 per cent and 78 per cent compared with 2019, depending on what happens with travel restrictions imposed via efforts to control the SARS-CoV-2 virus in the second half of the year. In March 2020, arrivals dropped by 60 per cent compared with 2019. (UNCCSA, 2020). Countries most impacted are those that rely substantially on tourism including island nations in the Pacific, Indian and Atlantic Oceans (Pacific Community 2020; UNCCSA 2020).

7.2. Scale and distribution of tourism

Tourism affecting the ocean, other than cruising, is predominantly located in the coastal zone. Statistics are not available globally to show the scale of tourism in the coastal zone. Because of their geography, some countries with large tourism industries (such as Greece) inevitably have a very large proportion of that industry in coastal areas. Elsewhere, evidence from different regions of the world continues to show that coastal tourism remains a major component of overall tourism. For example, in addition to the evidence quoted in WOA I:

(a) In the countries of the European Union, four of the five regions with the highest levels of tourist activity in 2016 (Canary Islands, Catalonia, Adriatic Croatia and Balearic Islands) were coastal regions (the other region was Île-de-France, around Paris) (European Commission, 2018);

(b) The percentage of tourists in the Republic of Korea who visited the coastal zone increased from 49.5 per cent in 2000 to 69.1 per cent in 2010, and the total number of beach visitors in 2014 was 69 million (Chang and Yoon, 2017);

(c) Destinations in the four coastal provinces of Northern Cape, Western Cape, Eastern Cape and KwaZulu-Natal in South Africa accounted for 28 per cent of the total tourism trips and 40 per cent of total tourism spending in 2015. Overall, coastal destinations were dominated substantially by domestic tourists: 9.8 million domestic tourism trips as compared to 1.6 million international tourist trips; tourism activity is particularly concentrated around Cape Town and in the eThekwini Metropolitan Municipality (which includes Durban), which in 2015 together accounted for 75 per cent of total tourism spending in South African coastal areas (Rogerson and Rogerson, 2018, 2019).

International travel and associated tourism play a major role in many parts of the world, particularly in the "sun, sea and sand" type of tourism. The relatively rapid rate of growth in international travel observed in WOA I continued throughout the 2010s (Table 3) and between 2011 and 2017. Throughout the world as a whole, the rate of growth in the numbers of international tourists continued between 2011 and 2017 at above the long-term rate, reaching an annual average rate of 5.7 per cent, slightly higher than that reported in WOA I. The estimated income derived from international tourism has continued to grow globally, at an annual average rate of 4.0 per cent, but not in line with the number of tourists. This implies that, on average, tourists are spending less. However, the global growth in tourist numbers is sufficient to more than offset this decline, and the share of tourism in export earnings globally has continued to increase (World Bank, 2019).

Table 3. Inbound international tourism by global region. Source: compiled from World Bank, 2019.

Area	Inbound international tourists (millions)	Average annual percentage increase 2011–2017	Inbound international tourism expenditure (billions of US dollars)	Average annual increase 2011–2017	Regional average of inbound international tourism spending as

							percentage of total exports	
	2011	2017		2011	2017		2011	2017
World	997.7	1,341.5	5.7%	1,231.0	1,525.7	4.0%	5.5%	6.7%
East Asia and Pacific	206.8	300.6	7.6%	291.2	373.0	4.7%	4.5%	5.2%
Europe and Central Asia	512.8	669.5	5.1%	534.6	594.5	1.9%	5.7%	6.3%
Latin America and the Caribbean	75.9	112.4	8.0%	70.9	101.8	7.3%	5.1%	7.8%
Middle East and North Africa	75.2	89.2	3.1%	74.0	112.5	8.7%	5.5%	10.8%
North America	79.1	98.0	4.0%	208.1	272.3	5.1%	7.8%	9.5%
South Asia	10.4	22.8	119.2%	23.0	37.9	10.8%	4.4%	6.5%
Sub-Saharan Africa	33.1	42.4	4.7%	29.0	34.4	3.1%	5.8%	9.2%

Global patterns in numbers of tourists and expenditure vary significantly between regions (Table 4). The absolute scale of tourism in different regions also varies significantly. Collectively, some of the countries in South Asia and South-East Asia (Bangladesh, India, the Maldives, Myanmar and Pakistan) achieved a 119 per cent increase in inbound international tourist numbers between 2011 and 2017 (though from a relatively low base), far outstripping other regions. Other regions have, in general, experienced growth rates of less than 10 per cent (Table 4). Nevertheless, Caribbean States, such as the Dominican Republic and Jamaica, have had growth rates of around 25%, well above the regional average (World Bank, 2019). The Middle East and North Africa has experienced relatively low growth in tourist numbers, but a substantial growth in tourist income, suggesting that the tourist industry is offering more up-market experiences (World Bank, 2019).

Table 4. Share of international tourist arrivals by global region. Source: compiled from World Bank, 2019.

Region	International tourist arrivals 2017	Region	International tourist arrivals 2017
World	100%	Middle East and North Africa	6.7%
East Asia and Pacific	22.5%	North America	7.4%
Europe and Central Asia	49.9%	South Asia	1.3%
Latin America and the Caribbean	8.4%	Sub-Saharan Africa	3.3%

Domestic tourism dominates the tourist market in most major economies (Figure 5) with 73 per cent of expenditure on tourism and travel derived from domestic sources globally (WTTC, 2018). While this will include much tourism and travel that does not impact on the marine environment, coastal tourism is, as noted above, a major component of total tourism.

Domestic tourism has grown generally in line with total tourism, and growth rates are estimated at over 10 per cent per annum in many Asia-Pacific countries, such as China, Malaysia and the Philippines over the period from 2011 to 2017 (WTTC, 2018).

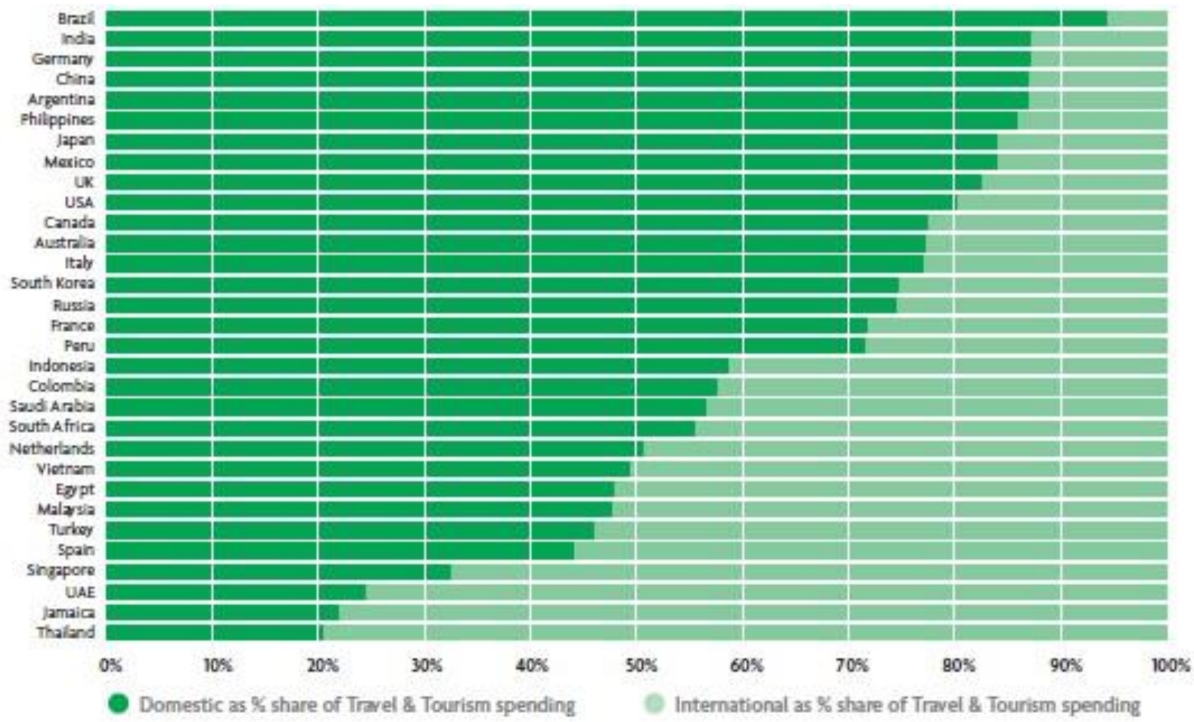


Figure 5. Relative importance of domestic and international tourism and travel expenditure in 31 countries. Source: WTTC, 2018.

7.3. Impacts on the marine environment

7.3.1. General

Throughout all tourist areas, the major impact on the marine environment comes from coastal development, including the proportion of land covered by buildings, such as hotels, restaurants and retail shops, and transport infrastructure, including ports, airports and train terminals, and the need for hard built coastal defences, street lighting and sewerage (see also Chapter 14). Where such development is not subject to effective planning and management, impacts on marine flora and fauna can be disastrous. For example, at Vlora Bay in Albania, unplanned development over 15 years has resulted in the disappearance of 50 per cent of the seagrass meadows and a substantial reduction in macroalgae (Fraschetti, 2011).

In tourist regions, beach feeding or beach nourishment, which is the replacement of sand on beaches which have had sand removed by coastal currents or extreme weather events, can have considerable economic benefits (Klein and Osleeb, 2010). For example, in the Republic of Korea, an evaluation of the economic benefits of the restoration of the Songdo beach at Busan after typhoon damage in 2003 put the benefits at around 230 million United States dollars (Chang and Yoon, 2017).

The management of beaches is a significant element in managing the impacts of coastal tourism on the marine environment. Beach cleaning and the building of sea walls is generally done to give "sun, sea and sand" tourists surroundings which they find more attractive, but have significant effects on the local flora and fauna, as recorded in WOA I. Studies continue to show that beaches used extensively for tourism support ecosystems that are less rich than on comparable beaches in the same vicinity which are in protected areas, for example, along the New Jersey coast in the United States of America, (Kelly, 2014) and near Cadiz, Spain

(Reyes-Martinez, 2015), and that seawalls supported 23 per cent less biodiversity and 45 per cent fewer organisms than natural shorelines (Gittman and others, 2016).

Other interventions to attract tourists to beaches have included the creation of artificial surfing reefs. The limited success of such structures was recorded in WOA I, but there is now a report of a new venture based on an inflatable artificial reef at Bunbury, Australia (West Australian, 2019). National legislation to promote public access to coasts and beaches can also be significant.

7.4. Enjoyment of marine wildlife

7.4.1. Diving

Diving, both with snorkels and with self-contained underwater breathing apparatus (SCUBA), continues to be a significant element in marine tourism, focused on enabling tourists to enjoy underwater wildlife. The substantial growth (around 25 per cent) in the levels of this activity recorded in the period from 2000 to 2013 and reported in WOA I has now slowed down but still continues. Based on the statistics of the Professional Association of Diving Instructors (PADI), between 2013 and 2019, there was about 6 per cent growth in the number of establishments offering diving training (about 6,600 in 2019), about 1 per cent growth in the number of individual trainers (about 137,000 in 2019) and about an 11 per cent increase in the number of people trained annually (about one million in 2019) (PADI, 2019).

The main interest in diving lies in areas endowed with coral reefs - the corals and other reef biota are spectacular and attract large numbers of tourists who want to see them. In some areas, as recorded in WOA I, studies suggest that it is possible to manage coral-reef tourism (for example, by limiting numbers of divers in an area, specifying divers' behaviour and generally increasing divers' awareness of the problems) compatibly with sustaining the condition and health of the reef. In other areas, however, studies continue to suggest that the interaction of divers with coral is damaging the reefs. A recent study of the coral reefs around the island of Bonaire in the Caribbean part of the Kingdom of the Netherlands showed that diving is at levels probably at least twice those considered to be the upper limit beyond which damage is likely to occur (see Hawkins and Roberts, 1997), and that damage, albeit largely unintentional, is resulting but could be controlled by better management measures (Jadot and others, 2016).

As part of the decommissioning of offshore installations, significant numbers of disused installations are being used to create artificial reefs. In the Gulf of Mexico alone, 532 installations had, by 2018, been used as artificial reefs (BSEE, 2020). In 2016, it was estimated that some 600 offshore installations would be decommissioned between 2017 and 2021. Not all of these were intended as places for divers to explore, but a substantial proportion are being so used (van Elden and others, 2019).

A new area of interest for SCUBA diving is emerging in the form of diving over muddy substrates, known as "muck diving", which focuses on finding rare, cryptic species that are seldom seen on coral reefs. A recent study investigated the value of muck diving, its participant and employee demographics and potential threats to the industry. Results indicate that "muck diving" tourism is worth more than 150 million United States dollars annually in Indonesia and the Philippines combined. It employs over 2,200 people and attracts more than 100,000 divers per year (De Brauwer and others, 2017).

7.4.2. Wildlife watching

Bird-watching ("avitourism") continues to be a significant element in coastal tourism, but coastal bird-watching can rarely be disaggregated from other bird-watching. Increased efforts are being made to promote bird-watching generally as a basis for tourism. The Netherlands Centre for Promoting Imports from Developing Countries (international tourism, of course, counts as an export from the country where it takes place), has identified India, Kenya, Namibia and Tanzania as significant goals for avitourism, and Brazil, Costa Rica, Ecuador, Morocco, South Africa and Sri Lanka as emerging destinations (NEA, 2019). Statistical evidence is sparse but it seems, however, that, in some areas, the market may be becoming saturated: in the United States of America, the National Survey on Recreation and the Environment reported that, in 2012, the number of people taking avitourism trips, including to domestic locations, stood at 19.9 million, but that in 2016, the numbers had declined to 17.6 million (USNSFHWAR, 2016).

Whale-watching, reported in WOA I as an activity with a global turnover of around 2,100 million United States dollars, continues to be a significant tourist activity: an estimated 13 million people engaged in whale-watching across the globe in 2017; in Iceland, the activity was reported to have been growing by 20 per cent a year since 2015 (Hoyt, 2009; Hoyt, 2017), and in Peru from zero to 3 million United States dollars between 2008 and 2018 (Guidino, 2020).. Whale-watching may benefit conservation through changing attitudes towards wild animals and natural habitats (Argüelles and others, 2016), especially if commercial tour operators educate tourists about related long-term sustainable benefits (Wearing and others, 2014). Species that live in coastal environments are the most utilized as tourist attractions because of easy access to them. If conducted properly, whale-watching is relatively benign (Argüelles and others, 2016). However, uncontrolled whale-watching may disturb whales, thus causing changes in their natural behaviour which could, in turn, modify their distribution, reproduction and survival (Williams and others, 2006; Lusseau and others, 2006). The International Whaling Commission, Governments and non-governmental organizations have attempted to reduce the impact of this activity worldwide by developing guidelines and codes of conduct that aim both to reduce the negative effects of this activity and to give an educational opportunity to visitors (Garrod and Fennel, 2004; Cole, 2007; Argüelles and others, 2016; IWC, 2019).

WOA I cited an estimate of 300 million United States dollars a year as the global revenue from shark-watching. A survey of shark-watching in Australia supports estimates of this order, since it evaluates annual expenditure on shark-watching in Australia alone at 28.5 million United States dollars a year (Huveneers and others, 2017).

7.4.3. Recreational boating

In its Chapter 27, WOA I (United Nations, 2017d) recorded a sustained growth in recreational boating for the countries for which statistics were available over the preceding 50 years, but noted that in the United States of America there had been a slight reduction between 2012 and 2013, the latest date for which information was available. In the United States of America, the growth has more or less halted: in 2018, the number of registered recreational boats, some of which are in inland waters, is still just under 12 million, as in 2013 (NMMA, 2018). Similarly, in the European Union, the number of recreational boats has remained roughly constant at around 6 million, while the age of those involved in boating has increased substantially, suggesting that younger people are not taking up the activity. On the other hand, outside these areas, there appears to be an active market for new boats (Ecorys, 2015).

8. Marine genetic resources

Most commercial activity with respect to marine genetic resources continues to be concentrated in a comparatively small number of countries. Some idea of the scale of activity in this sector can be gained from the fact that that 28 candidates are currently in clinical trials and a further 10 drugs derived from marine natural products have already gained regulatory approval, and that 76 publicly available cosmeceutical ingredients derived from marine natural products have been marketed. The investigation of marine genetic resources is not a separate sector from pharmaceutical and industrial research generally, and the economic and social aspects of the marine component are limited in scale and cannot yet be separated. More detail is given in Chapter 26 on marine genetic resources.

9. Marine renewable energy (MRE)

Energy from offshore wind, wave and tidal power, that is, marine renewable energy, is increasingly feeding national distribution systems in a number of countries, although not in Africa or, to any large extent, in the Americas. Of these power sources, offshore wind technology is the most mature and technically advanced, providing a capacity of about 28.3 megawatts in 18 countries (IRENA, 2020c). For further information see Chapter 22 on renewable energy sources.

Total employment in the onshore and offshore wind energy sector represented about 1.2 million jobs in 2018, of which perhaps 20 per cent (240,000) relate to offshore activities. Women account for about 21 per cent of persons employed in the wind energy sector as a whole (IRENA, 2020a, 2020b).

10. Desalinization

10.1. Situation as shown in the First World Ocean Assessment (WOA I)

WOA I, in its Chapter 28, showed that the global installed capacity for desalinization of seawater to produce freshwater had increased from negligible amounts in 1965 to around 86.5 million cubic metres a day in 2015 (United Nations, 2017e). Of the two techniques predominantly used in desalinization, 71 per cent of capacity was based on membrane processes, and the remaining 29 per cent of capacity for desalinization used thermal processes. About 27 per cent of the total global capacity was found in States in the Persian Gulf area, overwhelmingly (96 per cent of the total capacity in the area) in the six States members of the Gulf Cooperation Council (Bahrein, Kuwait, Oman, Qatar, Saudi Arabia and United Arab Emirates). Significant sea-related capacities also existed in Algeria, Australia, China, Israel, Japan, Spain, the United States of America and islands such as Malta and Singapore, and many Caribbean islands.

The environmental impacts of desalinization plants noted in WOA I included the emission of greenhouse gases, the intake of feedwater and the discharge of brine. The impact of intakes on marine biota above microscopic sizes and the effects of discharges (which can contain significant levels of chlorine, copper and antiscalants) can be minimized by proper design.

WOA I also noted that growth in the population of States with freshwater shortages, and the effects of climate change, would most likely lead to desalinization being increasingly considered as an adaptation measure for communities suffering increased and related water stress.

10.2. Current desalinization capacity and processes

The world's desalinization capacity has continued to grow. From an installed capacity of 86.5 million cubic metres a day in 2015, it reached 97.4 million cubic metres a day in 2018, with 48 per cent of this capacity in the Middle East and North Africa (IDA, 2019; Jones and others, 2019).

Membrane processes remain dominant in desalinization (more than 65 per cent of production), although multi-stage distillation is still important in the States members of the Gulf Cooperation Council where it is linked to power generation from oil or gas and provides about 60 per cent of capacity (IDA, 2019; Mogielnicki, 2020)

New demands for desalinated seawater seem likely from the mining industry. For example, substantial new growth in desalinization output is proposed in Chile in connection with copper mining, where around one million cubic metres a day of desalinated water are expected to be needed by 2027 for the copper-mining industry, an increase of nearly 200 per cent over 2016 levels (CCC, 2016).

Global statistics for employment in desalinization operations are not available. However, it has been estimated that, between 2010 and 2030, a further 50,000 technicians at different skill levels would be needed to service the desalinization industry in the Middle East and North Africa. If the projected increase in output in that region translated to staff required is consistent around the world, this would imply a total global current workforce in desalinization of around 400,000 people (Ghaffour, 2009).

10.3. Potential pressures on the ocean

As noted above, the predominant view of waste discharge from desalinization plants has been that proper design can minimize adverse impacts on the ocean. However, a recent study of the impact of desalinization on the ocean has argued that the amounts of brine discharged to the ocean from desalinization has been underestimated, together with its potential impact on the marine environment (Jones and others, 2019). It estimates that the amount of brine discharged daily stands at 142 million cubic metres, of which 48 per cent is discharged in the Persian Gulf area. It also argues that this high-salinity water can have a serious adverse impact on the seabed flora and fauna. On the other hand, reports from Australia, based on seven years' observation of the site where discharges are released from a large desalinization plant serving Sydney, have been mixed, with adverse impacts observed on some marine invertebrates within 100m of the discharges, while barnacles increased in numbers (Clark and others 2018) and, at the same time, a three-fold increase in fish numbers in the area was observed (Kelaher and others, 2020). Six years of monitoring brine discharges from two large desalinization plants in Israel observed almost no impact on seawater quality (Kress and others, 2020).

11. Salt production

11.1. Situation as shown in the First World Ocean Assessment (WOA I)

WOA I only briefly considered salt production in relation to its importance in the cultural aspects of food. It noted that, although salt production by evaporation of seawater was still important, most salt was produced from rock salt and brine deposits in the ground. It also noted that sea-salt production was still important for some countries such as Brazil, India and Spain (United Nations 2017f).

11.2. Current situation

Salt production from evaporation of seawater is still a significant source of salt around the world. However, comprehensive statistics at a global level remain unavailable. The British Geological Survey overview of world mineral production identifies production of about 35 million tons of salt from seawater out of a reported total world production of 265 million tons (Table 6), but does not identify the source of salt for many countries, and notes that salt is also produced in a number of countries for which data are not available (Brown and others, 2019). In most regions where reports are available, salt production from seawater has remained relatively stable, with the notable exception of a 34 per cent increase in India (Table 6). The size of the workforce involved in sea-salt production is unknown.

Table 6. Salt production from seawater in thousand tons (* estimated). Source: Brown and others, 2019.

Country	Sea-Salt production 2013	Sea-Salt Production 2017
Albania	49*	47*
Montenegro	10*	10*
Portugal	91	115
Spain	1 221	1 111
Algeria	172	160*
Brazil	5 926	6 000*
Colombia	113	165
Bangladesh	1 439	1 496
India	17 517	23 500*
Pakistan	297	209
Mauritius	4	1
Mozambique	150	140*
Bonaire (Netherlands)	400*	400*
El Salvador	100*	100*
Guatemala	60*	60*
Nicaragua	30*	30*
Philippines	992	993*
Total	**28,571***	**34,537***

12. Key knowledge and capacity-building gaps

In relation to coastal communities, better information on their state, the threats they face and their economic and social situation is needed (especially for communities of indigenous peoples), given the crucial roles they play in maritime industries, in social and cultural aspects, and in ocean conservation.

In relation to maritime industries, knowledge and capacity-building gaps are identified in the following Chapters: for harvesting food from the sea (Chapters 15, 16 and 17); for seabed mining (Chapter 19); for offshore hydrocarbons (Chapter 20); for marine renewable energy (Chapter 22); and for marine genetic resources (Chapter 26).

For shipping, the main knowledge gaps concern the social aspects. For example, better information is needed on the rates of injury and death of seafarers and other aspects of their welfare. Capacity-building gaps exist in some regions in terms of the training and development of seafarers: Africa and South America provide fewer seafarers than their share of the global population would support. Given the projected shortages in the supply of officers, there is clearly scope for expanding training in such areas.

For tourism, there is limited information on the scale of coastal and marine tourism and its growth, as compared with tourism generally. Equally, there is a lack of global information on the social and economic aspects of coastal and marine tourism. In particular, there is a lack of knowledge on the extent to which host countries benefit from their coastal and marine tourism industries, and on the status of employment in those industries.

For desalinization, there is scope for further examination of the relationship between discharge designs and impacts on the marine environment.

13. Outlook

The Chapters on specific industries (Chapters 15, 16, 17, 19, 20, 22 and 26) describe the outlook for the industries concerned.

The outlook for shipping is closely linked to development of the global economy. The shipping industry has largely overcome the problems resulting from the economic crisis from 2008 to 2011, but challenges in controlling air pollution remain, and increased concentration of cargo shipping seems likely. The future of the cruise industry is also closely linked to the development of disposable income in major economies.

The level of activity in the tourism industry, including coastal and marine tourism, is governed by the levels of available discretionary disposable income. The outlook for coastal and marine tourism is, therefore, dependent on maintaining current levels of expenditure from tourists from the regions and countries that are now the principal sources of tourists, and increasing the interest in coastal and marine tourism from other countries as their discretionary disposable income increases.

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Chapter 9
Pressures from Changes in Climate and Atmosphere

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Keynote points

- **Extreme climate events**. Marine heatwaves and tropical cyclones are shown to be increasing in severity due to human activities and are having an impact on nature and human societies. Extreme El Niño events have been observed but, because they occur infrequently, a human influence has not been detected. All three phenomena are projected to increase in the future with the severity of impacts also increasing, but such increases can be reduced by climate change mitigation efforts.
- **Sea level rise**. The alarming observed pace of sea level rise, combined with increasing storminess and coastal urbanization, has resulted in amplified susceptibility of coastal cities to erosion, flooding and increased the need for substantial investments in hard infrastructure and restoration of natural barriers like reefs.
- **Ocean acidification and deoxygenation**. The accelerated increase of anthropogenic carbon dioxide (CO_2) in the atmosphere is creating an increase in the acidification and deoxygenation of the ocean. Under these conditions, both in nature and in the laboratory, marine organisms that support ecosystems and human livelihoods and nutrition typically respond poorly. Marine habitats experience a loss of diversity, many long-lived organisms die, and a few resilient species proliferate. Less serious damage to life supporting ecosystems would be possible under lower emissions scenarios.
- **Other physical and chemical properties**. Changes in ocean temperature and salinity induced by climate change and human activities are affecting marine ecosystems by changing the distribution of marine species, decreasing the ecological value of coastal ecosystems and changing marine primary production. Human well-being and economy are consequently affected.

1. Introduction

This Chapter, "Pressures on Changes in Climate and Atmosphere", builds first on three topics in the context of extreme climate events related to the ocean, namely, marine heatwaves, extreme El Niño Southern Oscillation (ENSO) events and tropical cyclones. It looks at both physical aspects of the impact of climate change on the phenomena and potential impacts on natural and human systems. The conclusions are based on a much more detailed assessment that can be found in chapter 6 of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Oceans and Cryosphere in a Changing Climate (IPCC, 2019).

An extreme event is an event that is rare at a particular place and time of year. Definitions of "rare" vary, but an extreme event is normally as rare as, or rarer, than the 10th or 90th percentile of a probability estimated from observations. By definition, the characteristics of what is called an extreme event may vary from place to place in an absolute sense. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g. high temperature, drought or total rainfall over a season).

The second part of the Chapter expands upon pressures from changes in ocean physical and chemical properties. Projected sea temperature increases of up to 1.5 ^{0}C over pre-industrial levels by 2050 will continue to drive latitudinal abundance shifts in marine species, including those of importance for coastal livelihoods. Many large coastal cities are located in deltaic settings and vulnerable to floods because of their proximity to rivers and the sea, general low elevations and land subsidence (Nicholls and others, 2008).

Carbon dioxide emissions and global warming are also causing ocean acidification and deoxygenation. These changes have consequences for the people who depend on healthy marine ecosystems worldwide. At the time of the First World Ocean Assessment (WOA I) (United Nations, 2017), the chemistry of ocean acidification was well understood yet the consequences for ecosystems and society were poorly known. The effects of declining oxygen on nutrient cycles and fisheries were predicted to worsen, especially when climate change-driven oxygen depletion combines with coastal eutrophication. Reduced biodiversity and declines in fish populations were linked to falling oxygen levels across the world's ocean. New information is provided on marine organism and ecosystem responses to ocean acidification and deoxygenation and related capacity building.

The present Chapter, in conjunction with Chapter 5, develops the climate change aspects of the present Assessment. Chapter 9 expands on the pressures on marine ecosystems and human populations of some of the physical and chemical changes caused by climate change. Some related aspects are also covered in Chapter 7M and Chapter 15.

2. Climate pressures: extreme climate events and pressures from changes in ocean physical and chemical properties

2.1. Extreme climate events

Marine heatwaves (MHW) are periods of extremely high ocean temperatures that persist for days to months, that can extend up to thousands of kilometres and can penetrate multiple hundreds of metres into the deep ocean (Hobday and others, 2016). Over the last two decades, MHW have negatively impacted marine organisms and ecosystems in all ocean basins, including critical foundation species such as corals, seagrasses and kelps (Hughes and others, 2018; Smale and others, 2019). Satellite observations reveal that MHW doubled in frequency between 1982 and 2016, and that they have also become longer lasting, more intense and extensive (Frölicher and others, 2018; Oliver and others, 2018). Between 2006 and 2015, 84 to 90 per cent of all globally occurring MHW were attributable to the temperature increase since 1850–1900 (Frölicher and others, 2018).

MHW will further increase in frequency, duration, spatial extent and intensity under future global warming (Frölicher and others, 2018; Darmaraki and others, 2019)**,** pushing some marine organisms, fisheries and ecosystems beyond the limits of their resilience, with cascading impacts on economies and societies (Smale and others, 2019). Globally, the frequency of MHW is very likely to increase by a factor of around 50 times by 2081–2100 under the high-emissions RCP8.5 scenario and by a factor of around 20 times under the low-emissions RCP2.6 scenario (van Vurren and others, 2011), relative to the 1850–1900 reference period. These future trends in MHW frequency can largely be explained by increases in mean ocean temperature. The largest changes in the frequency of MHW are projected for the Arctic Ocean and the tropical ocean (Figure 1; IPCC, 2019, chapter 6, figure 6.4).

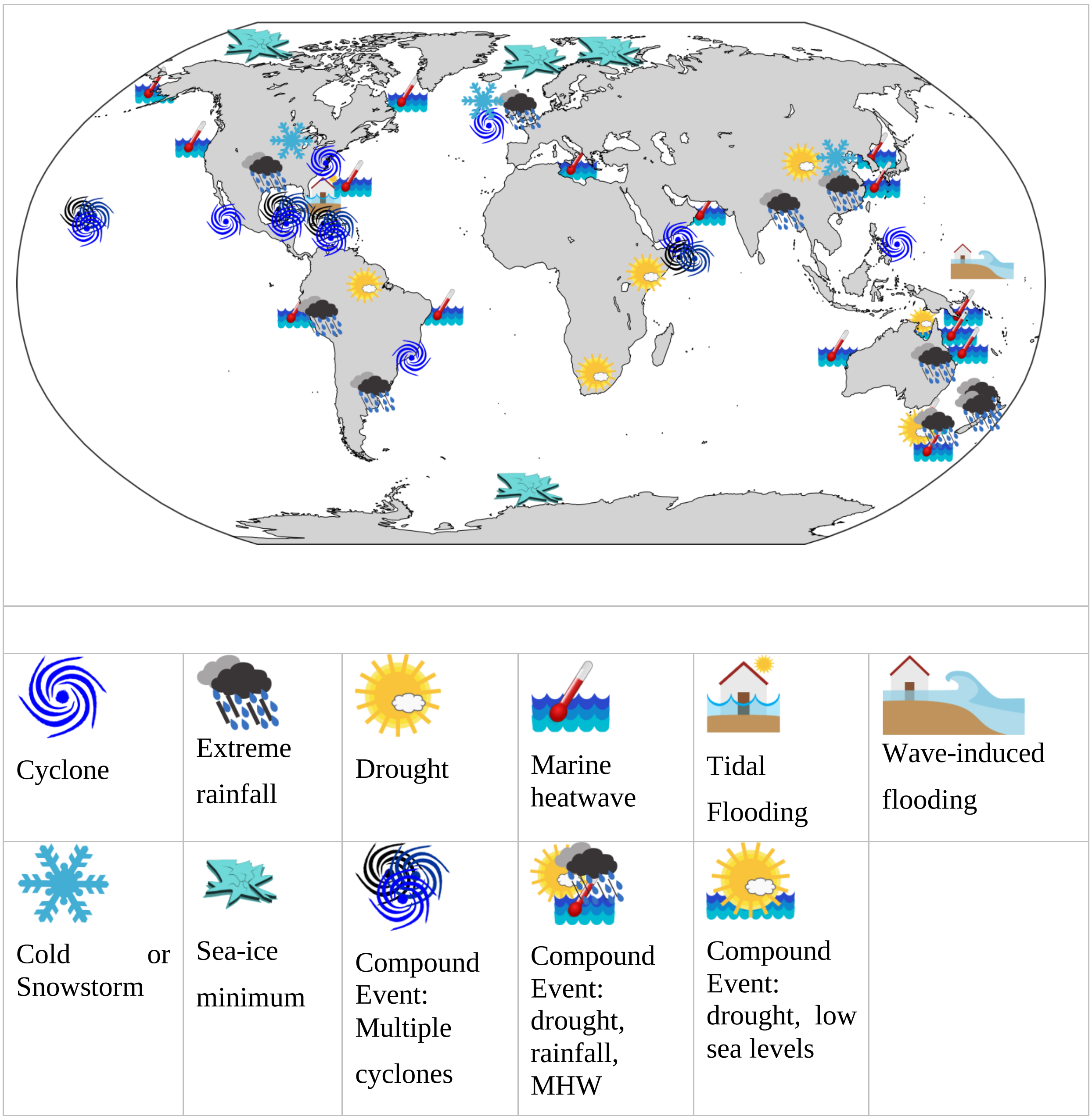

Figure 1. Locations of extreme events with an identified link to climate change caused by human activities (figure based on IPCC, 2019, Chapter 6, figure 6.2).

Limiting global warming would reduce the risk of impacts of marine heatwaves, but critical thresholds for some ecosystems (e.g. kelp forests and coral reefs) will be reached even at relatively low levels of future global warming (King and others, 2017). Early warning systems, producing skillful forecasts of MHW, can further help to reduce vulnerabilities in fisheries, tourism and conservation, but are yet unproven on a large scale (Payne and others, 2017; Tommasi and others, 2017).

One of the best data rich examples, of the impacts from a Marine Heat Wave to a well managed fisheries is of the North Pacific, Gulf of Alaska. That prolonged warm ocean event weakened benthic ocean and surface mixing, in turn disrupting trophies, invertebrate and forage fish populations, and decimated the Pacific Cod fishery, triggering and series of repeating mass marine mammal and sea bird die offs and that had a ripple effects through coastal economies.

El Niño Southern Oscillation (ENSO) is a coupled atmosphere-ocean phenomenon, identified by an oscillation between warm and cold ocean temperatures in the tropical central-east Pacific Ocean, and an associated fluctuation in the global-scale tropical and subtropical surface pressure patterns. Typically, ENSO has a preferred timescale of about two to seven years. It is often measured by the surface pressure anomaly difference between Tahiti, French Polynesia, and Darwin, Australia, and/or the sea surface temperatures in the central and eastern equatorial Pacific (Rasmussen and Carpenter, 1982). It has climatic effects throughout the Pacific region and in many other parts of the world, through global teleconnections. The warm phase of ENSO is called El Niño and the cold phase is called La Niña.

The strongest El Niño and La Niña events since the pre-industrial era have occurred during the last 50 years, and that variability is unusually high when compared with average variability during the last millennium (Cobb and others, 2013; Santoso and others, 2017). There have been three occurrences of extreme El Niño events during the modern observational period (1982–83, 1997–98, 2015–16), all characterized by pronounced rainfall in the normally dry equatorial east Pacific. There have been two occurrences of extreme La Niña (1988–89, 1998–99).

Extreme El Niño and La Niña events are likely to occur more frequently with global warming and are likely to intensify existing impacts, with drier or wetter responses in several regions across the globe, even at relatively low levels of future global warming (Cai and others, 2014; Cai and others, 2015; Power and Delage, 2018).

Sustained long-term monitoring and improved forecasts can be used in managing the risks of extreme El Niño and La Niña events associated with human health, agriculture, fisheries, coral reefs, aquaculture, wildfire, drought and flood management (L'Heureux and others, 2017).

Tropical cyclones. A tropical cyclone is the general term for a strong, cyclonic-scale disturbance that originates over the tropical ocean. Based on 1-minute maximum sustained wind speed, these cyclonic disturbances are categorized into tropical depressions (≤ 17 m s^{-1}), tropical storms (18–32 m s^{-1}) and tropical cyclones (≥ 33 m s^{-1}, category 1 to category 5) (Knutson and others, 2010). A tropical cyclone is called a hurricane, typhoon or cyclone, depending on geographic location.

Anthropogenic climate change has increased precipitation, winds and extreme sea level events associated with a number of observed tropical cyclones. For example, studies have shown that the rainfall intensity of tropical cyclone (Hurricane) Harvey increased by at least 8 per cent (8-19%) due to climate change (Risser and Wehner, 2017, van Oldenborgh et al., 2017). Anthropogenic climate change may have contributed to a poleward migration of maximum tropical cyclone intensity in the western North Pacific in recent decades related to anthropogenically forced tropical expansion (Sharmila and Walsh, 2018). There is emerging evidence for a number of regional changes in tropical cyclone behaviour, such as an increase in the annual global proportion of Category 4 or 5 tropical cyclones in recent decades, extremely severe tropical cyclones occurring in the Arabian Sea, cyclones making landfall in

East and Southeast Asia, an increase in frequency of moderately large storm surge events in the United States of America since 1923, and a decrease in frequency of severe tropical cyclones making landfall in eastern Australia since the late 1800s. There is low confidence that these represent detectable anthropogenic signals. Extreme wave heights, which contribute to extreme sea level events, coastal erosion and flooding, have increased in the Southern and North Atlantic Oceans by around 1.0 cm per year and 0.8 cm per year over the period 1985–2018 (Young and Ribal, 2019).

An increase in the average intensity of tropical cyclones, and the associated average precipitation rates, is projected for a 2°C global temperature rise, although there is low confidence in future frequency changes at the global scale (Yamada and others, 2017). Rising sea levels will contribute to higher extreme sea levels associated with tropical cyclones in the future (Garner and others, 2017). Projections suggest that the proportion of Category 4 and 5 tropical cyclones will increase (Knutson and others, 2015; Park and others, 2017). Such changes will affect storm surge frequency and intensity, and impact coastal infrastructure and mortality.

Investment in disaster risk reduction, flood management (ecosystem and engineered) and early warning systems decreases economic loss from tropical cyclones that occur near coasts and islands. However, such investments may be hindered by limited local capacities (e.g. aging infrastructure and other non-climatic factors) which, for example, can cause increased losses and mortality from extreme winds and storm surges in developing countries despite adaptation efforts. There is emerging evidence of increasing risks for locations impacted by unprecedented storm trajectories. Management of risk from such changing storm trajectories and intensity proves challenging because of the difficulties of early warning and its receptivity by affected populations.

2.2. Sea level rise and cities

Cities located along coastlines and in archipelagic and island states are becoming increasingly susceptible to erosion and sea level rise (De Sherbinin and others, 2007; Hanson and others, 2011; Takagi and others, 2016). Many comprise large areas of reclaimed land (the gain of land from the sea, wetlands or other water bodies), which is retained and protected from erosion by hard engineered structures such as seawalls and rock armouring (Sengupta and others, 2018). It is likely that many of these engineered coastlines will need to be adapted and upgraded to keep pace with rising sea levels. In highly urbanized environments that are often already heavily degraded, hard engineered structures are often the only option available and are considered to be successful options (Hallegatte and others, 2013; Hinkel and others, 2014), but there are a wide range of wider negative impacts of land reclamation and these structures on the surrounding environment (Dafforn and others, 2015). Globally, many regions (especially cities) are claiming that >50 per cent of their coastlines are armoured (e.g. Chapman, 2003; Burt and others, 2013), and this number will likely rise in the future in response to burgeoning economies, coastal populations and urbanization (e.g. see plans for reclamation of entire coastlines of two Malaysian states in Chee and others, 2017).

As an alternative for hard engineered coastal defences, which is complex and expensive, where possible, natural coastal ecosystems such as mangroves and saltmarshes should be used as natural barriers, or combined with hard infrastructure using hybrid approaches (Temmerman and others, 2013). The use of these ecosystems not only can protect the land but also provide valuable ecosystem functions and services. As hard engineered coastal defences may be considered an effective short-term solution to coastal flooding, more investment will be needed due to observed increasing storminess and sea level rise (Mendelsohn and others, 2012; Vitousek and others, 2017). By 2010, the global average sea level was calculated to be 52.4 mm above the 1993 level and, by 2018, this had risen to 89.9 mm above the 1993 level (NOAA, 2019). The rate of change is also increasing. For the period from 1993 to 2018, the rate of increase was calculated at 3.2 mm/yr, and for the period from 2010 to 2018 it was calculated to be much faster, at 4.7 mm/yr. Despite significant uncertainties remaining, IPCC predicts that sea level rise will continue for centuries, even if mitigation measures are put in place. The potential widespread collapse of ice shelves could lead to a larger twenty-first century sea level rise of up to several tenths of a metre (Church, 2013), which will have drastic consequences for coastal, archipelagic and small-island cities, particularly those in low-lying areas.

Urbanization could, however, also provide opportunities for risk reduction, given that cities are engines of economic growth and centres of innovation, political attention and private sector investments (Garschagen and Romero-Lankao, 2015). Hallegatte and others (2013) conducted a global analysis of present and future losses in the 136 largest coastal cities. They predicted that global flood losses would increase from an average of six billion United States dollars per year in 2005 to one trillion US dollars by 2050, with projected socioeconomic change, climate change and subsidence. Even if adaptation investments remain constant, flood probability, subsidence and sea level rise will increase global flood losses to 60–63 billion US dollars per year in 2050. The same study found that developing countries are particularly vulnerable to flood risk, with much lower investment in flood protection measures (Hallegatte and others, 2013).

Case study: Rotterdam

Low-lying cities in the Netherlands, a country which has long been a pioneer in both land reclamation and climate change adaptation, are taking a multi-pronged approach to the problem of sea level rise. For instance, Rotterdam’s adaptation system is based on a flood and sea level rise defence system (C40 Cities, 2019) consisting of the Maeslantkering flexible storm surge barrier, permanent sand dunes along the coast and dykes along the rivers and a tailored “inner-dyke/outer-dyke” approach. The inner-dyke city (mostly below sea level) is formed by a system of polders drained by water outlets and pumps and protected by smaller secondary dykes. The outer-dyke city area (3–5.5 m above sea level), of 40,000 inhabitants, is vulnerable to rising sea level or smaller temporary floods. This outer area is being adapted through use of innovative technologies (e.g. floating buildings) and more traditional approaches (e.g. insulation of building facades and raising of electrical installations).

2.3. Pressures from changes in temperature

Ocean warming caused by anthropogenic climate change will continue for centuries after the anthropogenic forcing is stabilized (IPCC, 2019). It will affect marine ecosystems through increasing cumulative pressures due to the changing climate and the intensity of human activities and is also interfering with other ocean properties, such as salinity and nutrient or carbon cycles, due to the interconnection of all such processes.

Temperature dependent biological sensitivity varies between species and it is affected by other ocean properties. For example, for pelagic species, analysis of long-term trends in primary production has revealed that a rise in ocean temperatures, leading to enhanced stratification, nutrient limitation and shifts towards small phytoplankton, will have the greatest influence on decreasing the flux of particulate organic carbon (POC) to the deep ocean (Boyd and others, 2016; Fu and others, 2016). Reductions in POC flux are predicted at low and mid-latitudes but increases are possible at high latitudes, associated with reduction in sea-ice cover (Sweetman and others, 2017; Yool and others, 2017; FAO, 2018).

The IPCC Special Report (2018) indicates that ocean ecosystems are already experiencing large-scale changes, and critical thresholds are expected to be reached at 1.5°C and higher levels of global warming. The changes to water temperatures are expected to drive some species (e.g. plankton and fish) to relocate to higher latitudes and cause novel ecosystems to assemble (Jonkers and others, 2019).

The increase in temperatures directly impacts coastal communities, not only in terms of the effects on coastal marine ecosystems, but also on the ecosystem goods and services they deliver (Worm and others, 2006; Pendleton and others, 2016). These include, for example, the number of viable fisheries, the provision of nursery functions and the filtering services provided by coastal wetlands (Cochard and others, 2008; Barange and others, 2019). Coral reefs is one of coastal ecosystems heavily affected by ocean warming, and coral bleaching phenomenon can impact not only marine life but also marine tourism.

Changes in temperature and salinity also have an impact on human well-being (food and health). With respect to food security, fish is one of the most consumed foods in the world and a major contributor to a healthy diet, due to its proteins, fatty acids, vitamins and other elements essential for health (Hilmi and others, 2014). Climate change could decrease seafood availability (Golden and others, 2016) and, as a consequence, reduce protein supply to coastal communities in general (Blanchard and others, 2017). This would have a strong impact on communities with high seafood dependence, including indigenous and other coastal communities

An increased prevalence and transmission of diseases is also likely to occur with warmer ocean temperatures. Ocean warming could raise the risk of waterborne diseases and bloom algae toxins (see Chapter 6a), impacting the populations and economies of affected areas. For example, the bacterial pathogen *Vibrio cholerae* is expected to grow faster due to the increase in ocean temperatures (Semenza and others, 2017).

2.4. Pressures from changes in ocean chemistry

Ocean acidification. Ocean uptake of carbon dioxide emissions is rapidly changing seawater chemistry in a process known as ocean acidification (see Chapter 5). As the partial pressure of carbon dioxide (pCO_2) in seawater increases, it causes the carbonate saturation state to fall below levels suitable for globally important reef-forming taxa (Albright and others, 2018). Most coral reefs (shallow and deep) are vulnerable to rising CO_2 concentrations (Lam and others, 2019). Ocean acidification is causing the depth at which seawater is corrosive to carbonate to shoal, threatening deep-water coral reefs worldwide through dissolution and intensified bio-erosion (Gómez and others 2018). Ocean acidification combines with warming, rising sea level and more severe storms to reduce reef resilience on a global scale and augment reef destruction. In the Arctic there has been a rapid expansion in the area where surface seawater is corrosive to calcareous organisms (Brodie and others 2014).

Ocean acidification may affect all marine life, for example through changes in gene expression, physiology, reproduction and behaviour (Riebesell and Gattuso, 2015; IPCC, 2019). Between 2005 and 2009, ocean acidification jeopardized a 270 million US dollar, 3,200 jobs per year, shellfish aquaculture industry in Washington State, United States of America. Billions of oysters died in hatcheries because seawater had become corrosive to larval shells (Ekstrom and others, 2015). In addition to negative impacts on calcifying phyto- and zooplankton, acidification can lower the nutritional value of seafood (Lemasson and others, 2019).

Ocean acidification also affects ecosystem properties, functions and services. Some groups of organisms do well in acidified conditions, but many taxa do not (Agostini and others, 2018). Many algae are resilient to the levels of ocean acidification projected under the IPCC RCP8.5, yet shifts in community composition greatly alter seaweed habitats (Brodie and others 2014; Enochs and others, 2015). Increased carbon availability stimulates primary production and can increase the standing stock of kelps and seagrasses (Russell and others, 2013; Linares and others, 2015; Cornwall and others, 2017), although microalgae and turf algae dominate acidified waters in exposed conditions (Agostini and others, 2018; Connell and others, 2018).

Research at natural marine CO_2 seeps has shown that there is around a 30 per cent decrease in macrofaunal biodiversity as average pH declines from 8.1 to 7.8 (Agostini and others, 2018; Foo and others, 2018). This is due to direct effects such as increased metabolic costs of coping with hypercapnia, or indirect effects such as increased susceptibility to predation (Sunday and others, 2017). Some corals grow well in seawater with elevated CO_2 concentrations, but the habitats they form lack diversity as reefs are degraded by ocean acidification due to chemical dissolution and enhanced bioerosion causing a shift to less diverse ecosystems. Chapter 7E also reviews the impacts of ocean acidification to coral reefs. The dual effects of increased CO_2 and decreased carbonate alter trophic interactions. Reductions in the abundance and size of calcareous herbivores contributes to the overgrowth of weedy turf algae and a simplification of food webs, with losses in functional diversity (Vizzini and others, 2017; Teixidó and others, 2018).

Damage from ocean acidification results in less coastal protection and less habitat for biodiversity and fisheries (Hall-Spencer & Harvey, 2019). Live coral cover on tropical reefs has nearly halved in the past 150 years, the decline accelerating over the past two decades due to increased water temperature and ocean acidification exacerbating other drivers of coral loss. When combined with rising temperatures, sea level rise and increasing extreme climate events, ocean acidification further threatens the goods and services provided by coastal ecosystems. This is particularly important for those people that are heavily reliant on marine resources for protection, nutrition, employment and tourism (Lam and others, 2019).

Proposed actions to lessen the impacts of ocean acidification and to build resilience are primarily to reduce CO_2 emission but also include: reduction of pollution and other stressors (such as overfishing and habitat damage); seaweed cultivation and seagrass restoration; water treatment, (e.g. for high-value aquaculture); adaptation of human activities such as aquaculture; and repair damaged ecosystems (Cooley and others, 2016) for example through rewilding the ocean.

Deoxygenation. Since the middle of the twentieth century, the ocean (including coastal waters such as estuaries and semi-enclosed seas) has lost about 2 per cent, or over 150 billion tons, of its total oxygen content (Schmidtko and others, 2017) and more than 600 coastal water bodies have reported oxygen concentrations less than 2 mg l^{-1} (Diaz and Rosenberg, 2008; Breitburg and others, 2018). Climate change is projected to cause more oxygen decline in many coastal systems where deoxygenation is currently driven primarily by an oversupply of anthropogenic nutrients. This deoxygenation is of great concern because oxygen is fundamental to life in the oceans (Figure 3; Laffoley and Baxter, 2019). It constrains productivity and biodiversity, regulates global cycles of nutrients and carbon, and is required for survival of individual organisms (Breitburg and others, 2018). When oxygen is sufficient, it does not limit or negatively affect physiology, behaviour and ecological interactions of organisms dependent on aerobic (oxygen utilizing) respiration. Waters are considered to be hypoxic when oxygen levels are insufficient and these processes are impaired. 2 mg dissolved oxygen l^{-1} is often used as a threshold value to define hypoxia, but the oxygen concentration or saturation at which life processes are impaired varies considerably among species, processes, habitats and with temperature.

As the oxygen content of water declines, an increasing fraction of production is diverted to microbes (Diaz and Rosenberg, 2008; Wright and others, 2012). Food webs change because of altered encounter rates and species-specific effects of low oxygen on feeding efficiencies of predators and escape behaviours of prey. Energy transfer to tolerant animals such as gelatinous species can increase (Keister and Tuttle, 2013). The roles of vision (McCormick and Levin, 2017) and carnivory (Sperling and others, 2016) can decline within low oxygen areas because these activities are energy intensive. In contrast, predation can intensify above low oxygen zones as visual feeders are forced into shallower waters with higher light levels (Koslow and others, 2011).

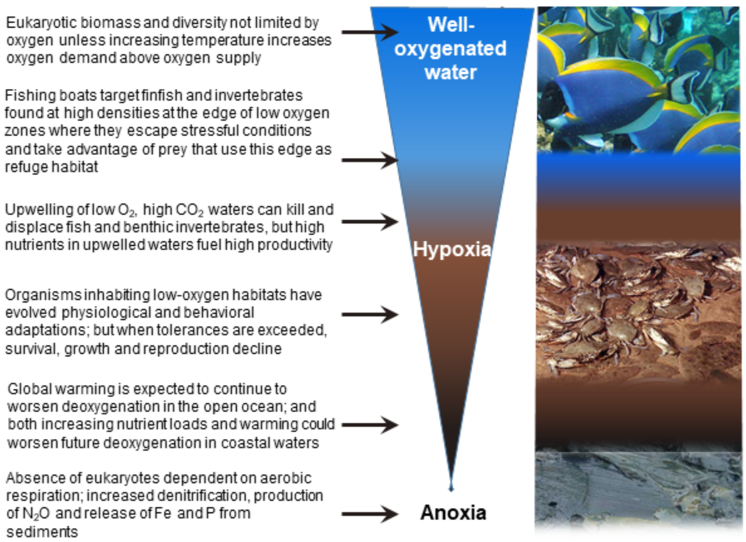

Figure 2. Oxygen exerts a strong control over biological and biogeochemical processes in the open ocean and coastal waters. Whether oxygen patterns change over space, as with depth, or over time, as effects of nutrients and warming become more pronounced, biological diversity, biomass, and productivity decline with decreasing levels of oxygen. (Top) Well-oxygenated coral reef with abundant fish and invertebrate assemblages. (Middle) Low oxygen event in Mobile Bay, the United States of America, in which crabs and fish crowd into extreme shallows where oxygen levels are highest. (Bottom) Anoxic mud devoid of macrofauna. Figure modified from Breitburg and others (2018).

Declining ocean oxygen is expected to negatively affect a wide range of biological and ecological processes. The magnitude of the effects will vary among species and processes, however, and whether the magnitude of responses will be directly proportional to the magnitude of oxygen decline is uncertain. Some effects of oxygen decline are dependent on direct exposure within low oxygen waters, while others involve the movement of organisms and material (nutrients, organic matter, greenhouse gases) among locations that vary in oxygen content, and still other effects are primarily dependent on oxygen levels at particular locations that are critical for a species or life stage. Many responses involve threshold oxygen levels at which biological functions can no longer be maintained.

Biomass and diversity of eukaryotic organisms tend to decline and species composition changes as oxygen declines (Gallo and Levin, 2016). As low oxygen waters expand, tolerant species can expand their depth range, while ranges of species that are more sensitive contract (Sato and others, 2017). The relative abundance of species within systems reflects variation in species tolerances to low oxygen and other co-stressors (Koslow and others, 2018). Organisms, including crustaceans and fish adapted to low oxygen environments, can reach very high densities in low oxygen areas (Pineda and others, 2016; Gallo and others, 2019). However, in naturally low oxygen habitats like oxygen minimum zones, even very small changes (representing <1% of the oxygen content of well-oxygenated surface waters) can result in exclusion of species that would otherwise be abundant (Wishner and others, 2018).

Chronic exposure to suboptimal oxygen conditions can reduce growth (Thomas and others, 2019) and reproduction (Thomas and others, 2015). Numerical models indicate these chronic effects can lead to population declines over time (Rose and others 2018) even in the absence of direct low oxygen-induced mortality. Increased acquisition or progression of infections and decreased host immune responses resulting from exposure to low oxygen have been reported for a range of vertebrate and invertebrate hosts (Breitburg and others, 2019) and may increase transmission of pathogens to humans through consumption of immunosuppressed hosts (Hernroth and Baden, 2018).

Microbes have evolved and adapted to exploit even the most extreme habitats on earth, including those that contain no oxygen. Biogeochemical cycling of elements by microbes in the absence of oxygen leads to production of greenhouse gases (GHG), including nitrous oxide and methane (Buitenhuis and others, 2018). Expansion of anoxic habitats could, therefore, lead to increased GHG release to the atmosphere, further increasing warming and stratification. This outcome is uncertain, however, because warming and stratification, both of which might increase GHG production, will also affect the rates and distribution of primary production upon which all other biological processes depend (Battaglia and Joos, 2018).

Ocean deoxygenation does not occur in isolation from other human-caused ocean stressors. With elevated ocean temperatures, microbes dependent on aerobic respiration and the vast majority of marine animals will need to consume more oxygen in order to survive (Pörtner, 2012). Elevated ocean temperatures therefore decrease the availability of suitable habitat both by increasing oxygen requirements and by inducing further oxygen loss. Predicted shifts in distribution poleward and into deeper, cooler waters, local extinctions and decreased maximum size of many fish species are attributed, at least in part, to increased oxygen requirements at warmer temperatures (Deutsch and others, 2015; Pauly and Cheung, 2018). Combined effects of ocean climate-change stressors, namely, deoxygenation, warming and acidification, may also result in spatial, temporal and evolutionary mismatches between zooplankton and fish larvae that lead to altered larval fish growth and survival, and ultimately negative effects on fisheries (Dam and Baumann, 2017). More generally, the role of oxygen in converting food to energy means that oxygen supply can determine energy available to respond to other stressors (Sokolova, 2013).

Fisheries catches are often low within oxygen-depleted waters as a result of avoidance behaviour of highly mobile species, as well as mortality and recruitment failure of species that are sessile or have limited mobility (Breitburg and others, 2009; Rose and others, 2019).

There is concern that low oxygen areas and their expansion make fish and mobile shellfish more susceptible to overfishing (Craig, 2012; Purcell and others, 2017) by leading to high-density aggregations above and at the edge of low oxygen waters (Craig, 2012; Stramma and others, 2012). For example, spatial shifts in fishing effort have been well-documented in both the brown shrimp fishery in the Gulf of Mexico, and Dungeness crab fishery in Hood Canal, United States of America, whereby the spatial overlap between fishing fleets and target species increases as hypoxic zones increases on a seasonal basis or among years that vary in the spatial extent of hypoxia (Purcell and others, 2017; Froehlich and others, 2017). Fishing mortality may increase where these refuge locations are targeted and where shallower distributions increase catch rates (Purcell and others, 2017). Low oxygen events have also been an important source of mortality in both finfish and shellfish aquaculture, causing substantial losses to local economies with consequences to both human health and food security (Cayabyab and others, 2002; Rice, 2014).

3. Capacity building: Global Ocean Acidification Observing Network (GOA-ON) and Global Ocean Oxygen Network (GO_2NE)

United Nations Sustainable Development Goal 14 (SDG 14) addresses the need to "conserve and sustainably use the oceans, seas and marine resources for sustainable development", including by meeting target 14.3, to "minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels".[148] Concern about the problem of deoxygenation was also noted in the Our ocean, our future: call for action declaration, the outcome of the United Nations Conference to Support the Implementation of Sustainable Development Goal 14.[149]

The ability to attribute ecosystem impacts to changing ocean chemistry requires continued advances in ocean observation systems. Global initiatives in ocean research such as Biogeochemical Argo, and the Intergovernmental Oceanographic Commission (IOC-UNESCO) Global Ocean Acidification Observing Network (GOA-ON) and Global Ocean Oxygen Network (GO_2NE) are reducing barriers and building capacity in support of improved global understanding of ocean acidification and deoxygenation. GOA-ON and GO_2NE provide access to collaboration and mentoring in support of improving ocean observations of pH and oxygen through training sessions, partnerships and supporting regional hubs creation. Currently, ocean acidification and deoxygenation observation and research efforts are concentrated in a relatively small number of countries, leaving large knowledge and capacity gaps around the world, especially in the southern hemisphere and small island developing States and least developed countries (GOA-ON, 2019). Higher capacity to collect complex data and deliver better observations across the globe means that the predictive power of experiments and ecosystem models may improve as they replicate real world scenarios more effectively to meet SDG 14.

Marine ecosystem services depend on what basic biotic functions are maintained (Connell and others, 2018), which ecosystem engineers and keystone species are retained (Sunday and others, 2017), and whether the spread of nuisance species is avoided (Hall-Spencer and Allen, 2015). Knowledge gaps for ecosystem responses to changes in ocean chemistry remain large. However, multi-stressor experiments and ecosystem models that incorporate advances in ecophysiology and genomics may better describe the scope of impact and reduce uncertainty

[148] See United Nations General Assembly resolution 70/1.
[149] See United Nations General Assembly resolution 71/312, annex; see also https://oceanconference.un.org/callforaction.

about its extent. How deoxygenation is altering microbial pathways and rates of processes within the water column and the deep ocean needs to be better understood (Breitburg and others, 2018). The call by Riebesell and Gattuso (2015) for a shift towards multi-stressor and multispecies experiments to understand more specifically the ecological impacts of ocean acidification on marine communities has been taken up (Munday, 2017). Further advances will result from deepening and broadening the understanding of relationships of ocean acidification and oxygen with other environmental drivers, how ecological processes and species interactions change under conditions that matter to them, and how individual variation, plasticity and adaptation in response to ocean chemistry change shape impacts on marine ecosystems. The research advancement on these aspects will be in support to take more effective measures to mitigate the impacts. Acknowledging that the impacts of ocean acidification and deoxygenation will have less serious consequences for the millions of people who are dependent on coastal protection, fisheries and aquaculture in lower emissions scenarios.

4. Summary

Marine heatwaves are shown to be increasing in frequency and intensity due to climate change caused by human activities and are having a mostly negative impact on marine ecosystems. Marine heatwaves and their impacts are projected to increase in the future but those increases can be strongly limited by efforts to mitigate climate change. Forecasting systems may be employed in adapting to the effects of marine heatwaves.

Extreme El Niño and La Niña events have been observed but, because they occur infrequently, a human influence has not been detected. Nevertheless, models indicate an increase in frequency of both phases of the oscillation under future scenarios of global warming. As in the case of marine heatwaves, forecasting systems, which already exist, may be employed in risk management and adaptation.

While changes in the frequency and spatial distribution of tropical cyclones are hard to detect in the observational record, studies of individual cyclones have shown a human influence on their intensity, in particular, the associated rainfall. Changes in intensity are projected to increase in the future with associated impacts on storm surges and coastal infrastructure.

Although all coastal cities are already facing rising sea levels, low-lying cities and developing countries that lack the ability to invest in coastal defence measures and natural barrier restoration will suffer damage and losses of a higher degree. Global population studies suggest people will/are relocate to coastal areas, thereby putting more population at risk economically and socially. Although cities are typically centres for innovation and investment, key examples demonstrate the difficulty in solving such complex problems in vulnerable locations.

Damage and losses are also driven by existing vulnerabilities in coastal infrastructure and may not be solely attributed to rising sea levels. Rather, increasing sea levels may exacerbate existing issues increasing risk.

The complex interactions between temperature and salinity with nutrients and chemical cycles of the ocean imply that variations in these variables due to climate change and anthropogenic impact thus affect marine ecosystems, population, coastal communities and the related economy. Ocean warming is causing significant damage to marine ecosystems and species are losing their habitats, forcing species to adapt or relocate to new temperatures or looking for new feeding, spawning or nursery areas.

Ocean acidity and the availability of sufficient oxygen both underpin the provision of marine ecosystems services to human society. We are now, however, observing rapid changes in ocean acidity and falling oxygen levels caused by climate change and anthropogenic CO_2 emissions, which is changing marine habitats and ecosystems worldwide. Warming is causing oxygen levels to fall and acidification is rapidly changing the carbonate chemistry of surface ocean waters - together these reduce the growth and survival of many organisms and degrade ecosystem resilience.

Closing knowledge gaps in ocean science by supporting capacity-building efforts that increase our understanding of how the ocean and its ecosystems are responding to changes in ocean physical and chemical properties is an important pathway to reducing impacts of such changes and achieving Sustainable Development Goal 14.

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Chapter 10
Changes in Inputs to the Marine Environment of Nutrients

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Keynote points

- Inputs of nitrogen (N) and phosphorus (P) to coastal ecosystems via river runoff and atmospheric deposition increased rapidly during the twentieth century due to anthropogenic inputs derived primarily from the use of synthetic fertilizer, combustion of fossil fuels, cultivation of legumes (N_2-fixation), production of manure by livestock, and municipal wastes.
- Increases in anthropogenic nutrient inputs have fueled a global increase in cultural eutrophication of the coastal ocean and now exceed inputs due to natural processes.
- Ecological responses to the process of cultural eutrophication include increases in the severity and extent of coastal hypoxia, acidification and toxic algal events. Thus, cultural eutrophication is a serious threat to the health of coastal ecosystems and their capacity to provide services valued by society.
- It is projected that anthropogenic N and P production will increase by nearly a factor of two during the first half of the twenty first century.
- Reducing anthropogenic inputs of N and P to the coastal ocean to minimize the extent and risk of coastal eutrophication during the course of the 21st century should be an international priority.

1. Introduction

During the course of the 20th century, increases in anthropogenic inputs of nitrogen (N) and phosphorus (P) to coastal ecosystems via river discharge became the primary cause of cultural eutrophication[150] and consequent ecosystem degradation of the coastal ocean worldwide (Rabalais and others, 2009a, b; Paerl and others, 2014; Beusen and others, 2016; Ngatia and others, 2019), a trend that is arguably the most widespread anthropogenic threat to the health of coastal ecosystems (Rabalais and others, 2009b; IPCC, 2014).

Nixon (1995) defined eutrophication as *an increase in the rate of supply of organic matter to an ecosystem* and noted that increases in the supply of organic matter to coastal ecosystems have various causes, the most common being excess inputs of biologically active, inorganic N and P. Since phytoplankton net primary production (NPP) in most coastal ecosystems is limited primarily by the availability of N (Howarth and Marino, 2006; Elser and others, 2007), phytoplankton biomass in the coastal ocean has increased accordingly (Howarth and

[150] Eutrophication driven by anthropogenic inputs of nutrients and organic matter that lead to undesirable changes in ecosystem health (Smith and others, 2006; Rabalais and others, 2009a, b).

others, 2011). Combined with additional anthropogenic inputs of organic nutrients from land-based sources, the resulting accumulation of organic matter has led to cultural eutrophication of many coastal ecosystems worldwide (Figure 1), a process that is arguably the most serious threat to marine ecosystem services valued by society, e.g. provision of biodiversity, production of oxygen, mitigation of coastal flooding, fisheries and sequestration of atmospheric CO_2 (Howarth and others, 2000; Bachmann and others, 2006; Martínez and others, 2007; Costanza and others, 2017).

Our focus here is on anthropogenic inputs of biologically reactive fixed N (such as dissolved nitrate, nitrite, ammonium, urea and free amino acids) and P (PO_4^{-3} such as orthophosphate, polyphosphate, and organically bound phosphates) to the coastal ocean as defined by the global network of Large Marine Ecosystems (LMEs).[151] In this context, the objectives of the present chapter are to: (1) document changes in anthropogenic inputs of N and P to selected coastal marine ecosystems; (2) assess the impacts of cultural eutrophication on these ecosystems; (3) project how these changes will likely impact the capacity of coastal ecosystem to support ecosystem services during the course of this century in the context of global climate change; and (4) identify gaps in current knowledge.

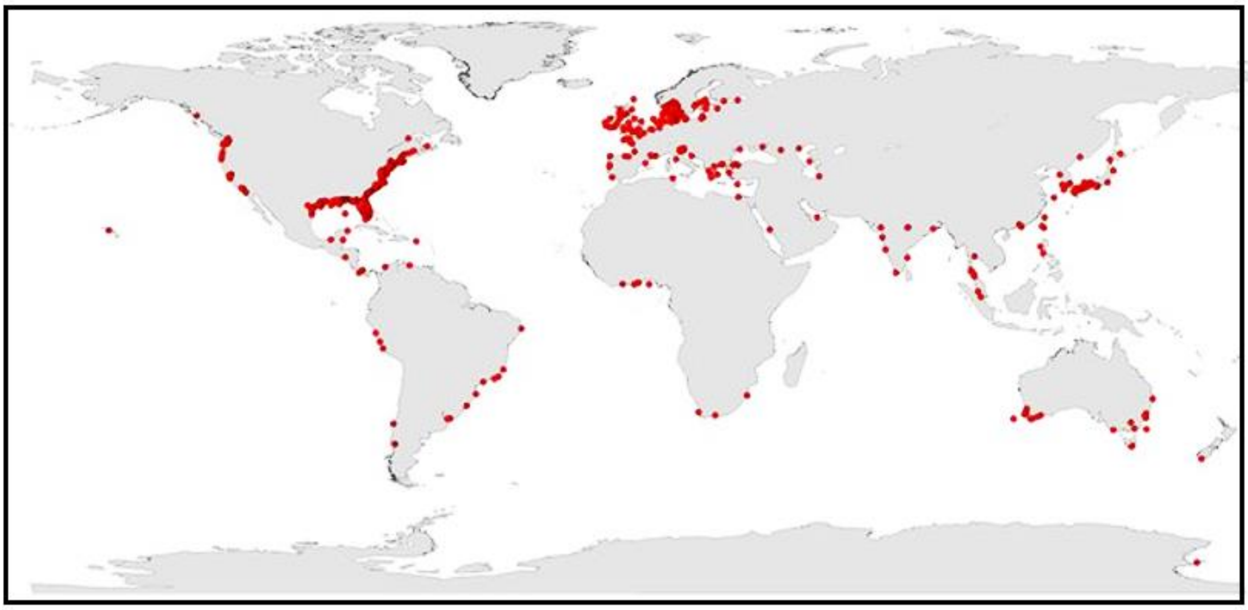

Figure 1. Global distribution of eutrophic coastal marine ecosystems (Breitburg and others, 2018). Recent coastal surveys of the United States and Europe found that a staggering 78 percent of the assessed continental United States coastal area and approximately 65 percent of Europe’s Atlantic coast exhibit symptoms of eutrophication.

The information presented herein is relevant to a number of Chapters in the present Assessment (Chapters 4–9, 11–15, 25, and 31). Chapter 5 (trends in the physical and chemical state of the ocean), and Chapter 6A (plankton diversity) are particularly relevant. The former is addressed here to the extent that changes in nutrient inputs and eutrophication are related trends in physical and chemical environment conditions (emphasis on climate-driven

[151] The global network of large marine ecosystems (LMEs) includes coastal watersheds and the coastal ocean (estuaries and the open waters of the continental shelves (available at http://lme.edc.uri.edu/). LMEs vary in size from ~ 200,000 km^{-2} to > 1,000,000 km^{-2} and encompass areas of the coastal ocean where primary productivity is generally higher than in the open ocean.

changes). The latter is addressed to the extent that changes in plankton diversity are relevant to the problem of coastal eutrophication.

2. Situation reported in World Ocean Assessment I (WOA I)

Chapter 20 of WOA I (United Nations, 2017) reviewed coastal, riverine and airborne inputs of contaminants from land-based sources, with an emphasis on hazardous substances, endocrine disruptors, nutrients and waterborne pathogens, and radioactive substances. Those aspects related to anthropogenic nutrient inputs to the ocean in general and coastal ecosystems in particular are most relevant to this chapter. In addition to the global view summarized below, Chapter 20 included a summary of inputs to and impacts of nutrients for different regions of the global ocean (Arctic Ocean and regions of the Atlantic, Indian and Pacific Oceans).

Major sources of anthropogenic nutrients include municipal wastewater, fertilizers used for agriculture, combustion of fossil fuels, and food-related industries. Transport routes to the ocean from these land-based sources include river runoff and atmospheric deposition. Controlling nutrient inputs from municipal wastes remains a challenge in the developing world. In regard to agriculture, the use of fertilizers has grown rapidly in recent decades, resulting in a 42 percent increase between 2002 and 2012 globally. However, fertilizer use in Latin America, southern Asia, eastern Asia and Oceania has more than doubled during the same period. Airborne inputs of nitrogen from the combustion of fossil fuels have also increased. In north-western Europe, over 25 percent of nitrogen emissions to the atmosphere are from these sources. The precise consequences of excess nutrient loading depend on local environmental conditions, including the rate at which semi-enclosed bodies of water are flushed by currents and the strength of density stratification of the water column.

Land-based inputs of nutrients are not, in themselves, harmful but can cause problems when they are excessive. Inputs of anthropogenic N and P, which more than doubled in the last century, have impacted the health of marine ecosystems worldwide. Increased inputs stimulate the growth of phytoplankton resulting in excessive NPP which often leads to accumulations of phytoplankton biomass and eutrophication. This has led to the development of oxygen-depleted “dead zones”, loss of sea grass beds and increases in the occurrence of toxic phytoplankton blooms. The global spread of oxygen depleted (“dead”) zones in coastal waters has increased exponentially to over 400 systems since the 1960s and has reached a cumulative area of about 245,000 km^2 worldwide.

3. Global-scale patterns and trends

3.1. Anthropogenic inputs of biologically reactive nitrogen (N) and phosphorus (P)

3.1.1. Sources

During the twentieth century, the global supply of biologically reactive N and P doubled due to anthropogenic activities (Beusen and others, 2016; Seitzinger and Mayorga, 2016). Over half of new[152] N and P loads to most coastal ecosystems (73 percent of LMEs) are related to anthropogenic sources, current inputs of which have been estimated to be in the range of 210-223 x 10^9 kg N yr^{-1} (Lee and others, 2016) and ~34 x 10^9 kg P yr^{-1} (Harrison and others, 2005). Inputs of these nutrients to LMEs are derived from agricultural practices,[153] combustion of fossil fuels and municipal wastes (Galloway and others, 2004; Howarth, 2008) as follows:

1) The single largest source of anthropogenic N and P is synthetic fertilizers[154] (Vitousek and others 1997; Mosier and others, 2004). The amount of synthetic fertilizer used for agriculture has grown exponentially from near zero in 1910 to ~118 x 10^9 kg N yr^{-1} and 17.5 x10^9 kg P yr^{-1} in 2013 (Penuelas and others, 2013; Lu and Tian, 2017). Hotspots of fertilizer use shifted from the United States of America and Western Europe in the 1960s to eastern Asia in the early twenty-first century. In 2013, East Asia, South Asia and Southeast Asia accounted for 71 percent of global fertilizer use, followed by North America (11 percent), Europe (7 percent), and South America (6 percent) (Lu and Tian, 2017). Of the N loading, volatilization of ammonia from agricultural fields emits an estimated 10 x 10^9 kg N yr^{-1}into the atmosphere (Vitousek and others, 1997; Bouwman and others, 2013).
2) Combustion of fossil fuels releases fixed N from long-term storage in geological formations back into the atmosphere in the form of nitrogen oxides (NO_X). Altogether, emissions from coal- and oil-fired power plants, automobiles, and other combustion processes release on the order of 40 x 10^9 kg N yr^{-1} (Penuelas and others, 2013). The global distribution of NO_X emissions is not uniform with Asia, Europe, North America and Sub-Saharan Africa accounting for 30, 20, 17 and 12 percent of emissions, respectively (Lamsal and others, 2011).
3) As large areas of natural vegetation have been replaced with monocultures of legumes that support symbiotic N_2-fixing bacteria, anthropogenic input from biological N_2-fixation to coastal watersheds is estimated to be 33 x 10^9 kg yr^{-1} (Boyer and Howarth, 2008).
4) Livestock production of manure has increased rapidly over the last century. Current loads of manure N and P are estimated to be ~ 18 x 10^9 kg N yr^{-1} and ~ 2.5 x 10^9 kg P yr^{-1}, with hotspots in Western Europe, India, north-eastern China and south-eastern Australia (Penuelas and others, 2013; Zhang and others, 2017).

[152] New N inputs are those coming from outside the ecosystem as opposed to those that are regenerated within the ecosystem as organic matter is decomposed.
[153] Agricultural practices include the use of synthetic fertilizers, animal husbandry, and the culture of legumes (biological N2-fixation).
[154] Synthetic fertilizers include ammonium nitrate, ammonium phosphate, superphosphate and urea.

5) Globally, 80 percent of municipal wastewater is released into the environment untreated (WWAP, 2017). Thus, the most prevalent urban source of nutrient pollution is human sewage, which is estimated to have released ~ 9 x10^9 kg N yr^{-1} and ~ 1.4 x 10^9 kg P yr^{-1} into the environment in 2018 (extrapolated from Van Drecht and others, 2009). The percentage of treated[155] sewage varies regionally from 90 percent in North America, 66 percent in Europe, 35 percent in Asia and 14 percent in Latin America and the Caribbean, to < 1 percent in Africa (Selman and others, 2010).

Nonpoint (diffuse) source inputs (1 - 4 above 218 x 10^9 kg N yr^{-1}) far exceed point source inputs from wastewater (5 above ~ 9 x10^9 kg N yr^{-1}) and are more difficult to control. Ultimately, most of these inputs are transported to the coastal ocean via river runoff and atmospheric deposition (Howarth, 2008; Spokes and Jickells, 2005; Jickells and others, 2017).[156] Both transport pathways are major routes of input for N while atmospheric deposition of reactive P is negligible relative to riverine inputs. Thus, climate-driven acceleration of the global water cycle and associated increases in the magnitude and frequency of major rainfall events (Sinha and others, 2017) will accelerate nutrient inputs from diffuse sources (e.g. agriculture) to coastal waters (Howarth and others, 2012). In this context, it should be noted that reductions in N and P loads have come primarily via advanced wastewater treatment in developed countries, while efforts to reduce diffuse inputs from agricultural sources have, for the most part, been less effective (Boesch, 2019).

3.1.2. Transport of anthropogenic nutrients to the coastal ocean

Anthropogenic inputs to the coastal ocean via river runoff are fueled by anthropogenic supplies to coastal watersheds, wet precipitation within watersheds and riverine transport from watersheds (Howarth and others, 1996; Green and others, 2004). Globally, there is a significant linear correlation between net anthropogenic N supplies to coastal watersheds and total river-borne N export to the coastal ocean (Boyer and Howarth, 2008). During the twentieth century, total riverine inputs of N and P to the coastal ocean increased from ~ 27 x 10^9 kg N yr^{-1} to ~ 48 x 10^9 kg N yr^{-1} and from ~ 2 x 10^9 kg P yr^{-1} to ~ 4 x 10^9 kg P yr^{-1} (Galloway and others, 2004; Beusen and others, 2016). Boyer and Howarth (2008) estimated riverine inputs of N to the ocean basins as follows: Atlantic (primarily from eastern North America and western Europe) 15-25 x 10^9 kg N yr^{-1}; Pacific (primarily from East Asia) 10-14 x 10^9 kg N yr^{-1}; Indian 7-8 x 10^9 kg N yr^{-1}; and Arctic 2-4 x 10^9 kg N yr^{-1}.

Atmospheric N compounds are derived from both agricultural sources (volatilization of ammonia) and fossil fuels (emission of NO_x). In contrast to river-borne nutrient loading, N inputs delivered via atmospheric deposition are fueled by anthropogenic supplies to and emissions from coastal airsheds (which are generally much larger than watersheds), atmospheric transport from airsheds and wet precipitation directly over the coastal ocean (Valigura and others, 2001). As for river-borne N inputs, atmospheric deposition of N to the

[155] Primary, secondary or tertiary treatment.

[156] Ground water discharge accounts for ~ 2.4 percent of nutrient inputs to the coastal ocean globally (Luijendijk and others, 2020) and is not documented for most of the Large Marine Ecosystems addressed here. Inputs from aquaculture operations are also low, i.e., it is estimated that nutrients released to the coastal ocean annually by finfish aquaculture operations account for ~ 1 percent of anthropogenic inputs worldwide (Hargrave, 2005). Thus, these input pathways are not considered here.

global ocean increased rapidly during the twentieth century from a pre-industrial rate of ~ 22 x 10^9 kg N yr^{-1} to > 45 x 10^9 kg N yr^{-1} today (Dentener and others, 2006; Duce and others, 2008). Of this, it is estimated that atmospheric deposition to the coastal ocean is currently in the order of 8 x 10^9 kg N yr^{-1} and 0.4 x 10^9 kg P yr^{-1} (Seitzinger and others, 2010; Ngatia and others, 2019). The relative importance of atmospheric deposition as a new N source varies among coastal ecosystems from 2 – 5 percent in ecosystems with large riverine N inputs (e.g., the northern Gulf of Mexico, continental shelf of Barazil) to as much as 40 percent in ecosystems with relatively low riverine inputs (e.g., the Kiel Bight in the Baltic Sea and Pamlico Sound in North Carolina) (Paerl and others, 2002). Globally, atmospheric deposition of N accounts for ~ 4 percent of anthropogenic inputs to the coastal ocean.

3.2. Documented impacts of anthropogenic nutrient inputs

3.2.1. Oxygen depletion and acidification

Since 1950, the number of coastal ecosystems experiencing hypoxia (dissolved $O_2 \leq 2$ mg $litre^{-1}$ or 63 mmol $litre^{-1}$) has increased from ~ 50 in 1950 to > 500 in 2015 as a consequence of anthropogenic nutrient loading and ocean warming (Diaz and Rosenberg, 2008; Kemp and others, 2009; Breitburg and others, 2018). In 2019, a further estimate suggests that the number was actually higher, i.e., around 700 (Diaz and others, 2019). The spread of coastal hypoxia has not only resulted in the loss of oxygenated habitats for aerobic organisms, it threatens the survival of coral reefs (Fabricius, 2011; Altieri and others, 2019). In addition, the global spread of hypoxia is amplifying ocean acidification as increases in biological oxygen demand produces CO_2 as a by-product of aerobic respiration (Wallace and others, 2014).

3.2.2. Toxic algal events

The production of toxins can cause mass mortalities of fish and shellfish and cause harm to the health of people who consume contaminated fish and shellfish or are exposed to toxins via direct contact (Glibert and others, 2005). Globally, there have been more toxic algal events in coastal waters during the past decade than in previous decades (Heisler and others, 2008), largely as a consequence of anthropogenic nutrient inputs and changing N:P ratios (Glibert and Bouwman, 2012; Glibert and others, 2018), introductions of non-native toxic species, ocean acidification (Riebesell and others, 2018) and increases in water temperature and vertical stratification of the upper ocean[157] (Glibert and others, 2014).

3.2.3. Loss of critical, biologically engineered habitats

Coral reefs and seagrass meadows support a wide range of ecosystem services, including coastal protection, erosion control, the maintenance of biodiversity, and fisheries (Barbier and others, 2011). At the same time, warm water coral reefs and seagrass meadows are threatened by multiple anthropogenic stresses (e.g. ocean warming and acidification, eutrophication,

[157] Upper 1000 m of the water column.

overfishing and destructive fishing practices). Ocean warming has been impacting coral reefs for more than three decades through the bleaching and mortality of corals due to heat stress (Heron and others, 2017), and the risk of bleaching has increased globally at a rate of 4 percent per year, with 8 percent of reefs being affected by bleaching per year in the 1980s and 31 percent affected in 2016 (Hughes and others 2018), a trend that is expected to be exacerbated by coastal eutrophication (Wear and Thurber, 2015). The spatial extent of seagrass beds has been shown to be negatively impacted by eutrophication and increases in water temperature (Waycott and others, 2009; Mvungi and Pillay, 2019). Thus, seagrass meadows have declined in area by about 29 percent since the beginning of the twentieth century at an annual rate of about 1.5 percent (Fourqurean and others, 2012).

4. Patterns and trends within regions

Many LMEs are hotspots of anthropogenic nutrient loading in both developed and developing countries. In order to provide regional and global perspectives on changing nutrient inputs to coastal systems throughout the world, an international workgroup[158] developed a global watershed model that relates human activities and natural processes in watersheds to nutrient inputs to coastal systems globally (Seitzinger and others, 2005; Lee and others, 2016). Based on the contribution of anthropogenic dissolved inorganic N (DIN) to the total DIN loads to LMEs (Lee and others, 2016), nine LMEs are highlighted here that represent a range of sizes and anthropogenic DIN inputs (Table 1).

Ecosystem	Area	N Loading
North Sea	0.7×10^6 km^2	4.8×10^9 kg y^{-1}
Baltic Sea	0.4×10^6 km^2	0.6×10^9 kg y^{-1}
Gulf of Mexico	1.5×10^6 km^2	1.3×10^9 kg y^{-1}
Brazil Shelf	1.0×10^6 km^2	1.0×10^9 kg y^{-1}
Guinea Current	2.0×10^6 km^2	1.0×10^9 kg y^{-1}
Bay of Bengal	3.7×10^6 km^2	7.1×10^9 kg y^{-1}
South China Sea	5.7×10^6 km^2	0.7×10^9 kg y^{-1}
Great Barrier Reef	1.3×10^6 km^2	0.1×10^9 kg y^{-1}
East China Sea	1.0×10^6 km^2	2.0×10^9 kg y^{-1}

Table 1. Surface areas and anthropogenic nitrogen loads of the nine ecosystems addressed below.

4.1. North Sea (LME 22; 690,000 km^2)

[158] Available at http://www.marine.rutgers.edu/globalnews

The North Sea encompasses two sub-regions: (i) shallow, eutrophic coastal waters along the southeast boarder of the Sea and (ii) deeper, oligotrophic waters of the open Sea. Nutrient inputs to the latter have remained virtually unchanged over the past 50 years while coastal waters have experienced an increase in N load from about 2.9 to 4.8 x 10^9 kg N y^{-1} between 1950 and 1990; Over the same period, the P-load increased from 0.44 to 0.64 kg P y^{-1} (Vermaat and others, 2008). River-borne inputs of N and P to the coastal sub-region account for most anthropogenic loading, 75 percent of which occurs via the Rhine and Elbe Rivers that discharge into coastal waters of the southeast North Sea (Radach and Pätsch, 2007; Paramor and others, 2009). The discharge of N and P to these coastal waters increased rapidly during 1965–1985 as illustrated by the Rhine River where N and P increased fivefold and tenfold, respectively. As a result, the frequency and magnitude of blooms of *Phaeocystis pouchetii*[159] increased during this period (Lancelot and others, 1987; Lancelot, 1995). While summer hypoxia (< 2 mg O_2 $litre^{-1}$) occurs in some locations, this is limited to parts of the stratified open sea (Greenwood and others, 2010).

From 1990 to 2000, the P load decreased to the pre-eutrophication levels of the 1950s (Vermaat and others, 2008). The anthropogenic portion of the annual nutrient budget of the coastal North Sea is currently declining and is less than inputs from the benthos or open sea.

4.2. Baltic Sea (LME 23; 400,000 km^2)

The Baltic Sea a is a brackish, shallow sea (mean depth = 55 m, maximum depth = 460 m) with limited water exchange with the North Sea. By virtue of its bathymetry and estuarine circulation regime,[160] the Baltic Sea is particularly vulnerable to eutrophication. Thus, the Baltic is host to the largest anthropogenically induced hypoxic zone in the world (Carstensen and others, 2014). The change from a healthy state without eutrophication problems began in the late 1950s and early 1960s.

Riverine inputs of N and P account for most inputs to the Baltic Sea from 1995–2015 (Sonesten and others, 2018). Inputs of N and P were generally higher during 1995–2002 (650 – 900 x 10^6 kg N yr^{-1} and 33 – 43 x 10^6 kg P yr^{-1}) compared to 2003–2015 (500 – 775 x 10^6 kg N yr^{-1} and (22 – 35 x 10^6 kg P yr^{-1}). Natural background loads of N and P made up ~33 percent of these inputs during the latter period (Sonesten and others, 2018). Atmospheric deposition also declined during this period from ~300 x 10^6 kg N yr^{-1} in 1995 to 210 x 10^6 kg N yr^{-1} in 2011. Low inputs during 2003–2015 were due, in part, to dry periods with low river flows (2003, 2014, 2015).

Over roughly the same period (1993–2016), the spatial extent of seasonal hypoxia-anoxia increased from ~5,000 km^{-2} (1.3 percent of the Baltic) to > 60,000 km^{-2} (> 16 percent of the Baltic) (Limburg and Casini, 2018), in part because of increases in the strengths of the

[159] *Phaeocystis* can produce large amounts of foam (which often impacts coastlines and beaches) and can also produce dimethylsulphide (DMS), an aerosol that contributes to cloud formation and acid rain.
[160] A sill < 20 m deep separates the Baltic and its basins from the North Sea. Estuarine (density driven) circulation with surface water flowing from the Baltic through the Danish Straits into the North Sea and bottom water flowing into the Baltic's basins through the Danish Straits from the North Sea (Szymczycha and others, 2019).

seasonal thermocline and halocline in the upper water column (< 100 m) (Liblik and Lips, 2019) and in part because episodes of deep water ventilation in the basins have been less frequent and of shorter duration during the past two decades (Carstensen and others, 2014; Schmale and others, 2016). Seasonal hypoxia not only impacts aerobic benthic life, it may also promote development of more blooms of cyanobacteria. Massive surface accumulations of nitrogen fixing cyanobacteria (largely *Nodularia* spp.) during summer have intensified since 1982, a trend that is correlated with increases in the spatial extent of hypoxia and anthropogenic P loading (Pliński and others, 2007; Funkey and others, 2014). The enhanced downward flux of degradable organic matter from these blooms elevate oxygen demand and the regeneration of P in bottom waters, creating a positive feedback between anthropogenic nutrient enrichment, cyanobacteria blooms and oxygen depletion. In addition, some species of cyanobacteria produce toxins that impact recreation and fisheries. Thus, although ocean warming and shifts in circulation patterns are important factors modulating the extent of hypoxia, further nutrient reductions in the Baltic Sea will be necessary to reduce the ecosystems impacts of deoxygenation.

Abatement of eutrophication in the Baltic Sea has received more concerted effort and sustained research than any other coastal region in the world (Boesch, 2019). Since the mid-1990s, statistically significant reductions in anthropogenic loads of N and P have been achieved (HELCOM, 2018; Sonesten and others 2018). Relative to the reference period (1997–2003), flow-normalized riverine inputs of N and P have declined by 12 percent and 25 percent, respectively, and, compared to 1995, precipitation-normalized atmospheric deposition of N declined by 29 percent. Following introduction of nutrient abatement measures, recovery began in some basins during the late 1990s while in others it commenced early in the twenty-first century (Murray and others, 2019). However, given the sustained increase in vertical stratification and associated isolation of deep water from oxygenated surface water (Liblik and Lips, 2019), the susceptibility of the Baltic to eutrophication will increase if this trend continues. This emphasizes the importance of achieving the maximum allowable inputs specified in the Baltic Sea Action Plan.[161] To this end, inputs of N and P from anthropogenic sources as a whole (riverine plus atmospheric sources) need to be further reduced by 12 percent and 25 percent, respectively, to ensure a healthy Baltic Sea.

4.3. Gulf of Mexico (LME 5; 1,530,400 km^2)

Impacts of anthropogenic nutrient loading are greatest in the northern Gulf of Mexico. Inter-annual variations in nutrient loading are directly related to variations in the flow of the Mississippi and Atchafalaya Rivers (Rabalais and others 2007). During 1980–2017, annual DIN inputs fluctuated around 1,000 x 10^6 kg yr^{-1} with a minimum of ~ 600 x 10^6 kg yr^{-1} in 2000 and a maximum of ~ 1,800 x 10^6 kg yr^{-1} in 1993.[162] As a consequence, during the summer, the northern Gulf has the second largest coastal hypoxic zone in the world, the spatial extent of which has varied between < 5,000 km^2 in 2000 to 22,720 km^2 in 2017, with a mean of 13,700 km^2 (Rabalais and others, 2007; Matli and others, 2018).

[161] Available at http://www.helcom.fi/Documents/Balticpercent20seapercent20actionpercent20plan/BSAP_Final.pdf
[162] Available at https://nrtwq.usgs.gov/mississippi_loads/#/GULF

In addition to bottom water hypoxia, increases in nutrient loading appears to be promoting toxic phytoplankton blooms. The abundance of *Pseudo-nitzschia* spp. has increased over the shelf since the 1950s, a trend that may be related to the long-term increase in nutrient loading (Dortch and others, 1997; Parsons and others, 2002). Seasonal blooms develop when surface waters begin to warm in spring and river discharge is increasing, but before seasonal peaks in flow and phytoplankton biomass occur (Bargu and others, 2016). Peaks in the abundance of potentially toxin-producing dinoflagellates (*Dinophysis* spp. and *Prorocentrum* spp.) have been observed to coincide with the seasonal peak in river flow (Bargu and others, 2016).

4.4. North Brazil Shelf (LME 17; 1,034,600 km^2)

With mean freshwater discharge of 120,000 m^3 s^{-1} (seasonal maximum ~ 240,000 m^3 s^{-1} in May, and minimum 80,000 m^3 s^{-1} in November), the Amazon River forms an extensive and dynamic surface plume of low salinity, relatively nutrient-rich water that extends well offshore over the northern Brazil shelf. The river is the primary source of silicate (83–91 percent), nitrate (62–76 percent), and phosphate (48–65 percent) to this LME (Demaster and Pope, 1996). The annual supply of river-borne N (mean ~ 1,050 x 10^6 kg N yr^{-1}) supports a eutrophic ecosystem (730 g C m^{-2} yr^{-1}) in the mesohaline (salinity 30-35) waters of the coastal plume (Dagg and others, 2004; Santos and others, 2008; Coles and others, 2013).

NPP is nitrate limited, and extensive blooms of diatom-diazotroph associations[163] have been observed in the mesohaline plume during both spring and autumn (Gomes and others, 2018). Given the spread of plume water into the Caribbean and equatorial Atlantic (Coles and others, 2013), these blooms may be a significant source of new N to support primary production and the Great Atlantic Sargassum Belt (Wang and others, 2019) in nutrient-poor, tropical waters (Subramaniam and others, 2008; Yeung and others, 2012).

[163] The diatoms *Hemiaulus hauckii* and *Rhizosolenia clevei* containing the symbiotic cyanobacteria *Richelia* sp. formed ~28 percent of the biomass in mesohaline waters of the plume.

4.5. Guinea Current (LME 28; 1,958,800 km^2)

Lying within the Guinea Current LME (Heileman, 2008), the Gulf of Guinea receives freshwater discharges from 15 rivers, including the Congo (the second largest river on Earth) with an annual mean discharge of ~ 40,000 $m^3 s^{-1}$ (Hopkins and others, 2013). It is also the world's second largest exporter of terrestrial organic carbon into the oceans (Spencer and others, 2012). The outflow of such a large volume of water into the southeast Atlantic produces a vast low salinity plume with a signature of high chlorophyll that can be detected as far as 700–800 km to the west and north from the river's mouth (Hopkins and others, 2013).

Most of the coastal cities bordering the Gulf lack basic infrastructure for sewage treatment, and substantial quantities of N and P from municipal and agricultural sources are transported to the Gulf via river runoff.[164] The current anthropogenic river-borne N loading is estimated to be between 600 and 1,000 x 10^6 kg yr^{-1}, which places the region in the high-risk category for eutrophication (Seitzinger and Mayorga, 2016).

Consequently, the Gulf is characterized by high phytoplankton NPP (356 - 438 g C m^{-2} yr^{-1}, 2003–2013) supported by nutrient input from both river runoff and coastal upwelling.[165] Nutrient pollution in coastal lagoon systems, particularly near urban centres, has caused increases in phytoplankton biomass and oxygen depletion, resulting in decreases in fisheries and increases in waterborne diseases (Scheren and others, 2002). In addition, while the phytoplankton community of coastal waters beyond the lagoons has been shown to be dominated by diatoms and cyanobacteria, potentially toxic dinoflagellate species (*Dinophysis caudata*, *Lingulodinium polyedrum* and *Prorocentrum* spp.) have been detected (Zendong and others, 2016).

4.6. Bay of Bengal (LME 34; 3,657,500 km^2)

Freshwater inputs to the Bay of Bengal are high as a consequence of monsoonal rainfall and river runoff (Yaremchuk and others, 2005). Five of the world's 50 largest rivers flow into the Bay (Sengupta and others, 2006). Salinity is lowest in the northern Bay, off the Ganges-Brahmaputra River delta and off the Irrawaddy River delta in the in the Gulf of Martaban, especially during the June–October monsoon season (Akhil and others, 2016). Rivers exported 35–45 percent more N and P to the Bay of Bengal in 2000 than in 1970, largely as a consequence of increases in fertilizer use (Sattar and others, 2014). In 2000, rivers exported 7,100 x 10^6 kg N yr^{-1} and 1,500 x 10^6 kg P yr^{-1} to the Bay. Three rivers (Ganges, Godavari and Irrawaddy) account for 75–80 percent of the total river input of N and P (Pedde and others, 2017). Atmospheric deposition has been estimated to be in the range of 100 – 3,100 x 10^6 kg N yr^{-1}, with most estimates near the upper end of the range (Srinivas and Sarin, 2013). Thus, atmospheric deposition may be a major source of N in addition to riverine inputs. Ratios of N and P to silicon (Si) have also been increasing, indicating an increasing risk for blooms of non-diatom species that may produce toxins and otherwise disrupt coastal ecosystems (Pedde and others, 2017).

[164] Available at https://some.grida.no/media/23569/state-of-the-coastal-and-marine-ecosystems-in-gclme.pdf.
[165] Available at http://onesharedocean.org/public_store/lmes_factsheets/factsheet_28_Guinea_Current.pdf.

A strong halocline limits nutrient enrichment from deep water so the central Bay is oligotrophic (Kay and others, 2018). Coastal waters are much more productive[166] (> 300 g C m^{-2} yr^{-1}) as a consequence of riverine N and P inputs. Hotspots of coastal eutrophication occur off the Ganges-Brahmaputra River delta (Bangladesh) of the northern Bay and in the Gulf of Martaban off the Irrawaddy River delta (Myanmar) of the eastern Bay (Kay and others, 2018; Monolisha and others, 2018). Phytoplankton biomass from these fertile areas that is not consumed in the euphotic zone sinks and decays at depth (150–600 m), leading to one of the largest hypoxic zones (60,000 km^2) in the global ocean (Bristow and others, 2017; Kay and others, 2018). In addition, potentially toxic species have been observed along the east coast of India (Mohanty and others, 2007; Sahu and others, 2014).

4.7. South China Sea (LME 36; 5,661,000 km^2)

The South China Sea as a whole is considered to be moderately productive[167] (150-300 g C m^2 yr^{-1}) but has the "highest" risk of eutrophication (Seitzinger and Mayorga, 2016). Riverine inputs of freshwater and nutrients to coastal waters of the Sea are dominated by the rivers that flow into the Pearl River estuary (Harrison and others 2008; Chen and others, 2009). During the wet season (April–September) when 80 percent of river discharge occurs (Yin and others, 2001), the two-layered estuarine circulation extends onto the inner shelf as the surface, nutrient-rich plume is transported along the coast and spreads at least 250 km into the interior of the Sea (Jilan, 2004; Chen and others, 2017).

In the late 1970s, the fertile river delta to the north of Hong Kong, China, was primarily used for agriculture. Since then, the Pearl River Delta has been transformed from farmland into a large megalopolis. As a consequence, dissolved N and P inputs via the Pearl River Delta increased by a factor of 2–5 during the 1980s and 1990s, largely due to increases in urban waste discharges and nutrients released from aquaculture operations (Yin and Harrison, 2008). Inputs plateaued during 2006–2012 when concentrations remained in the range of 500-1,000 x 10^6 kg N yr^{-1} and 20-40 x 10^6 kg P yr^{-1} with no inter-annual trend (Tong and others, 2015). Although atmospheric deposition of N over the South China Sea as a whole is estimated to be nearly an order of magnitude higher (~ 9,200 x 10^6 kg N yr^{-1}) than the riverine input (Luo and others, 2014), deposition is dispersed over the entire Sea with little impact on coastal eutrophication relative to river-borne inputs.

Overall, the impact of anthropogenic nutrient loading appears to be limited to the coastal margins of the Sea (Sun, 2017) with hotspots of seasonal hypoxia and toxic algal events located in the vicinity of major river deltas with substantial urban development (UNEP and others, 2005; Qian and others, 2018). The areas with the most severe eutrophication are associated with estuaries of the main rivers. Among the most severely impacted is the lower Pearl River estuary which has experienced annual summer hypoxia in bottom waters. Oxygen depletion in bottom waters of the lower Pear River estuary has occurred every summer for at least the last 25 years (Qian and others, 2018). During this period, the annual minimum dissolved oxygen (DO) concentration in bottom water decreased at a rate of ~2 ± 0.9 mmol

[166] Available at http://lme.edc.uri.edu/LME/images/Content/LME_Briefs/lme_34.pdf.
[167] Available at http://lme.edc.uri.edu/images/Content/LME_Briefs/lme_36.pdf.

litre^{-1} yr^{-1} as a consequence of DIN loading which increased as a rate of ~1.4 ± 0.3 mmol N litre^{-1} yr^{-1} (Qian and others, 2018).

The frequency of toxic algal events in Chinese coastal waters increased from no reports during the 1950s and 60s, to 10 in the 1970s, 25 in the 1980s and > 100 in the 1990s (Yan and others, 2002). From 1980–2003, the area affected expanded to include estuaries of the Pearl River, Manila Bay, and the Masinloc River Bay (Wang and others, 2008). Toxic species include potentially toxic *Noctiluca scintillans* (Pearl River estuary) and *Pyrodinium bahamense* (Philippine estuaries). *N. scintillans* has also been associated with hypoxia and the clogging of fish gills, and may act as a vector of algal toxins to higher trophic levels (Escalera and others, 2007; Turkoglu, 2013).

4.8. Great Barrier Reef (LME 40; 1,300,000 km^2)

Since European settlement, annual riverine inputs of N and P to the Great Barrier Reef (GBR) lagoon have increased from ~ 0.014 x 10^9 kg N yr^{-1} to 0.080 x 10^9 kg N yr^{-1} and from 1.8 x 10^6 kg P yr^{-1} to 16 x 10^6 kg P yr^{-1} (Brodie and others, 2011; Kroon and others, 2012). River-borne inputs of dissolved inorganic P (P-PO_4) can promote the growth of *Trichodesmium* spp.. While limited broadscale monitoring of *Trichodsmium spp.* occurs across the Great Barrier Reef, long-term data at one site near the Yongala Wreck since 2010 indicates a gradual increase in its abundance (Robson et al, 2018; GBRMPA, 2019). The nitrogen-fixing ability of *Trichodesmium* suggests that increasing levels of P-PO_4 alone may be driving increases in phytoplankton biomass, and there is some evidence that these trends are a significant factor in the decreasing condition of fringing reefs in the inner GBR lagoon. Long-term monitoring now shows that hard coral cover on the GBR has decreased by more than 70 percent over the past century (Bell and others, 2014). The decline has been attributed mainly to storm damage, coral bleaching events, the widespread growth of *Acanthaster planci* (crown-of-thorns starfish) and coral skeletal diseases. Record levels of nanophytoplankton growth in river-affected regions of the lagoon appear to be promoting the growth of *A. planci* larvae and adult *A. planci* outbreaks (Bell, 1992). There is growing evidence that *A. planci* predation events and coral bleaching are promoted by eutrophication and that this is one of the reasons why the reefs have not recovered (Bell and others, 2014; GBRMPA, 2019).

4.9. East China Sea[168] (LME 47; 1,008,100 km^2)

The East China Sea is considered to be a highly productive system (> 300 g C m^{-2} yr^{-1}) and is in the “highest” risk category for eutrophication (Seitzinger and Mayorga, 2016). The flow of the Changjiang (Yangtze) River (annual mean = 30,200 m^3 s^{-1}) accounts for > 90 percent of nutrient inputs to the Sea (Yuan and others, 2007; Tong and others, 2015). From 1968 to 1997, it is estimated that the anthropogenic nutrient load (e.g. nitrates) exported from the Changjiang River into the Sea increased more than tenfold (Yan and others, 2003). A comparison of nutrient concentrations in the Yangtze River Estuary and the receiving waters of the Sea before (2002) and after (2006) impoundment of the Three Gorges Dam (Chai and others, 2009) showed increases in the concentrations of total N (41.8 to 82.2 µM), dissolved

[168] Available at http://lme.edc.uri.edu/LME/images/Content/LME_Briefs/lme_47.pdf.

inorganic N (24.4 to 37.5 μM) and soluble reactive P (0.9 to 1.3 μM), and from 2006–2012, total N load increased from 1,350 x 10^6 kg yr^{-1} to 2,040 x 10^6 kg yr^{-1}, while total P load increased from 122 x 10^6 kg yr^{-1} to 240 x 10^6 kg yr^{-1} (Tong and others, 2015). Atmospheric deposition of N was estimated to be ~ 1,750 x 10^6 kg yr^{-1} which is in the range of riverine inputs during this period (Tong and others, 2015).

While the atmospheric input is generally distributed over the entire East China Sea, during the summer monsoons, the impact of river-borne nutrients targets coastal waters. Thus, the concentration of sea surface chlorophyll-*a* in the Sea is highest nearshore within the plume (> 10 mg m^{-3}) and decreases rapidly with distance to low concentrations (< 0.5 mg m^{-3}) in open waters beyond the continental shelf (Yuan and others, 2007). Inter-annual increase in nutrient loading has also led to increases in phytoplankton biomass over the years (Zhou and others, 2019).

Sinking organic matter produced by phytoplankton in the lower estuary and coastal plume fuel oxygen consumption and summer development of bottom water hypoxia. The occurrence, frequency and spatial extent of hypoxia have been increasing since the late 1990s (Li and others, 2011; Wei and others, 2015). Today, the area of the Sea influenced by the coastal plume of the Changjiang River is regarded as one of the largest coastal hypoxic zones (> 12,000 km^2) in the world (Chen and others, 2007; Wang and others, 2016; Zhu and others, 2017).

As nutrient input from the Changjiang River increased, reported toxic algal bloom events along the coast of the Sea increased from zero in the 1950s and 60s to 10 in the 1970s, 25 in the 1980s and > 100 in the 1990s (Yan and others, 2002). In particular, large-scale blooms (covering an area of more than 1,000 km^2) have been recorded every year since 1998, and *Prorocentrum donghaiense* has become the recurrent bloom species for more than ten years (Li and others, 2009; Lu and others, 2014). Blooms of potentially toxic *Karodinium veneficum*, *Karenia mikimotoi*, *Alexandrium tamarense*, *Alexandrium. catenella*, and *Heterosigma akashiwo* have also been observed (Lu and others, 2014; Zhou and others, 2015; Wang and others, 2018).

5. Outlook

It is projected that anthropogenic N production will increase by nearly a factor of two during the first half of the twenty-first century and, based on projected increases of 40–45 percent in DIN loading by 2050, the risk of coastal eutrophication will increase in 21 percent of LMEs, most of which are in Africa, South America, South Asia and Oceania. The impacts of continued increases in N loading are likely to be exacerbated by climate-driven increases in ocean temperatures, vertical stratification, rainfall and the flux of atmospheric CO_2 into the ocean (Guinder and Molinero, 2013). Thus, it is likely that the severity and extent of coastal hypoxia, acidification and toxic algal events, will also continue to increase in the absence of aggressive actions to reduce anthropogenic inputs of N and P (Townhill and others, 2018).

Important gaps in our current understanding of the impacts of anthropogenic nutrient inputs on the coastal ocean fall into two broad categories: (i) The lack of data on coastal ecosystems in the southern hemisphere (Altieri and others, 2019; Diaz and others, 2019); and (ii) The need to understand synergies between the impacts of nutrient loading and climate-driven changes in coastal ecosystems (Paerl and others, 2014).

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Chapter 11
Changes in Liquid and Atmospheric Inputs to the Marine Environment from Land (including through Groundwater), Ships and Offshore Installations

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Keynote points

Persistent organic pollutants

- Persistent organic pollutants (POPs) continue to be a global issue, persisting at concentrations likely to cause biological effects.
- POPs are detected in remote locations far from their source of production - this includes the deepest parts of the ocean and the polar regions.
- The number of POPs continues to increase and thus the mixtures to which biota are exposed become more complex, making determination of the likelihood of individual or population effects ever more challenging.

Metals

- There is a critical need to develop and expand coastal metal time series globally.
- Trends in metal concentrations vary regionally, though most show levelling of dissolved metals and a slight increase in higher trophic organisms.

Radioactivity

- There have been no significant nuclear accidents affecting the ocean since the First World Ocean Assessment (WOA I) (United Nations, 2017c).
- Generation of electricity from nuclear power plants continues to increase - by about 5 per cent globally between 2013 and 2018. Improved technology may be reducing discharges of many radionuclides, but those of tritium are probably increasing in line with electricity generation. Tritium is, however, only weakly radioactive.
- Published information on recent discharges of radioactive substances to the ocean from nuclear power plants and nuclear reprocessing plants is not available except for the North-East Atlantic and its adjacent seas. In that area, discharges to the ocean of radioactive substances from nuclear power plants and nuclear reprocessing plants continue to decline.
- On the basis of information available, there is no reason to think that adverse impacts of radioactivity on the ocean have become significantly worse since the situation reported in WOA I.

Pharmaceuticals and personal care products

- Hundreds of pharmaceuticals and personal care products (PPCPs) have been detected in the ocean, including in the Arctic and Antarctic.
- Novel analytical techniques have been developed for non-target analysis of PPCPs and their transformation products in the marine environment.
- A "watch list" of PPCPs should be formulated and implemented into long-term international, national and regional monitoring programmes to serve as a scientific data basis for assessing the status of PPCPs in the ocean.

Shipping

- There is a globally decreasing trend regarding shipping accidents leading to oil spills (over 7 tonnes) and regionally improved surveillance and action capabilities indicate increased awareness leading to fewer spills.
- There is a general knowledge gap on the nature and impact of liquid input from ships and discharge of water from exhaust gas cleaning systems (scrubbers) is an emerging source of metals and PAHs.

Hydrocarbons

- Produced water from oil and gas exploration containing both hydrocarbons and metals are known to impact the marine environment, but knowledge gaps exist on the long-term impact of produced water discharges.
- There is a need for further studies at community and population level to advance the current knowledge on single species toxicity data.
- An increased rate of offshore platform decommissioning poses a challenge for the marine environment.

1. Introduction

Chemical production has continued to increase and change since 2003. The potential geographic impact of the chemical industry continued to change from the Atlantic to the Pacific Ocean, where almost 70 per cent of the industry is expected to operate by 2030, while new products are continually being developed, thus adding to the mixture of chemicals to which biota in the ocean is being exposed.

Different lists of hazardous substances have been identified by international organizations, although there is still no agreed single global list of substances that are of concern. The present Chapter will assess changes, since WOA I, in water and airborne inputs to the marine environment from land (including groundwater), ships and offshore installations. In addition, it builds upon the assessment of the list of hazardous substances used in WOA I, namely, POPs, metals, hydrocarbons and radioactive substances. It includes new information on rare earth elements (REEs), PPCPs and airborne inputs of nitrogen oxides and sulphur oxides that were not included in WOA I.

2. Situation recorded in the First World Ocean Assessment (WOA I)

Chapter 20 of WOA I (United Nations, 2017b) identified the sources, main uses, production and related development, movements and impact of different hazardous substances included in the so-called black or grey lists of substances of concern that had been identified at national level and by international organizations. These lists evolved into a list of “priority substances” based on their toxicity, tendency to bioaccumulate and persistence in the ocean. Therefore, the hazardous substances included in WOA I were selected based on those where action was taken in all or some parts of the world ocean and included: metals (mercury, lead, cadmium), organometallic compounds (tributyltin), POPs (for example, halogenated hydrocarbons), polycyclic aromatic hydrocarbons (PAHs) and radioactive substances. Other substances, including pharmaceutical compounds (both human and veterinary) and cosmetic ingredients (e.g. musk xylene), identified as emerging contaminants of concern are included in the present evaluation. Land-based point sources (wastewater treatment plants (WWTPs) or industrial plants discharging into the ocean directly or via rivers), diffuse sources (run-off from land, seepage of ground water directly to the ocean, accidental land-based or sea-based emissions of discharges) and atmospheric deposition (wet and dry deposition and emissions from sewage and from several industrial processes) that can reach and affect the ocean and their impact in several areas were identified.

The international commitment at the United Nations, and the obligation at the regional level, to take measures to reduce the impact of recognized emerging substances was also highlighted. From the data available at that time, it was difficult to make meaningful comparisons between areas and set priorities, not least because the data on hazardous substances in water, biota or sediments were expressed in different units. Methodological differences further complicated the picture, and the need to control sampling procedures and analytical methods was highlighted. For this reason, no detailed figures on concentrations of contaminants were included in WOA I. The selected hazardous substances were found in all parts of the ocean and those from waterborne origins were concentrated in coastal areas, whereas contaminants were transported much further out to the ocean. WOA I was not able to develop a general assessment of the relative impacts of those hazardous substances but was able to identify the slow progress made to reduce concentrations in some parts of the world ocean. It also pointed out that there was increasing evidence of the significance of airborne inputs of metals and other hazardous substances to the ocean.

3. Persistent organic pollutants (including run-off from the use of agricultural pesticides)

3.1. Introduction

Persistent organic pollutants (POPs) represent a complex group of (often halogenated) substances and, as their name suggests, endure in the environment. Although the production of compounds such as polychlorinated biphenyls (PCBs) is no longer allowed under the Stockholm Convention on Persistent Organic Pollutants,[169] the convention allows for equipment containing PCBs to continue to be used until 2025, thereby providing for a possible small, but new, source of PCBs. Movement through trophic levels and environmental recirculation of PCBs means that they continue to be present in marine systems at concentrations likely to affect marine biota. As other halogenated hydrocarbons have been developed, these have added to the mixture of POPs to which marine biota are exposed. The mixtures, and their respective components, have very different physicochemical characteristics. The consequence of this is that they exhibit different distributions in environmental compartments, distribution equilibria and analytical requirements.

[169] United Nations, *Treaty Series*, vol. 2256, No. 40214.

Once in the environment, POPs recirculate and, through both atmospheric transport and transport by ocean currents, are translocated to locations far from their source. It is for this reason that POPs remain of concern in both the Arctic and Antarctic, as well as throughout the ocean.

3.2. Situation recorded in the First World Ocean Assessment (WOA I)

New substances are constantly being developed, and international organizations have prepared lists of chemicals presenting hazardous characteristics, including organohalogens and pesticides/biocides. Many of these are covered under the Stockholm Convention but others are not. Knowledge of the extent of the presence of these hazardous substances in the marine environment was patchy. The main observations in WOA I were:

- POPs are a global issue, however, concentrations in the open ocean were generally low, but detectable, with polybrominated diphenyl ethers (PBDEs) identified in tissues.
- Concentrations of POPs are often associated with urbanization and densely populated regions, such as densely populated coastal areas around the Mediterranean, in Africa, South America and the South Pacific, where there was also significant industrial activity.
- Some coastal areas were being impacted by pesticides.
- POPs were found in the Arctic and concentrations, although decreasing, were likely to cause biological effects in some seabirds and polar bears.
- Biological effects of POPs were likely to be detected in coastal areas of the North-East Atlantic.
- Concentrations of POPs in the North-West Atlantic and North-East Pacific were quite low, with a decreasing trend in concentration.
- A reduction in the concentrations of POPs was observed, but these tended to be localized.
- POPs were measurably present in most coastal areas of the East Asian Seas.
- An area of concern was the exposure of the Great Barrier Reef to pesticides associated with intensive agriculture along the north-east coast of Australia.
- There was a dominance of comprehensive studies or time series in the northern Atlantic/Arctic/Baltic/northern Mediterranean areas.

3.3. Description of the environmental changes (between 2010 and 2020)

POPs continue to be a cause for concern in the marine environment, especially in top predators such as cetaceans which have been found to have mean blubber PCB concentrations likely to cause population declines and supress population recovery (Jepson and others, 2016).. In addition to the "legacy POPs", new POPs that represent a threat to the marine environment, including pesticides, industrial chemicals and by-products, have been regularly added to the Stockholm Convention (Stockholm Convention, 2018).[170]

Many studies continue to focus on the legacy chemicals, including PCBs and

[170] Twelve POPs, namely aldrin, chlordane, dichlorodiphenyltrichloroethane (DDT), dieldrin, endrin, heptachlor, hexachlorobenzene, mirex, toxaphene, polychlorinated biphenyls (PCBs) hexachlorobenzene; polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofurans (PCDD/PCDF) are recognized as causing adverse effects.

dichlorodiphenyltrichloroethane (DDT) (and its metabolites DDD and DDE). PBDEs, were not, however, among the initial 12 POPs covered by the Stockholm Convention and are still grouped with the emerging contaminants, despite being monitored in marine systems for many years. PBDEs are among the 16 "new" POPs to have been incorporated in the convention since 2009. They include pentachlorobenzene, polychlorinated naphthalenes, short-chain chlorinated paraffins (SCCPs), perfluorooctane sulfonic acid (PFOS), its salts and perfluorooctane sulfonyl fluoride (PFOSF).[171] Chemicals recommended for listing include dicofol and pentadecafluorooctanoic acid (PFOA, perfluorooctanoic acid), its salts and PFOA-related compounds. Chemicals under review by the POPs Review Committee[172] are perfluorohexane sulfonic acid (PFHxS), its salts and PFHxS-related compounds. The inclusion of additional chlorinated molecules, as well as both brominated and fluorinated compounds, means that the breadth of contaminants covered by the term "POPs" has greatly increased, resulting in new challenges for environmental analytical laboratories. Short-chain chlorinated paraffins were detected in the Firth of Clyde but the concentrations were method specific (Hussy and others, 2012). This was most likely due to the presence of significant concentrations of medium- and long-chain chlorinated paraffins.

In the recent draft report on progress towards the elimination of PCBs (Stockholm Convention, 2018), it was highlighted that, for many countries, little, if any, relevant quantitative information was available. Extensive analytical work continues to be undertaken in some regions of the world, and shows evidence of high concentrations of PCBs in some top predators with the possibility of population consequences (Desforges, and others, 2018) or altered adipose function in seal pups (Robinson, and others, 2018). Both these examples come from the North-East Atlantic. Recent data for the Arctic, based on long-term time series of PCBs in marine mammals and fish, show that concentrations are generally decreasing (Carlsson and others, 2018), although the rate of decrease has slowed in recent years (AMAP, 2016; Boitsov and others, 2019). Hexachlorobenzene (HCB) in fish liver decreased less with time compared with PCBs, sumDDT, TNCs and PBDEs (Boitsov and others, 2019). Exceptions exist, however, which are associated with changes in diet or change in environmental processes that impact run-off and re-emissions (AMAP, 2016). For example, significant increasing trends for the concentration of a group of 10 PCBs have been observed in blue mussels from Iceland and juvenile polar bears from the east of Greenland and for two blue mussel time series from Iceland (AMAP 2016).

There is some evidence that the presence of POPs, such as PCBs, peaked in ocean water in the 1970s has been declining since (Wagner and others, 2019). In line with declining atmospheric concentrations, the Arctic Ocean has started to export these legacy POPs back into the atmosphere and via currents into the Atlantic Ocean (Ma and others, 2018).

The concentration of PCBs in fish and shellfish in the North-East Atlantic has decreased, although local problems continue. Of the 7 PCBs identified by the International Council for the Exploration of the Sea (ICES),[173] only PCB118 is found at a concentration in fish and shellfish likely to cause biological effects (OSPAR, 2017b). The other 6 PCBs are generally above Background Assessment Concentrations (BAC) although in 4 of the 11 OSPAR contaminant assessment areas, PCB28 is at the BAC level. Furthermore, in 9 of 10 contaminant assessment areas where a temporal trend could be determined, the trend is

[171] See http://chm.pops.int/TheConvention/ThePOPs/TheNewPOPs/tabid/2511/Default.aspx (Accessed 18 June 2019).

[172] The Persistent Organic Pollutants Review Committee (POPRC) is a subsidiary body under the Stockholm Convention established for reviewing chemicals proposed for listing in the annexes to the Convention.

[173] PCB28, PCB52, PCB101, PCB118, PCB138, PCB153 and PCB180.

downward. A similar state was described for PBDEs in fish, mussels and oysters in the majority of assessment areas of the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR),[174] with declining concentrations being noted in all but the Skagerrak and Kattegat, where no change in concentration has been observed (OSPAR, 2017b).

PCBs were detected in fish from depths between 600 and 1,800 metres on the European continental slope to the west of Scotland (Webster and others, 2014). Concentrations of the ICES 7 PCBs in the liver of three fish species were highly variable, ranging from 58.7 ng/g lipid weight in black scabbard to 3,587 ng/g lipid weight in roundnose grenadier. Concentrations were mainly <500 ng/g lipid weight (or <1,250 ng/g lipid weight for the sum of 28 PCBs), a value used by some researchers as an indicator of concern. Twenty-three of the 95 fish livers collected between 2009 and 2012, inclusive, gave PCB concentrations for the ICES 7 PCBs of >500 ng/g lipid weight. PCB118 was at a concentration at which biological effects are likely to be observed for all three fish species. Although there were species differences with respect to concentration, there were no temporal trends between 2006–2012, nor were there any differences detected with depth. Concentrations of PCBs were also examined in prey species and were significantly lower (including lanternfish and bean's bigscale) compared to predators. PBDEs were also detected in the predators, but at much lower concentrations than the PCBs.

PCBs mean concentrations in sediments in the Greater North Sea and the Celtic Seas are generally significantly above the congener's BAC, but below the Environmental Assessment Criteria (EAC) (OSPAR, 2017b). Sediments in both the northern North Sea and the Irish Sea were found to contain PBDEs, although most of the measured concentrations of PBDEs in sediments are low and often below detection levels. However, the lack of assessment criteria for PBDEs in sediments means that it is not possible to determine the environmental significance of the observed PBDE concentrations (OSPAR, 2017b).

Inputs of hazardous substances to the Baltic Sea are defined, on the basis of the Baltic Sea Impact Index (HELCOM, 2018a), as the second most widely distributed pressure (HELCOM, 2018a, 2018b). In terms of POPs, PCBs dioxins and furans do not appear to be a major driver of the integrated assessment status 2011–2016. Atmospheric deposition of PCBs and polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) shows a steady decrease due to increased efficiency of various combustion and chlorination processes (HELCOM, 2018b). Hexachlorocyclohexane (γ-HCH, lindane), and DDT and its metabolites (DDD, DDE) are no longer considered of significant concern in the Baltic. The improved breeding success in the white-tailed sea eagle is attributed to such reductions (HELCOM Indicators, 2018c). However, elevated concentrations of PBDEs in fish is a major contributor to the current impeded overall status of the Baltic Sea. Similarly, undue inputs of PCBs contaminating the food web in the Lagos Lagoon in Nigeria had been reported from activities on land (Alo and others, 2014).

Even if the PCDD/Fs deposition on the Baltic Sea is reducing, atmospheric deposition has been found to be the major external source and there is still noticeable elevated deposition in coastal areas of the North-East Atlantic, and the Baltic, Mediterranean and Caspian seas (Wiberg and others, 2013). The atmospheric deposition of PCDD/Fs and HCB is quite high in coastal areas to the North-East Atlantic, and the Baltic, Mediterranean and Caspian seas, although there has been no intentional global production of HCB for decades (e.g. Wang and

[174] United Nations, *Treaty Series*, vol. 2354, No. 42279.

others, 2010) and emissions of PCDD/Fs are supposed to cease in 2018 (Josefsson and Apler, 2019).

It is clear that various POPs continue to be present in the atmosphere (Figure 1), with a hotspot for PCB-153 over Western Europe (Figure 1b). High atmospheric concentrations of PCDD/Fs have also been detected over Europe (Figure 1a).

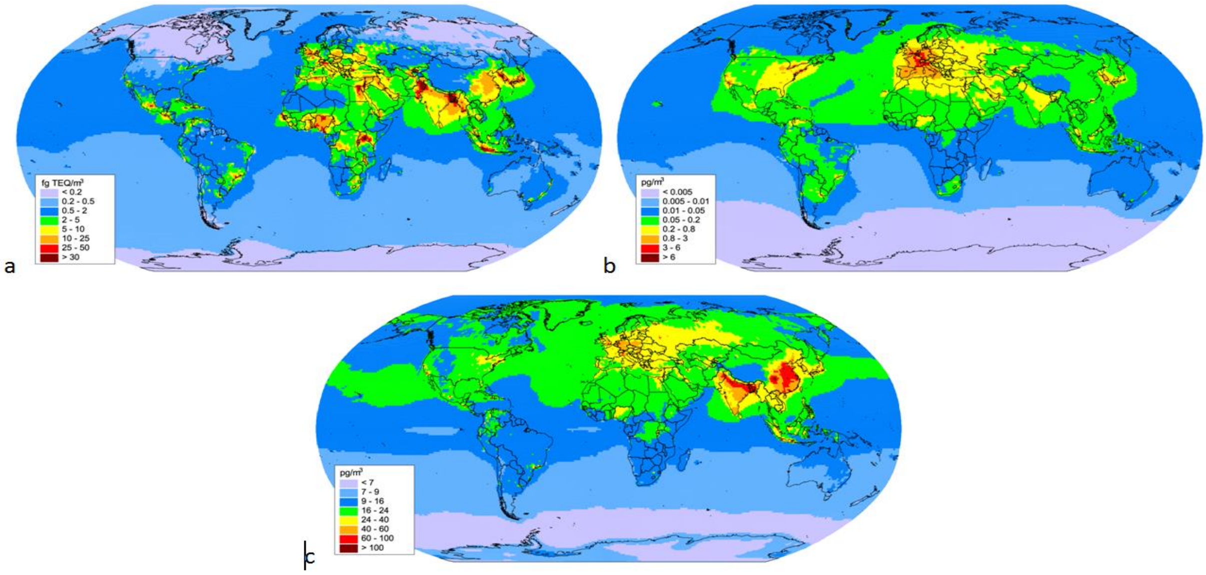

Figure 1. Spatial distribution of global scale annual mean air concentrations of a) PCDD/Fs (fg TEQ/m^3), b) PCB-153, pg/m^3, and c) HCB (pg/m^3) simulated for 2016. Source: European Monitoring and Evaluation Programme (EMEP) homepage, 3 March 2019.

PBDEs have been used as flame retardants for many years and have become widespread across marine systems. As with other POP mixtures (e.g. PCBs), concentrations are based on a small number of the possible congeners. The lipophilic nature of PBDEs means that they, in the same way as PCBs, can be trapped in sediments. A review of PBDE concentrations on a worldwide basis the samples were collected prior to 2010 concluded that, in more open ocean sediments, concentrations do not vary that much and are approximately 1 ng/g (Zhang and others, 2016). This contrasts with close to source sediment concentration which was in excess of 7,000 ng/g. However, PBDEs were detected in amphipods from both the Mariana and Kermadec Trenches, with the deepest sample collected at 10,250 m. The concentration for the sum of seven congeners ranged from 9.33 ng/g lipid weight to 318.71 ng/g lipid weight. PCBs were also detected in these samples with concentrations, again for the sum of seven congeners, ranging from 62.02 ng/g lipid weight to 1,866.25 ng/g lipid weight (Jamieson and others, 2017). Although there is a scarcity of POPs data from the open ocean, the data available strongly indicate that these chemicals continue to be universally present in marine components far from their source. Concentrations of PBDE47 and PBDE99 in water to the west of Los Angeles were found to be in excess of 12,500 pg/l in 2012. In subsequent water samples, collected from progressively more westerly sites (towards Honolulu), concentrations were very much lower (< 20 pg/l) but PBDEs were evident at all sites (Sun, 2015). Further studies show the presence of organophosphate flame retardants (OPFRs) and PBDEs in the atmosphere, sediments, surface and deeper waters of the Arctic and North Atlantic Ocean (Li and others, 2017; Ma and others, 2017; McDonough and others, 2018) At present, atmospheric transport is presumed to be dominating over other modes of long-range transport for OPFRs and PBDEs (Sühring and others, 2016; Vorkamp and others, 2019). Therefore, monitoring of these compounds needs to continue.

Fish from around the South China Sea were found to contain PBDEs, PCBs and DDTs, but concentrations in muscle (PBDEs, sum of 8 congeners, and PCBs, sum of 19 congeners, < 200 ng/g lipid weight) were at the lower end of the global range and related to feeding habits amongst the various fish species (Sun and others, 2014). Staying in the South China Sea, more recent data from a range of species (xanthid crab, whiparm octopus, striated cone, bower's parrotfish, bigeye scad and pike conger) from the Xuande Atoll illustrated that PCBs, PBDEs and DDTs occur in these various components of that marine ecosystem; the PCB (17 congeners) concentrations ranged from 8.8 ng/g lipid weight in the whiparm octopus to 117.9 ng/g lipid weight in pike conger (Sun and others, 2017).

Sediments from the Bering Sea via the Bering Strait, Chukchi Sea, Canada Basin and Amundsen Basin to the Iceland Stations (central Arctic Ocean) contained organochlorine pesticides, PCBs and PBDEs. In depths below 500 m, the top 5 cm of sediments contained 286 ± 265 pg/g d.w. PCBs (47 congeners). This was greater than concentrations from deeper sediments (149 ± 102 pg/g d.w.). There is also some evidence of increasing sediment concentrations of HCB, at least in the Baltic Sea (Josefsson, 2018), while in some environmental compartments in China there is minimal change in the concentrations of HCB detected in the blubber of finless porpoises from the South China Sea. There were minimal differences between 1990, when the range of concentrations for HCB was 140–230 ng/g lipid weight, and 2000/2001 when the range was 87– 250 ng/g lipid weight (Wang and others, 2010). The lack of reducing or even increasing HCB levels might be due to unintentional production as a by-product in various combustion and chlorination processes (Josefsson and Apler, 2019).

There is no doubt that, in addition to widespread contamination of the marine environment by POPs, there are localized hotspots associated with urban proliferation and industrial establishments. A complex mix of POPs has been discharged into the Lagos lagoon on a daily basis. As well as direct discharges, sawdust and other inland domestic waste are ready sources of contaminants. POPs of interest were organochlorine pesticides (OCs) since, in Nigeria and other developing countries, OCs, including DDT and lindane, are still used for pest control and as insecticides.

The Mediterranean Sea has also been described as a hotspot area for POPs (Marsili and others, 2018 and references within Table 7.1). The mean concentrations of PCBs in blubber from bottlenose dolphins in the Gulf of Ambracia in 2013 were low (26,770 ng/g lipid weight; Gonzalvo and others, 2016) relative to the mean for the same species from the North Adriatic Sea in 2011 (110,460 ng/g lipid weight; Jepson and others, 2016). However, the mean concentration for the North Adriatic Sea was ~40,000 ng/g lipid weight higher than the mean obtained for bottlenose dolphins from Scotland that had been sampled over the period 2004–2012. Values for the Gulf of Mexico (Texas), Hawaii and Reunion Island were 47,700 (Balmer et al. (2015), 11,800 (Bachman and others, 2014) and 5,200 (Dirtu and others, 2016) ng/g lipid weight, respectively, with the animals all sampled around 2009–2012. Mean sperm whale blubber PCB concentration in animals from the Corso-Ligurian Basin of the Mediterranean between 2006–2013, was 24,240 ng/g lipid weight and 16,880 g/g lipid weight for males and females, respectively (Marsili and others, 2018, Table 7.2 and references within; Pinzone and others, 2015). This was not as high as in the Ligurian Sea/Gulf of Lion (107,810 ng/g lipid weight; Praca and others, 2011) sampled between 2006–2009, but was very much greater than the means obtained from the Galapagos (1,320 ng/g lipid weight) and Papua New Guinea (1,140 ng/g lipid weight) in 2000 and 2001, respectively (Godard-Coding and others, 2011)

Although decreasing, the change in concentration of dieldrin in Arctic biota is slow, which is consistent with the air observations, where the change was very small over the period between 1993 and 2016. Chlordane compounds were also shown to be decreasing in concentration in Arctic biota (AMAP, 2016). The story for other “legacy” POPs ((e.g. α-HCH, β-HCH and γ-HCH, PCBs) tends to be similar for Arctic biota.

As highlighted earlier, there are a range of fluorinated compounds that are of increasing interest. At coastal sites in the eastern North Sea, concentrations of 3.8 ng/l were observed for PFOA, and 1.8 ng/l for PFOS. These reduced further, to 0.13 ng/l and 0.09 ng/l for PFOA and PFOS, respectively, towards the open sea (Theobald, and others, 2011). Perfluorinated compounds (PFCs) have been found in seabirds in the Baltic (Rubarth and others, 2011), fish caught around Charleston, South Carolina (Fair and others, 2019), a range of seafood in the Republic of Korea (Jeong, and others, 2019), the marine food web of the Arctic (Butt, and others, 2010), as well as in biota from the Antarctic. This illustrates that these POPs are as ubiquitous in the global environment as the original 12 POPs detailed in the Stockholm Convention.[169]

The presence of per- and polyfluorinated alkyl substances (PFASs) was documented in the Arctic and global ocean over the last decade (Ahrens and others, 2010; Benskin and others, 2012; Yeung and others, 2017). The phase-out of PFOA and PFOS from production in the United States of America and Europe will result in declining concentrations in the surface ocean (Zhang, and others, 2017) while replacement PFAS are likely to increase. Observed high concentrations of PFOS in the South Atlantic could be due to the use of a precursor chemical as a pesticide in Brazil (González-Gaya and others, 2014).

The ultimate challenge remains insofar as human ingenuity has resulted in the production of a wide range of halogenated hydrocarbons which have had significant benefit to humankind but have been identified in the abiotic and biotic environment at a global scale. The full impact of these compounds on marine biota, especially when there is biomagnification, remains unclear, particularly as monitoring programmes tend to focus on a sub-set of compounds rather than the full spectrum of fluorinated, chlorinated and brominated compounds that are known to be present in the marine environment and which contribute to the total contaminant loading of individual animals. A detailed study of each sub-group is necessary due to the toxicity and bioavailability of each compound.

3.4. Economic and social consequences and/or other economic or social changes

Highly toxic compounds, such as gamma-HCH and p,p'-DDT, pose potentially unacceptable risks to aquatic organisms. More widely, there are risks to animals at the pinnacle of the food web, including humans. The pesticide residues gamma-HCH and p,p'-DDE were shown to be the most persistent of all the POPs assessed and extrapolated for the Gulf of Guinea. Gamma-HCH was also found to have high potential for long-range transport. The fact that such compounds can exert dioxin-like toxicity on lagoon biota is an indication of likely health risks to biota and to humans (Rose and others, 2017).

As the climate changes on a global basis, marine plants and animals will be subjected to additional stress from increasing temperatures and ocean deoxygenation. A reduction in pH has the potential to cause further stress. The marine plants and animals that are already experiencing some form of stress due to their contaminant loading may be more vulnerable. Research is required to provide an understanding of the implications of multiple stressors, not only from the perspective of biodiversity, but also in the context of the shellfish and finfish industries, should there be population-level impacts.

POP concentrations alone could cause adverse biological effects which might impact beyond the level of the individual marine plant or animal. Localized population effects, or where contaminant concentrations exceed compliance concentrations, have the potential to impact local industries. In 2018, the European Food Safety Authority Panel on Contaminants in the Food Chain reduced the tolerable weekly intake for dioxins and dioxin-like PCBs in food to 2 pg/kg body weight, a figure that is seven times lower than the previous European Union tolerable intake.[175] This compares with the long-standing World health Organisation (WHO) tolerable daily intake (TDI) for dioxin-like PCBs of 1–4 pg Toxic Equivalency/kg body weight. UNEP, who provide the secretariat for the PCB Elimination Network have recently published a report (UNEP, UNITAR, (2018) detailing the progress with respect to meeting the elimination deadline of 2028 as set out in the Stockholm Convention. Parties are not currently on track to achieve the 2028 goal. The consequence of this is that we need to continue to follow POP concentrations. This is to both understand the impact of an increasingly complex mixture of anthropogenic chemicals on our marine systems and to assess the concentrations in seafood. Fish and shellfish provide a valuable and nutritious source of protein which must be safe to eat. This requires that emissions, discharges and losses of POPs are reduced and that concentrations in marine biota decline.

4. Metals

4.1. Introduction

Metals continue to be transported at elevated concentrations around the globe, with the potential to affect human life and the environment even in remote locations. Although metals occur naturally and are released into the environment from natural sources, anthropogenic emissions make important contributions to metal fluxes and even dominate fluxes for a number of metals. Highly toxic metals such as mercury, cadmium and lead along with tributyltin (TBT) assessed in WOA I and rare earth elements (REEs) are included in the present Chapter.

4.2. Situation recorded in the First World Ocean Assessment (WOA I)

In WOA I, sources, main uses, production and impact of metals (mercury, cadmium and lead) and TBT, an endocrine disruptor compound, were discussed but, due to the different analytical methods used and data was expressed in different units, the comparison was cumbersome.

The main sectors contributing to mercury emissions to the air were found to be combustion plants, mainly burning coal, and artisanal, small-scale gold mining. The share of these sources was estimated by the United Nations Environment Programme (UNEP) to be approximately 50 per cent of total anthropogenic mercury emissions, based on 2010 data (UNEP, 2019).

[175] See https://www.efsa.europa.eu/en/press/news/dioxins-and-related-pcbs-tolerable-intake-level-updated (accessed on 23 December 2019).

4.3. Description of the environmental changes (between 2010 and 2020)

Observations of metal concentrations in the global ocean have improved over the past ten years, primarily due to integrated efforts such as the international GEOTRACES programme. Coastal observations and assessments of trends are lacking for most regions, with the exception of HELCOM,[176] OSPAR[177] and AMAP[178] regions, and are thus focused on the European coasts and North Atlantic and Arctic regions. The currently established trends vary across regions and for the different metals. Generally, there appears a levelling off in water column concentrations in the cases of lead and cadmium. However, mercury concentrations in fish and other biota appear to be increasing in the Arctic regions. Efforts to address the lack of time series data in key regions, including the South Atlantic and South Pacific, should be prioritized, particularly in the midst of changing global temperatures and increased projected mobility of metals. This is of particular importance in regions of decreasing permafrost that will mobilize metals and increase exposure across food chains. Global fish catch[179] shows that all regions yield at least some higher trophic level species that exceed recommended levels and, therefore, all ocean regions are impacted. In summary, cadmium, mercury and lead can still be found at concentrations in biota above background levels, with both temporal and spatial differences. Top predators continue to be under pressure, with metal concentrations as a contributing factor.

According to the World Mineral Statistics Archive (Brown and others, 2019), the annual world production of cadmium has been fairly constant at about 21,000–26,000 tonnes over the last decade, although production was at the higher end from 2014–2017. The mine production of lead has decreased almost ten per cent since the peak production of 5,300, 000 tonnes per year in 2013–2014. The production of refined lead has been fairly constant at around 11,000,000 tonnes during the same period. China alone is responsible for about half the annual lead production. Annual mercury production doubled from 2010–2012 and reached 4,000,000 tonnes in 2017 (WMS). Also, during this period, the main producer, China, increased its share from about 75 to almost 90 per cent.

Presently, based on 2015 data, UNEP estimates that stationary combustion of coal and artisanal gold mining are responsible for 60 per cent of total anthropogenic atmospheric mercury emissions (UNEP, 2019). However, it is not clear if the difference compared to 2010 is based on improved information or actual changes in emissions from these sectors. Overall, total anthropogenic emissions constitute about 30 per cent of the total mercury emissions to the air, whereas natural processes like evaporation of mercury previously deposited to soils and water are estimated to constitute 60 per cent, with the final 10 per cent from natural emissions from volcanoes (UNEP, 2019).

The global spatial distribution of mercury emissions to the air and atmospheric deposition reveals large hotspots in eastern and southern Asia, Central Africa, South America, as well as Central America and south-eastern North America (figure 2). Sub-continental contributions to the global inventory in 2015 are very similar to those of 2010.

[176] Baltic Marine Environment Protection Commission.
[177] Convention for the Protection of the Marine Environment of the North-East Atlantic.
[178] Arctic Monitoring and Assessment Programme.
[179] See http://www.fao.org/state-of-fisheries-aquaculture.

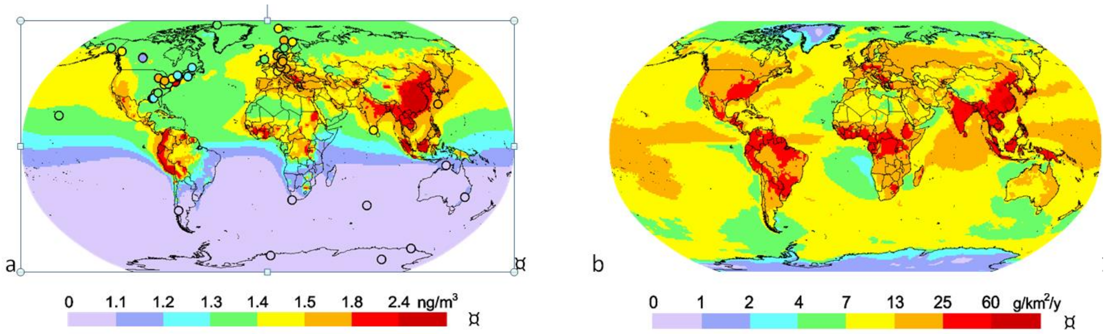

Figure 2. Global distribution of model ensemble median Hg^0 concentration in surface air (a) total (wet and dry) deposition flux (b) in 2015. Source: EMEP homepage, 3 March 2019, and UNEP (2019).

4.4. Key region-specific changes and consequences

4.4.1. Arctic Ocean

The Arctic is changing rapidly and is the subject of increased research and monitoring efforts. Permafrost thawing is projected to increase the transfer of terrestrial mercury and other metals to Arctic coastal environments (Fisher and others, 2012). Metals do not disappear over time but can be trapped in sediments. However, data on metals in sediments in the Arctic are limited. The mean cadmium concentration in biota from the Barents Sea (north-west coast of Norway) was above the OSPAR background assessment concentrations (BAC) but significantly below the European Commission maximum level for food (OSPAR, 2017d). The mean concentrations for both mercury and lead were at the BAC. None of the metals showed upward trends in concentrations in the water column.

A review of mercury in the marine environment of the Canadian Arctic has shown that our understanding of the biogeochemical cycling of this metal has improved but needs further characterization. Total mercury concentration in sediments from the Hudson Bay are lower (8 – 58 ng/g d.w.) than in other marine regions of the circumpolar Arctic Ocean (e.g. up to approximately 290 ng g^{-1} d.w., Greenland Coast, 2000) (Fisher and others, 2012).

The mercury reservoir in permafrost is poorly quantified, and surface soils in the Arctic likely contain some portion of legacy mercury. Current estimates of riverine mercury export to the coastal Arctic stem from limited data and models and vary widely, ranging

from 13–80 Mg/y (Dastoor and Dunford, 2014), while mercury export through coastal erosion is estimated at 15–30 Mg/y (Soerensen and others, 2016). Riverine mercury concentrations can increase up to six-fold in coastal areas following scenarios projecting up to 30 per cent increased terrestrial run-off (Jonsson and others, 2017). Riverine transport also exports a significant amount of toxic mercury, i.e. methylmercury. Present flux estimates cannot close the mercury budget in the Arctic, and thus hypothesized major mercury processing occurs in coastal zones with evasion of gaseous mercury species to the atmosphere (Heimbürger and others, 2015).

There remains significant spatial variation in the total mercury concentration in Arctic biota, including with respect to marine mammals and birds. In the latter (thick-billed murres), the total mercury concentration increased in birds breeding at a higher latitude. There was an increase in total mercury concentrations in the eggs of seabirds (various species) over the period 1975–2012. The reasons for this remain unclear but are likely to be multifactorial.

Greenland sharks have been found to contain high total mercury concentrations in their muscle (1.62 ± 0.52 μ/μg w.w.). This is consistent with their high trophic position in the Arctic marine food web.

The fourth Global Mercury Assessment (2018) joint venture between UNEP and AMAP highlights that:

- Loss of sea ice in the Arctic due to climate change allows greater exchange of mercury between the ocean and atmosphere.
- Coastal Arctic sites in Norway have slightly elevated levels of atmospheric mercury compared to those in Greenland. This is associated with direct transportation from continental Europe, especially during winter and spring.
- The Arctic is predominantly influenced by long-range transport of atmospheric mercury.
- Dry deposition of mercury may be important in inland Arctic tundra.
- The deposition of mercury to the Arctic will not diminish by 2035 under current policies.
- The impacts of climate change on marine ecosystems in the Arctic are occurring rapidly. This amplifies its significance for a global understanding of mercury trends.
- Arctic birds tend to be at moderate or low risk with respect to mercury.
- Some Arctic marine mammals are in a high-risk category as a result of uptake of methylmercury through their diet, with the mercury concentration in the muscle of pilot whales at the higher end of the concentration spectrum for toothed whales.
- Mercury in ringed seals from the North American Arctic has increased.
- Changes in mercury concentration in marine mammals and seabirds are a result of changes in feeding patterns, in environmental conditions and climate change. This means that the reasons for the observed changes in mercury concentration in marine mammals and seabirds are not necessarily identifiable.
- The consumption of fish and marine mammals by Arctic people continues to put them at high risk from mercury. However, exposures have dropped over the last two decades.

In summary, cadmium, mercury and lead can still be found at concentrations in biota above background levels, with both temporal and spatial differences. Top predators continue to be under pressure, with heavy metal concentrations as a contributing factor.

4.4.2. North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean and North Sea

North Atlantic (including the OSPAR maritime area)

The Greater North Sea is the only OSPAR sea area that has sufficient waterborne metal input data to be used in an assessment. Mercury inputs via continental run-off have approximately halved between 1990–1995 and 2010–2014 (and atmospheric inputs have been reduced by approximately one-third). Cadmium inputs via the atmosphere and run-off have both been reduced by two-thirds. Advances in analytical methods resulting in improved (lowered) detection limits and higher precision mean that, while there is a downward trend in riverine inputs, the change is likely overestimated. However, it will require longer-term observation to establish the significance of this change (OSPAR, 2017a). Lead inputs through continental run-off have more than halved, while atmospheric lead deposition is less than a third of the level it was in 1990. Secondary atmospheric pollution from re-suspended material and from sources outside the OSPAR maritime area are now the major sources of airborne pollution.

Cooperation is needed beyond the OSPAR area to manage these in addition to the waterborne inputs. Analyses of lead isotopes in the tropical North Atlantic show that up to 30–50 per cent of natural lead detected came from North African mineral dust. This indicates successful global efforts to reduce anthropogenic lead emissions (Bridgestock and others, 2016). Concentrations of dissolved lead in surface waters of the Celtic Seas in the North-East Atlantic decreased fourfold over the last four decades to 8 ng/l (Rusiecka and others, 2018), which is still one or two orders of magnitude higher than background concentrations. Atmospheric lead inputs have been reduced, and benthic dissolved lead fluxes (5.6 – 8.5 µg lead /(m^2d) now exceed the atmospheric lead fluxes (0.006 – 2.5 µg lead /(m^2d) in the Celtic Sea, indicating the significance of sediments as a contemporary lead source (Rusiecka and others, 2018).

Mean concentrations of mercury, cadmium and lead in marine sediments are either decreasing or show no significant change in the majority of areas assessed. Nevertheless, concentrations in all areas are above natural background levels, and four of the six areas assessed are above levels where adverse ecological effects cannot be ruled out (OSPAR, 2017c). Following bans on tributyltin (TBT) in antifouling paints there has been a marked improvement in the reproductive condition of marine snails in the North-East Atlantic over the assessment period 2010–2015. Compared to an assessment in 2010, levels of imposex have markedly improved. In most assessment areas, imposex induced by TBT is at or below the level at which harmful effects are expected to occur and there is also evidence of downward temporal trends in the severity of imposex in all areas assessed. Nevertheless, some areas are still subject to high imposex levels. Although levels of imposex are reducing, imposex remain above background levels in all of the areas assessed (OSPAR, 2017d).

Following the ban on TBT, mean concentrations in sediments have measurably reduced in the southern part of the Greater North Sea and are very low or undetectable elsewhere in the North-East Atlantic. Most countries in the area have stopped monitoring organotins in sediments, especially at offshore locations, because concentrations are now often so low that they are below the limit of detection. This means that a reliable assessment of organotins in sediments could only be carried out in the southern North Sea (OSPAR, 2017e).

In most areas assessed in WOA I, concentrations of mercury, cadmium and lead in mussels and fish are higher than the estimated BAC evels (Figure 3). Nevertheless, all concentrations are below European Commission (EC) limits for foodstuff. Concentrations are decreasing or show no significant change in all areas assessed except for cadmium in a few Greater North Sea and Irish Sea locations (OSPAR, 2017b). EC maximum levels for metal concentrations in fish and shellfish are at least five times greater than background concentrations. In all OSPAR regions assessed since 2009, the average metal concentrations are below EC maximum levels.

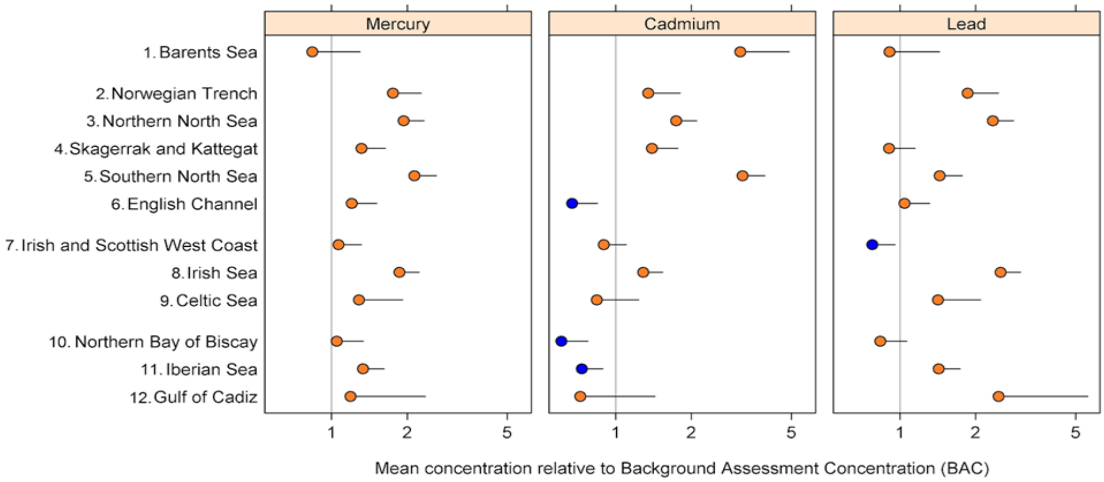

Figure 3. Mean concentrations of mercury, cadmium and lead in fish and shellfish in each assessment area relative to BAC(OSPAR, 2017b. Value of 1 means that the mean concentration equals BAC. Blue: mean concentration statistically significant below BAC and EC maximum levels for food (p <0.05); orange: mean concentration at (if confidence limit crosses 1), or above BAC, but significantly below the EC maximum levels for food. The EC maximum levels are more than five times higher than the BAC and hence not shown.

Baltic Sea

There are quite large differences in the estimated total amounts of metals that enter the Baltic Sea every year, and their main route of entry is quite variable (HELCOM, 2018a). It is estimated that the inputs of cadmium, mercury and lead to the Baltic Sea between 2012–2014 were in the range of 23–45, 4.8–5.6 and 443–565 tonnes per year, respectively (HELCOM, 2018a).

Mercury entering the Baltic Sea via atmospheric deposition constitutes around 70 per cent of the total but levels have decreased by 15 per cent in the period since the 1990s up to 2014.

Mercury concentrations in fish muscle (the most common species measured are herring and cod in open sea areas and flounder and perch in coastal areas) exceeded the established threshold level (20 µg/kg w.w.) in almost all monitored open sea sub-basins, indicating "not good" environmental status during the period 2011–2016 (HELCOM, 2018a). The threshold was also exceeded in some coastal areas and "good" status was achieved only in the Arkona Basin and in Danish and Swedish areas. There is no general trend for mercury in fish muscle for the investigated time series.

Riverine inputs of cadmium are dominant and make up 79 per cent of cadmium inputs to the Baltic Sea. Inputs via rivers with existing time series show quite large inter-annual variability that makes it hard to reveal any trend. Atmospheric cadmium deposition decreased by 60 per cent from the 1990s up to 2014.

For cadmium concentrations in seawater, biota (mussels) and sediments assessed by applying the "one-out-all-out" method, "good" status was achieved in only 35 per cent of open sea sub-basins assessed (HELCOM, 2018a) but no significant trends were observed in 89 per cent of the 38 trends evaluated, while there was a decreasing trend in four of 33 trends and only 1 showed an increasing trend. Threshold concentrations were 0.2 µg/l in water, 960 µg/kg d.w. (137.3 µg/kg w.w.) in mussel tissues and 2.3 mg/kg d.w. in sediments.

Riverine inputs of lead make up 64 per cent of the total input of lead to the Baltic Sea. The lead inputs of the existing time series show quite large inter-annual variability that makes it hard to reveal any tendencies. Atmospheric lead deposition has decreased by 80 per cent since the 1990s up to 2014.

Lead concentrations in biota (fish and mussels) and sediments using the "one-out-all-out" approach indicate that "good" status was achieved only in four open sea sub-basins and in some coastal areas (HELCOM, 2018a). Furthermore, lead generally fails the established threshold value in biota (26 µg kg^{-1} w.w. for fish liver, and 1,300 µg/kg d.w. and 185.9 µg/kg w.w. in mussels). No consistent trend was observed.

In most areas, TBT is still a problem in water, sediments and biota (HELCOM, 2018b). For sediments, most of the sites failed the threshold level (1.6 µg/kg w.w.), and even after two to three years of monitoring no temporal trends could be assessed.

Levels of imposex measured for six or more years were found to be below the threshold value in the southern Kattegat and Skagerrak. In eight other sites, declining effects were observed. This is consistent with the findings in the North Sea area, where 48 per cent of the imposex sites showed decreasing trends.[180]

While the TBT situation is improving, levels of TBT in sediments and causal effects in marine gastropods indicate that historic pollution continues to impact the Baltic Sea. Uses of organotins other than in antifouling paints, and release from previously contaminated sediments, should be investigated to ensure that decreasing trends continue.

Mediterranean Sea

Metal contamination in the Mediterranean is the result of human activities (drivers and pressures) that take place all around the coastal and marine areas of the Mediterranean Sea and cause imbalance to ecosystems from their natural steady-state conditions. Harmful contaminants enter the marine ecosystem through different routes, such as atmospheric deposition or inputs from land- and sea-based sources. In the Mediterranean coast, small recreational marinas up to major commercial ports, have created a number of different pressures in terms of chemical pollution. At present, there are still old threats and new pressures, although the trends and levels of metals, have significantly decreased in most impacted areas after the implementation of environmental measures (e.g. leaded-fuels ban, mercury regulations, anti-fouling paints ban), as observed in the Western Mediterranean Sea (UNEP/MAP/MEDPOL, 2011a) but Mar Menor is still highly affected by metals.

The latest available datasets of contaminants reported to the MED POL Database continue to indicate lower levels of legacy pollutants and contaminants in the biota (mainly bivalves), despite known hotspots, similarly to the previous assessment reports (UNEP/MAP, 2009; UNEP/MAP/MED POL, 2011a; UNEP/MAP, 2012a, 2012b) and temporal trends reports (UNEP/MAP/MED POL, 2011b, 2016b), whilst chemicals show their accumulation and persistence in coastal sediments. The monitored chemical contaminants in bivalves (e.g. mussels, clams), fish and sediments and their assessment against (BACs and ECs and ERLs) also point to this conclusion. For biota (bivalves and fish), the percentage of sites with acceptable environmental conditions (below the EC threshold criteria), range from 92% to

[180] See https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/pressures-humanactivities/contaminants/imposex-gastropods/.

100% for cadmium, lead and total mercury. Only, 8% of sites assessed for lead in mussels were above EC. Therefore, all the MED POL assessed sites for biota show acceptable marine environmental conditions except 8% of them for lead according these criteria. On the contrary, levels in the coastal sediments above the assessment criteria (ca. >ERLs), that is non-acceptable environmental conditions, are 4%, 53% and 15% for cadmium, total mercury and lead, respectively while for mercury was 53% reflecting the need of revised sub-regional assessment criteria, thus a mixture of natural and anthropogenic known sources might influence the assessment, especially in the Adriatic Sea, the Aegean Sea and Levantine Seas. To this regard, a revision of the current assessment criteria is under consideration (UNEP/MAP/MED POL, 2016a) which should further refine these findings in future assessments.
Based on the values EAC recommended for indicative purposes by COP 19 Decision IG. 22/7, overall, assessments reflect non-acceptable environmental conditions, particularly, for lead in mussels in some locations and for lead and total mercury (53% of sites >ERL criteria) in coastal sediments, although some are known Mediterranean Sea hotspots and natural input areas. To guarantee the control and achievement of targets to maintain acceptable conditions for cadmium and total mercury in biota, there is a need for continuous monitoring and assessment.

4.4.3. South Atlantic Ocean and Wider Caribbean

GEOTRACES cruises in the South Atlantic are providing new assessments of dissolved lead inputs. A major flux (0.9 to 1.5 x 10^6 kg/y) to the South Atlantic is the Indian Ocean via the Agulhas Leakage, which supplies waters with elevated lead concentrations (annual mean ca. 5.8 µg/kg) which is equivalent to that provided by global atmospheric mineral dust deposition (1.6 x 10^9 g/y assuming 8 per cent of lead released from dust to seawater) (Paul and others, 2015). Nowadays dissolved Pb concentrations in the South Atlantic remain higher than preindustrial levels, with 58 per cent of the dissolved Pb in these waters originating from anthropogenic sources (Schlosser and others, 2019). It is expected that GEOTRACES data will continue to develop and contribute to the next WOA.

Significant concentrations of aluminium, mercury and copper were found in sediments and fish the Caribbean mainly in Sea Lots and Point Lisas Harbors, Trinidad and Tobago. (Mohammed and others, 2012) and tributyl tin remains a concern.

Phosphorus Mining

Phosphate deposits are found across the world both in sedimentary and igneous minerals. Currently China mines the largest volume of phosphate, but Morocco is the largest exporter but most of the phosphate extraction and processing is far from the sea. Phosphorite mining and processing is a main source of metal input of mercury, cadmium and lead, as well as chromium, nickel, copper, arsenic, thorium and uranium in coastal waters (Gnandi and others, 2011). For example, in Togo, severe sediment, water and biota impact by metals has been documented, though other mining regions likely exhibit similar impacts. The phosphorite deposits of Togo, extracted since 1960 in the phosphate mines at Hahatoé-Kpogamé in southern Togo, are naturally enriched with metals and rare earth elements (Tanouayi and others, 2016). The ore processing allows the separation of the phosphorus rich industrial fraction, and the fraction greater than 1 mm as in sea water once phosphorite tailings are dumped into the ocean. Coastal sediments are highly enriched in trace metals and the calculated enrichment factors relative to the Earth’s crust are high. Such high loads of trace metals were also found in the biota (fish and mussels). The ratio of measured trace metal concentrations in biota to threshold limits set by the World Health Organization herein defined as relative health factor (RHF) was high in fish and decreased according to the following order: selenium> arsenic> silver> nickel> manganese> iron> lead> cadmium> chromium> copper> zinc, while cadmium and aluminium were not accumulated. In mussels, RHF decreased according to the trend: iron> arsenic> lead> selenium> manganese> nickel> silver> cadmium> copper (Gnandi and others, 2011).

4.4.4. Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

Fish continues to be an important food product and the potential for fish to be contaminated with a range of metals remains. In the Persian Gulf, the metals most regularly exceeded maximum allowable levels in fish muscle, but cadmium and mercury concentrations exceeded only by 10 per cent (Cunningham and others, 2019).

Recent studies of a fish off Qatar (Al-Ansari and others, 2017) in the Persian Gulf have helped improved resolution in this region. Total mercury was highest in the liver (602 ± 192 µg/kg w.w.) and lowest in the gonad (71 ± 31 µg/kg w.w.), with muscle falling between the two. There is an increasing trend compared to the levels detected 20 years earlier but the levels were more in line with those reported in 2007. Concentration of mercury in sediments was in the range of 8 µg/kg – 34.3 µg/kg for total mercury (Hassan and others, 2019).

Stable isotope studies showed that in the Indian Ocean and Arabian Sea, lead concentrations have been largely impacted by anthropogenic inputs (Lee and others, 2015). These data serve as a baseline but will require future sampling to establish trends. In the Western Indian Ocean, lead and cadmium levels were below levels of concern, although mercury in higher trophic species (swordfish, wahoo and blue marlin) often surpassed (1 mg/kg w.w.) (Bodin and others, 2017). Over 13 per cent of swordfish sampled in the Indian Ocean had mercury levels that surpassed 1 mg/kg w.w. and in a global catch for comparison mercury levels, Indian Ocean swordfish levels had the most frequent and highest average mercury concentrations (Esposito and others, 2018).

4.4.5. North Pacific Ocean

Inputs from the Asian continent to the East China Sea and North Pacific exhibit large episodic and seasonal pulses related to biomass burning and fossil fuel combustion (Qin and others, 2016). Total mercury levels in the North Pacific deep waters are elevated relative to surface and intermediate waters but comparisons with historical data suggest that concentrations have not increased over the past 20 years (Munson and others, 2015).

4.4.6. South Pacific Ocean

Detailed mercury distribution in the South Pacific showed elevated concentrations in the Peruvian upwelling region and significant methylmercury, as high as 20 per cent of total mercury (Bowman and others, 2016). Data in the region are not adequate to ascertain trends since WOA I but values appear stable. The tropical South Pacific is a net source for mercury to the atmosphere but the exchange flux is lower than that of the North Atlantic (Mason and others, 2017).

4.4.7. Southern Ocean

Total mercury concentrations in the Southern Ocean are comparable to the Southern Pacific and the Atlantic Ocean. However, there are distinct regional features that include net mercury deposition along the ice edge of Antarctica sea ice, mercury enrichment in brine during sea-ice formation and methylmercury formation south of the southern polar front (Cossa and others, 2011). Lead concentrations in water (6.2 µg/L) compare to those measured in more industrialized regions such as the Baltic Sea despite its remote location (Schlosser and others, 2016). Metal data in this region are too sparse to detect any trends since WOA I.

Rare earth elements

The contamination due to “technology-critical elements” that are widely used in cost-effective low carbon technologies, such as nuclear, solar, wind and bioenergy and carbon capture and storage technologies and electricity grids, and in medical products, has been observed since the beginning of the millennium (Bau and Dulski, 1996). Rare earth elements (REEs) have been considered as critical for the development and establishment of high-technology products. As a result of their application, an unavoidable release of these elements into the environment has been recently observed, thus increasing the number of trace elements acting as contaminants in the ocean. One of these elements, gadolinium, is used as a tracer of anthropogenic input by studying positive anomalies (increased values relatively to natural concentrations). The input of these elements to the marine environment has been identified mainly through domestic sewage systems. In the last decade, positive anthropogenic gadolinium anomalies were found in marine waters globally as a result of draining from densely populated areas, such as the North Sea (Northeast Atlantic; Kulaksiz and Bau, 2007), San Francisco Bay and adjacent Pacific waters (Hatje and others, 2014), Indian Ocean (Zhu and others, 2004; Ogata and Terakado, 2006; Akagi and Edanami, 2017) and the South Atlantic (Pedreira and others, 2018). Besides gadolinium, other rare earth elements have been detected in raw phosphorite and mine tailings from phosphate mining at Hahatoé-Kpogamé (southern Togo) (Gnandi and others, 2011). However, scarce information exists on the environmental behaviour of these elements and on their impact on biota in marine systems. Although concentrations of anthropogenic gadolinium are rather low in marine waters, potential concerns regarding the effects on aquatic organisms and human health from continuous exposure to low levels of gadolinium have been arising (Hatje and others, 2018). The anthropogenic gadolinium complexes, originally considered to be safe for humans, have been shown to accumulate in humans and aquatic organisms.

4.5. Economic and social consequences and/or other economic or social changes

Metals of concern here are non-essential trace elements that transfer through the trophic chain, which ultimately bioaccumulate in the upper trophic levels of the oceans. The main social impact is that, despite some decreases in emissions, there are observed increases in metals concentrations in higher trophic level fish species. This has a direct impact on ecosystems, leading to apparent changes in food chains and has a subsequent impact on human health risks (see Chapter 8B of the present Assessment) through ingestion. This is of particular concern for indigenous communities who rely on specific food sources. A second impact is the potential decrease in fish stock and the subsequent hardship of fishers who are constrained to go further from the coast, often with poor equipment, to catch fish. In certain regions, inputs and mining activities lead to regional deterioration that impacts tourism and local economies.

5. Radioactive Substances

5.1. Introduction

The waters, biota and sediments of the ocean all contain radioactivity. Much of this is from natural sources. Since the 1940s, however, there have been significant inputs from human activities. It is important to distinguish between the occurrence of ionizing radiation, emitted through the decay of radionuclides, and the impact of such radiation on biota, which varies according to the nature of the radiation (in particular, whether the radiation is of α (alpha) or β (beta) particles) and the part of the biota concerned. Studies of radioactive impacts on biota have concentrated on humans, but in the period since 2000, the International Commission on Radiation Protection (ICRP), the international body of experts that agrees standards of radiation protection, has developed approaches for considering how to protect non-human biota.

5.2 Situation recorded in the First World Ocean Assessment (WOA I)

WOA I noted the ranges of levels of naturally occurring radioactivity in the ocean, ranging from the lowest levels in the South-West Atlantic to the highest levels in the North-East Atlantic, and levels of a typical anthropogenic radionuclide, ranging from the lowest in the Southern Ocean to the highest in, again, the North-East Atlantic. The most significant anthropogenic input has been from the testing of nuclear weapons, but this is now purely historic. Nuclear reprocessing plants were the second most significant anthropogenic source: such plants existed in 2014 in China, France, India, Japan and the Russian Federation, and further plants were under construction or planned in China, India, Japan and the Russian Federation. The nuclear accidents at Chernobyl and Fukushima resulted in large inputs of radioactive material to the ocean but were of limited concern by 2014; immediately after the accident at Fukushima, increments to the input were limited. At the end of 2013, there were 434 nuclear power reactors in 30 countries, resulting in radioactive discharges to the ocean in orders of magnitude less than those from weapons testing, reprocessing plants and major accidents, and such discharges tend to decrease over time with improved technology, except for discharges of tritium, which have low radiotoxicity. Also noted was an anthropogenic concentration of naturally occurring radionuclides, particularly from scale cleaned from offshore oil and gas pipelines and phosphogypsum.

5.3. Description of the environmental changes (between 2010 and 2020)

General

The WOA I assessment of global levels of natural and anthropogenic radioactivity in the ocean was based on studies carried out in 1995 (MARDOS)[181] and 2005 (WOMARS)[182] by the International Atomic Energy Agency (IAEA). No similar studies have since been undertaken, and the picture given by WOA I thus remains the best available. However, the IAEA is planning new studies of this kind in the early 2020s (IAEA personal communication, 5 July 2019).

For radioisotopes with long half-lives, carriage by ocean currents can be significant, unlike terrestrial radioactive contamination. In the same way as airborne transport of radionuclides, transport by ocean currents means that radioactive substances introduced into the marine environment can be transported to areas thousands of kilometres away from the point of introduction. For example, the ratio of ^{240}Plutonium to ^{239}Plutonium in the Kuroshio current zone in the North-West Pacific provides evidence that these radionuclides are being transported to that zone from the former atomic-bomb and nuclear-bomb Pacific Proving Grounds in Micronesia (Hong and others, 2011; Wu and others, 2019).

Although there have been no global surveys of the level of radioactivity in the ocean, there have been major advances over the last decade in the ability to measure low levels of the long-lived radioisotope ^{129}I (half-life 15.7 million years), a product of nuclear weapons testing and nuclear fuel reprocessing plants. Studies have now revealed its global distribution throughout the ocean and its application as a circulation tracer (He and others, 2013).

In addition, the Scientific Committee on Oceanic Research (SCOR) under the International Council for Science, has instituted the international GEOTRACES programme for determining the distribution of trace elements and their isotopes (TEIs) throughout the ocean. The programme also includes anthropogenic radionuclides. As part of GEOTRACES, intercalibration efforts have demonstrated the ability to identify 239 Pu, 240 Pu and caesium-137 from relatively small samples (Kenna and others 2012). Radioisotope data collected during GEOTRACES have also contributed substantially to understanding of movements of material in the ocean (Malakoff, 2014).

In 2015, SCOR also set up Working Group 146, Radioactivity in the Ocean, 5 decades later (RiO5), reverting to the theme of the first SCOR Working Group in 1959. This working group has been tasked, amongst other things, with improving online resources for data on natural and anthropogenic radioisotopes in the ocean within the framework of the IAEA Marine Radioactivity Information System (MARIS) database, which contains measurements of radioactivity data in the marine environment found in seawater, biota, sediment and suspended matter (SCOR – WG 146, 2020).

Sources of radioactivity in the ocean

Developments with regard to the main sources of radioactive inputs to the ocean since 2014 (the base date for the relevant section of WOA I) have been as follows.

Nuclear weapon testing

The absence of atmospheric tests of nuclear weapons since 1980 has continued, and this

181 Sources of Radioactivity in the Marine Environment and their Relative Contributions to Overall dose Assessment from Marine Radioactivity (MARDOS).

182 Worldwide marine radioactivity studies (WOMARS).

source of radioactivity inputs to the ocean therefore remains purely historic.

Nuclear reprocessing plants

The nuclear reprocessing plants mentioned in WOA I as functioning in 2014 (Gansu, China; Cap de la Hague, France; Kalpakkam, Tarapur and Trombay, India; Tokai, Japan; Mayak, Russian Federation; and Sellafield, United Kingdom of Great Britain and Northern Ireland) remain in operation, but the Tokai plant is being decommissioned.

In respect of the nuclear reprocessing plants at Cap de la Hague and Sellafield, these continue to represent the dominant source of anthropogenic radioactive inputs to the North-East Atlantic, and contributed approximately 90 per cent of the total alpha discharges and approximately 80 per cent of the total beta (excluding tritium) discharges over the period 2007–2013. Nevertheless, there had been substantial reductions by 2016 in average discharges from the reprocessing plants in that period over the average levels in 1995–2001 – a reduction of about 40 per cent in total alpha discharges and about 85 per cent in total beta discharges (OSPAR, 2017b).

In China, planning of a further nuclear reprocessing plant in Gansu is continuing. In India, work started on a nuclear reprocessing plant at Kalpakkam in 2017. In Japan, the nuclear reprocessing plant at Rokkasho is expected to come into operation by October 2022 (JNFL, 2020). In the Russian Federation, a new nuclear reprocessing plant at Zheleznogorsk is expected to be operational as of 2022 (WNA, 2020).

Nuclear power plants

There were 450 commercial nuclear power reactors in 30 countries in operation at the end of 2018 (as compared with 434 in the same 30 countries at the end of 2013). The plants containing them have a total capacity of over 395,000 megawatts (MW). A little over 300,000 MW of this capacity is in countries of the Organization for Economic Cooperation and Development (OECD). About 55 more reactors are under construction. These plants produce over 15 per cent of the world's electricity: the proportion ranges from about 70 per cent of the national supply in France to 2 per cent in the Islamic Republic of Iran (see Table 1). This is a global average increase since 2013 of about 5 per cent. Other States which do not have nuclear power plants, such as Denmark and Italy, import substantial amounts of their electricity from neighbouring States which rely substantially on nuclear power (IAEA, 2019).

Table 1. Proportion of electricity generated from nuclear power 2018 (figures for 2013 in brackets for comparison) (IAEA, 2019)

State	Per cent of electricity from nuclear power	State	Per cent of electricity from nuclear power	State	Per cent of electricity from nuclear power
France	71.7 (73.3)	Bulgaria	34.7 (30.7)	Pakistan	6.8 (4.4)
Slovakia	55.0 (51.7)	Armenia	25.6 (29.2)	Japan	6.2 (1.7)
Ukraine	53.0 (43.6)	Korea, Republic of	23.7 (27.6)	Mexico	5.3 (4.6)
Hungary	50.6 (50.7)	Spain	20.4 (19.7)	South Africa	4.7 (5.7)

Sweden	40.3 (42.7)	United States of America	19.3 (19.4)	Argentina	4.7 (4.4)
Belgium	39.0 (52.1)	Russia	17.9 (17.5)	China	4.2 (2.1)
Switzerland	37.8 (36.4)	United Kingdom	17.8 (18.3)	Netherlands	3.1 (2.8)
Slovenia	35.9 (33.6)	Romania	17.2 (19.8)	India	3.1 (3.5)
Czech Republic	34.5 (35.9)	Canada	14.5 (16.0)	Brazil	2.7 (2.8)
Finland	32.5 (33.3)	Germany	11.8 (15.4)	Iran, Islamic Republic of	2.1 (1.5)

For the nuclear power plants in the catchments of the Baltic and North-East Atlantic, the latest assessments show continuing reductions in the discharges of the various radionuclides which are monitored (other than tritium) (HELCOM, 2013; OSPAR, 2017b).

Detailed figures are not available for discharges in other global regions: the IAEA DIRATA database on discharges of radionuclides to the atmosphere and the aquatic environment (information provided by national authorities on a voluntary basis) has not been updated since 2012, and much of the data in it are substantially older than that. As recorded in WOA I, tritium discharges from nuclear power plants are generally related to the level of electricity generation, and there is no accepted abatement technology.

Non-nuclear sources of radioactive discharges to the ocean

A number of human activities other than nuclear installations result in discharges to the ocean both of naturally occurring radioactive material (NORM) and of artificial radionuclides produced other than for nuclear-energy purposes. The main activities of this kind are offshore hydrocarbon installations and pipelines, nuclear medicine and the production of agricultural fertilizer from phosphate rock. Except for the North-East Atlantic and its adjacent seas, published data on such discharges are not available.

The collection of information on discharges of NORM and other non-nuclear discharges to the North-East Atlantic and its adjacent seas started in 2005. For the oil and gas industry, there is enough data to set a baseline (2005–2011) but it is not possible yet to identify trends in such discharges to the marine environment (OSPAR, 2017b). Recent studies by the OSPAR Commission conclude that the major source of NORM reaching the North-East Atlantic is the offshore oil and gas industry, where produced water (water coming from the reservoir with the oil and gas) and the scale that it deposits in pipelines (which has to be cleared periodically) contain low levels of radionuclides (mainly ^{210}Pb, ^{210}Po, and $^{226/8}$Ra). The total alpha and total beta discharges from the oil and gas sector are 97 per cent and 10 per cent of the discharges from all sectors, respectively (OSPAR, 2017b; OSPAR, 2018c). Of the non-nuclear total beta discharges, the largest contribution is ^{131}I from the medical sub-sector. Tritium discharges from the non-nuclear sector are insignificant compared to the nuclear sector (OSPAR, 2018c).

The production of agricultural fertilizers from phosphate rock results in the production of phosphogypsum (which is mainly a compound of calcium, but also containing NORM). It has often been discharged as slurry to the sea, but this now seems widely to have been phased out. Such discharge continues in Morocco (where there are new regulations and a review), Tunisia, and elsewhere (Hermann and others, 2018; El Kateb and others, 2018). Morocco has, however, set up a system of improved management of phosphogypsum discharges (an investment of 120 M$) in order that discharges comply with international standards, in particular through marine outfalls equipped with diffusion systems along their ends (communication from the Government of Morocco).

Nuclear incidents

There have been no significant major nuclear incidents since 2011.

In relation to the 2011 Fukushima (Japan) incident, the United Nations Scientific Committee on the Effects of Atomic Radiation has reviewed the scientific work carried out on the maritime transport of radionuclides from the Fukushima plant since its 2013 report (which had concluded that effects on marine biota would only be local), and concluded that there were no reasons to change its conclusions.[183]

Activities to track the plume of low-level radioactivity in the North Pacific resulting from the Fukushima incident are ongoing (Men and others, 2015; Buesseler and others, 2017) and the plume has now been tracked into North American continental waters (Smith and others, 2015). Most notably, measurements of the long-lived ^{129}I (Hou and others, 2013; Otosaka and others, 2018; Suzuki and others, 2018) have provided critical information about ocean circulation and iodine biogeochemistry in the waters receiving radionuclides from Fukushima. Five years after the Fukushima accident, measurements of ^{137}Cs found highest activities in brackish groundwater underneath sand beaches (Sanial and others, 2017), suggesting a previously undocumented submarine groundwater pathway for the storage and release of radionuclides to the ocean. However, the levels measured by Japan in the marine environment are low and relatively stable (IAEA, 2019).

A study of Pacific bluefin tuna (*Thunnus orientalis*) caught off the Californian coast around four months after the Fukushima accident showed a tenfold increase in radio-caesium concentrations (derived from Fukushima) compared with pre-Fukushima specimens. However, such radioactivity was approximately thirty times less than that emanating from concentrations of the naturally occurring radionuclide ^{40}K in both pre- and post-Fukushima fish (Madigan and others, 2012).

The IAEA maintains databases on dumping of radioactive waste at sea (which occurred between 1947 and 1993) and inputs from accidents and losses at sea. The last compilation of an inventory from these databases was published in 2015 (IAEA, 2015). The only incident that it records since 2010 is the entry into the ocean in 2015 of a Russian satellite with a small nuclear power pack.

5.4. Economic and social consequences and/or other economic or social changes

The pressures to increase the proportion of the world's supply of electricity that is not derived from fossil fuels means that there continues to be significant interest in the generation of electricity from nuclear power plants. As noted above, there has been a 5 per cent increase in

[183] See *Official Records of the General Assembly, Seventy-second Session, Supplement No. 46* (A/72/46), Chap. II, sect. B, para.1.

the generation of such electricity in the period 2013–2018.

A new development is the construction of the world's first floating nuclear power plant by the Russian Federation. The Akademik Lomonosov completed initial testing in April 2019, to be ready to enter into service in December 2019 in the sea off the Russian port of Pevek, to replace an existing nuclear power plant and a combined heat and power plant (PEI, 2019). The Russian nuclear industry has also suggested collaboration with India over the development of floating nuclear power plants (Times of India, 2019). China is also reported to be considering the construction of floating nuclear power plants (Asia Times, 2019).

5.5 Regional aspects

There have been no significant studies of the global distribution of natural or anthropogenic radionuclides since WOA I, but, as noted above, IAEA is proposing to carry out some new assessments. As recorded in WOA I, both naturally occurring radioactivity in the ocean and the nuclear sources of anthropogenic inputs of radioactive material derive are significantly concentrated in the northern hemisphere - only Argentina, Brazil and South Africa in the southern hemisphere have nuclear power plants.

5.6. Outlook

As noted in section 5.4, there may well be an increase in the number and scale of nuclear power plants. Linked with such increases is a likely increase in the scale of reprocessing of nuclear fuel. However, experience over recent decades suggests that there will be some offsetting reductions in the levels of radioactivity in discharges from such plants. As recorded in WOA I, the estimated highest current levels of committed effective doses to humans of radioactivity from food from the sea are less than a quarter of the IAEA recommended annual limit for the exposure of the general public to ionizing radiation. There is no evidence to suggest any recent significant change. Provided that adequate monitoring is maintained, therefore, such developments are not likely to be of concern.

6. Pharmaceuticals and personal care products (PPCPs)

6.1. Introduction

As the population in the coastal regions grows, the size and number of cities grows with them. In particular, as megacities grow near the coast, river mouths and deltas, the anthropogenic pressure on coastal and marine ecosystems is increasing. The urbanization of coasts has direct implications for the input of PPCPs. An increasing number of people will need an increasing amount and number of pharmaceuticals and will apply an increasing amount and number of personal care products. At the same time, food production such as aquaculture will be of increased importance and will also lead to the input of pharmaceuticals for veterinary purposes. The picture is even more complicated when looking at demographic change and ageing populations, in particular in the western world. This will result in an increasing application of certain pharmaceuticals per capita.

PPCPs include all chemicals used for health care, cosmetics and medical purposes. More than 3,000 PPCPs are currently marketed and new compounds enter the market yearly (Arpin-Pont and others, 2016). It is clear that the development of pharmaceuticals and their use in medicine is of considerable value to human society. Nevertheless, their fate is an environmental issue. PPCPs are often analysed together because their input pathways to the environment are similar. PPCPs reach the environment mainly indirectly with wastewater from households or agriculture (livestock farming). They are mostly washed off or excreted unchanged and released directly in the wastewater systems. As processes to remove PPCPs from wastewater are not efficient, and most of the compounds are not degraded or only slowly degraded, these products reach the aquatic environment via the wastewater effluents. (Heberer, 2002; Verlicchi and others, 2012; Caldwell, 2016). Some PPCPs, such as UV-filters in sunscreens, can also enter the ocean directly during recreational activities. They are often considered "pseudo-persistent" as their degradation is slow in relation to the large quantities input/discharged into the environment (Rivera-Utrilla and others, 2013; Bu and others, 2016).

However, it has been shown that several PPCPs may also be degraded to transformation products that could be more toxic (Kallenborn and others, 2018). Until now, most studies on PPCPs were conducted in relation to the occurrence of PPCPs in influents and effluents of wastewater treatment plants (Fang and others, 2012; Rodil and others, 2012; Tamura and others, 2017), lakes and rivers (Sköld, 2000; Loos and others, 2010; Gothwal and Shashidar, 2015; Molins-Delgado and others, 2017). Many PPCPs have been detected in freshwater systems and, consequently, may end up in marine ecosystems. However, the available data are very limited. Consequently, PPCPs were not discussed or evaluated in WOA I.

The broad range of medicinal products available for human or veterinary use that can reach the marine environment may lead to a global environmental problem (Klatte and others, 2017). Due to the continuous presence of pharmaceuticals in the aquatic environment through different entry pathways, they are regarded as a class of pseudo-persistent contaminants (Bu and others, 2016). Pharmaceuticals reach production volumes of up to 100,000 tons per year (aus der Beek and others, 2016) representing nearly 1.5 trillion United States dollars in the global pharmaceutical market by 2021, with further expansion predicted. The main drivers for this development are market expansion and demographic changes, including an ageing population (IFPMA, 2017; Roig, 2010; Arnold and others, 2014). Pharmaceuticals go through a strict approval procedure in order to ensure effectiveness and patient safety (Taylor, 2016). However, long-term ecotoxicological studies for risk assessment to prevent undesirable environmental effects have been only rarely considered (Sanderson and others, 2003; Fent and others, 2006; Boxall and others, 2012). Since only limited data on the occurrence of a variety of pharmaceuticals in the coastal environment are available, pharmaceuticals with environmental relevance need to be monitored (Gaw and others, 2014; Richardson and Ternes, 2014; Arpin-Pont and others, 2016; Pazdro and others, 2016).

6.2. Situation recorded in the First World Ocean Assessment (WOA I)

Pharmaceuticals and personal care products (PPCPs) were included in section 2 of Chapter 20 on hazardous substances (United Nations, 2017b), alongside classical POPs and heavy metals. They were not considered or evaluated in their own right.

6.3. Description of the environmental changes (between 2010 and 2020)

To date, there are few studies on the occurrence of PPCPs in marine ecosystems. However, there is increased interest in the occurrence of PPCPs in the ocean, not least because marine ecosystems are assumed to be affected by PPCPs contamination and increasingly sensitive analytical capabilities are available (Picot-Groz and others, 2014). Available data based on the occurrence of PPCPs in seawater, sediment, and marine organisms have recently been collected and published by Bebianno and Gonzalez-Rey (2015) and Arpin-Pont and others (2016). The most frequently investigated and detected compounds were antibiotics (erythromycin, sulfamethoxazole and trimethoprim; see Figure 4), antiepileptics (carbamazepine), caffeine, non-steroidal anti-inflammatories (ibuprofen, ketoprofen) and analgesics (acetaminophen). Among cardiovascular drugs, atenolol and gemfibrozil are most frequently detected or exhibited the highest relative concentrations (Arpin-Pont and others, 2016).

Limited amounts of data were available for personal care products (Bebianno and Gonzalez-Rey, 2015; Arpin-Pont and others, 2016). Available data cover musk fragrances, disinfectants (triclosan) and some UV filters, the most relevant of which are benzophenone 3 (BP-3) and octocrylene (OC). Triclosan was detected at concentrations up to 99.3 ng/L in water in Victoria Harbour (China) (Wu and others, 2007). Concentrations of BP-3 up to 2013 ng/L were detected in water at Folly Beach, South Carolina (Bratkovics and Sapozhnikova, 2011. OC that are used not only in sunscreens but also in food additives enter coastal areas either directly or indirectly through wastewater. Concentrations of OC were up to 1409 ng/L in water and up to 3992 ng/g d.w. in mussel tissues (Arpin-Pont and others, 2016; Picot-Groz and others, 2014).

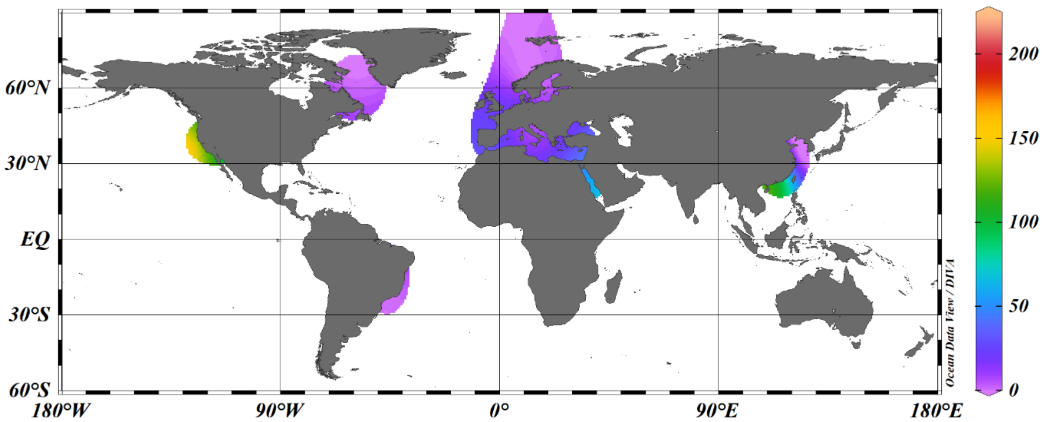

Figure 4. Geographical distribution of antibiotics (ng/L) in the world's oceans.

The majority of the measurements of PPCPs in marine waters have been conducted in the North Atlantic, North Sea, Baltic Sea and Mediterranean Sea, and the Asian Pacific (Table 2). In Asia, particularly in China, a number of different PPCPs were measured in seawater, sediments and biota in estuaries and in the Chinese marginal seas (Xu and others, 2013; Zhang and others, 2013b; Na and others, 2013; Nödler and others, 2014; Kallenborn and others, 2018; Kötke and others, 2019). These studies showed that PPCPs are present in all areas of the ocean, with higher levels in areas directly impacted by anthropogenic activities. Recently, a number of studies have been carried out at coastal sites in the Arctic and Antarctic. In contrast, however, very few PPCP measurements have been taken in the marine environment of the Southern Hemisphere and very little information exists for PPCP levels in sediments (Arpin-Pont and others, 2016).

In addition to the occurrence of antibiotics and their transformation products in the marine environment, antibiotic resistant (AR) genes have also been found in bacteria, and soil in the Pacific and Arctic Oceans (McCann and others, 2019; Hatosy and Martiny, 2015). The occurrence of AR genes in the marine environment can be linked to the coastal run-off of AR bacteria from terrestrial sources, anthropogenic antibiotic run-off and selection for resistance in response to antibiotics introduced in the marine environment (Allen and others, 2010;

Hatosy and Martiny, 2015).

The availability of data on PPCPs in the Arctic environment has been even more limited than for temperate marine systems. Nevertheless, Kallenborn and others (2018) concluded that this group of compounds are relevant pollutants, even in remote regions, including the Arctic. Based on recent studies, the character of local PPCP sources, such as sewage treatment, in combination with the low-temperature Arctic climate and limited technological standards for waste treatment facilities in Arctic settlements all contribute to extending the environmental stability of these residues compared to conditions found in lower latitude regions (Kallenborn and others, 2018). More than 100 PPCP-related compounds have been identified in virtually all Arctic environmental matrices, from coastal seawater to high trophic level biota. Twenty-two of a total of 110 compounds were identified in seawater (Kallenborn and others, 2018), with the highest concentrations registered for citalopram (antidepressant), carbamazepine (anti-epileptic) and caffeine (stimulant). Relatively high levels of certain PPCPs in the Arctic environment are not necessarily linked to higher consumption rates but may be more likely explained by higher environmental stability in the low-temperature Arctic climate. This is considered to be of critical relevance when significant amounts of antibiotics/antimicrobial agents are released, thus enhancing the potential for the development of resistance (Gullberg and others, 2011; Kallenborn and others, 2018).

Although PPCPs have been suggested for inclusion in the list of hazardous substances for decision making on control measures, and there is clear evidence that PPCPs are present in all ocean areas and in marine organisms, the data are still insufficient for most PPCPs detected to assess the trend levels in water and the exposure effects on marine organisms.

Table 2. Concentrations of major PPCPs measured in coastal waters (ng/L).

Location	**Erythromycin**	**Clarithromycin**	**Sulfamethoxazole**	**Sulfamethazine**	**Roxithromycin**	**Iomeprol**	**Iopromide**	**Diclofenac**	**Carbamazepine**	**Bezafibrate**	**Ibuprofen**	**Reference**
Arctic, Tromsø	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	Kallenborn and others, 2018
Arctic, Longyearbyen	n.a.	n.a.	n.d.	n.a.	n.a.	n.a.	n.a.	1.0 4.0	n.a.	n.a.	0.4-1	Kallenborn and others, 2018
Arctic, Tromsø	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.d. - 0.7	Weigel and others, 2004
Baltic Sea	n.d. - 0.14	0.03 - 0.42	0.74 - 3.29	n.d.	n.d. - 0.48	1.05 - 34.5	0.42 - 3.34	n.d. - 0.84	1.98 - 10.6	n.d. - 0.64	n.a.	Kötke and others, 2019
North Sea	0.13 - 0.94	0.4 - 1.66	1.78 - 13.0	n.d.	n.d. - 2.86	7.66 - 207	7.27 - 34.1	n.d. - 4.82	4.78 - 29.7	n.d - 2.06	n.a.	Kötke and others, 2019
Himmerfjärden	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	4.0 - 12.0	n.a.	n.a.	Magnér and others, 2010
Baltic Sea	n.d.	14	21	n.a.	n.a.	98	45	9.2	22	n.a.	n.a.	Nödler and others, 2014
Baltic Sea, Oslo	n.a.	n.a.	n.d.	n.a.	n.a.	n.a.	n.a.	n.d. 48.0	n.a.	n.a.	n.d.-52	Kallenborn and others, 2018

Aegean Sea	n.d.	16	3.8	n.a.	n.a.	83	109	4.6	2.9	3.5	n.a.	Nödler and others, 2014
Adriatic Sea	5.8	n.d.	3.6	n.a.	n.a.	29	n.a.	n.d.	3.1	n.a.	n.a.	Nödler and others, 2014
Adriatic Sea	n.a.	n.a.	0.02 - 1.02	n.a.	n.a.	n.a.	n.a.	n.a.	0.11 - 0.36	0.02 - 0.14	n.a.	Loos and others, 2013
Mediterranean	9	5	14	n.a.	n.a.	n.a.	n.a.	n.a.	n.d.	n.a.	n.a.	Moreno-González, and others, 2015
Santos Bay	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.d.	n.a.	n.a.	326.1 - 2094	Pereira and others, 2016
Red Sea	n.a.	n.a.	63	n.a.	n.a.	n.a.	n.a.	14020	110	n.a.	508	Ali and others, 2017
Bohai and Yellow Seas	0.69	0.07	1	0.01	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	Zhang and others, 2013b
Jiaozhou Bay	4.5	0.58	9.6	0.04	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	Zhang and others, 2013a
Yantai Bay	0.82	0.03	1.4	0.02	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	Zhang and others, 2013a
Southern Yellow Sea	0.5	3	7.7	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	Du and others, 2017
East China Sea	n.a.	n.a.	0.5 - 3.5	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	Fisch, and others, 2017
Pearl River Delta	n.d. - 126	n.a.	n.d. - 40.6	n.a.	n.d. - 12.0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	Xu and others, 2013
South China Sea	21	n.a.	11.4	7.03	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	Liang and others, 2013
Boulder Basin, USA	<1.0	n.a.	5.4 ± 11	n.a.	n.a.	n.a.	n.a.	<1.0	3.9 ± 5	n.a.	n.a.	Vanderford and others, 2003
Sydney Estuary	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	3.0 - 12.5	n.a.	n.d - 2.7	n.a.	n.a.	Birch and others, 2015
Antarctic	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	Hernández and others, 2019

n.d. – not detected; n.a. – not available.

7. Atmospheric pollutants (nitrogen oxides, sulphur oxides)

7.1. Introduction

Combustion is a major source for air emissions of nitrogen oxides (NOx) and sulphur oxides (SOx). Of particular interest for the marine environment are the emissions from shipping that contribute to air pollution. The local and regional environmental issues connected to shipping emissions are to a large degree coupled to shipping intensity, but can also contribute to global pollution.

7.2. Situation recorded in the First World Ocean Assessment (WOA I)

Chapter 17 of WOA I (United Nations, 2017a) discussed emissions of NOx and SOx in areas from heavy traffic as well as the contribution of these compounds to acid rain and to human health.

7.3. Description of the environmental changes (between 2010 and 2020)

Total annual NO_x emissions from shipping have been estimated at about 19,000 kilotonnes (2013 – 2015), of which about 91 per cent derives from international shipping, and the rest from domestic shipping and fishing vessels (6 per cent and 3 per cent, respectively) (Olmer and others, 2017). Total annual nitrogen emissions by international shipping on the Baltic Sea is approximately 80 tonnes, which is about 5 per cent of the total NO_x emissions in the Baltic Sea countries (Gauss and others, 2018).

The adverse effects of air pollution caused by shipping are an issue of interest to the International Maritime Organization (IMO) which, on the basis of Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL Convention),[184] endeavours to reduce emissions of e.g. SOx (and indirectly particulate matter, PM) and NOx from ships through international agreements. There are also IMO-designated Emission Control Areas (ECA), where the restrictions with respect to emissions of SOx and/or NOx, are more stringent. As of 1 January 2020, the global limit for sulphur content in the fuel oils used by shipping was reduced from 3.5 per cent (m/m) to 0.5 per cent, while it since 2015 was reduced to 0.1 per cent in the ECAs. There are four ECAs, in the Baltic Sea and North Sea areas (presently only SOx, but will include NOx from 2021), the North America and United States Caribbean Sea areas. The implementation of the North Sea and Baltic Sea SOx ECA led to a significant reduction of sulphur dioxide concentrations in bordering port cities and coastal regions for the benefit of the health of coastal citizens (EU, 2018). The requirement was also set to reduce acidification resulting from SOx deposition in the sea (EEA, 2013). The implementation of the Baltic Sea NOx ECA is estimated to reduce nitrogen deposition at the sea by about 40 per cent (Karl and others, 2019). Despite these improvements, a modelling study of the longer-term perspective shows that without additional measures, the current IMO and EU regulations will cut SO_2 emissions of international shipping up to 2030, but then emissions will grow again. The pattern is even more pronounced for NOx emissions; it is expected that after 2030 the emissions from international shipping will exceed those from land-based sources in the EU, if no further control is applied (IIASA, 2018).

To meet the stricter sulphur regulations without switching to more expensive fuel of lower sulphur content, an increasing number of ships (7 ships in 2010, 256 ships 2015 and more than 4400 in 2020) have been equipped with an exhaust gas cleaning system, also known as scrubbers, which allows for continued use of heavy fuel oil. In the scrubber the exhausts are washed in a fine spray of water, and in the simplest and most common form, open-loop scrubbers, the wash water is directly discharged back to the sea. Beside sulphur oxides, other substances such as metals and organic pollutants are also washed out of the exhausts, and there is increasing concern that wide-scale discharge of scrubber wash water may affect the marine environment negatively (Koski and others 2017, Ytreberg and others 2019, Teuchies and others 2020). For this reason, some ports, regions and countries have taken a precautionary approach and prohibited such discharges in their waters (Turner and others, 2017), this include many European ports, such as Rotterdam, ports in California and

[184] United Nations, *Treaty Series*, vol. 1340, No. 22484.

Singapore and recently, China and Egypt also proposed such a ban in Chinese waters and the Suez Canal respectively.

Further efforts to reduce the environmental impact of shipping include the IMO Polar Code[185] that promotes identification of hazardous substances on the basis of routine operations and navigational and shipping accident reports. As a consequence of the stricter global sulphur rules and the encouragement to not use Heavy Fuel Oil in the Arctic, more alternative fuel blends have entered the market. More research is needed to determine the potential toxicity of these new fuels.

8. Hydrocarbons from terrestrial sources, ships and offshore installations, (including arrangements for response to spills and discharges)

8.1. Situation recorded in the First World Ocean Assessment (WOA I)

As described in WOA I, the impact of hydrocarbons, for example, from oil spills can affect the marine ecosystem both physically through oiling of birds, mammals and beaches, and chemically through toxic components such as polycyclic aromatic hydrocarbons (PAHs). Depending on concentration and exposure, the effects may be acute or chronic (Lindgren and others, 2012). Hydrocarbons enter the marine environment through many pathways. Land-based sources include urban run-off and coastal refineries, while shipping-related sources include operational discharges and accidents, and, for offshore oil and gas facilities, include operational discharges, accidents and blow-outs. Additionally, atmospheric fallout and natural seeps are substantial sources. It was posited in 2003 that the total range from all sources may have reached 470,000 tons to 8.4 million tons a year (NRC, 2003), which can be compared with world crude oil production for example in 1999, which was about 3,500 million tons. The levels of PAHs are expected to decrease due to tighter regulations of combustion plants, vehicles and so forth. In 2017, crude oil production increased by almost 25 per cent and was approaching 4,400 million tons (Global Energy Statistics Yearbook, 2018).

8.2. Description of the environmental changes (between 2010 and 2020)

Based on global models of long-range atmospheric deposition of Benzo(a)pyrene (B[a]P), one of the PAH compounds, it is notably higher at some hotspots in the North-East Atlantic, and the Baltic, Mediterranean and Caspian seas. Especially high levels are found on the Adriatic and Aegean seas in the Mediterranean, coastal areas of the North Sea in the North-East Atlantic, and in the south-eastern part of the Baltic Sea, as well as in the northern Caspian Sea (Figure 5a). However, on a global scale, the major emissions and deposition of B[a]P are to be found in the eastern and southern parts of Asia, where the atmospheric deposition is a magnitude higher or even more, compared to the levels illustrated in Figure 5 (Gusev and others, 2018). The deposition of B[a]P on the Baltic Sea increased up to 2000, after which time the deposition rate seems to have levelled off.

[185] See International Maritime Organization, document MEPC 68/21/Add.1, annex 10.

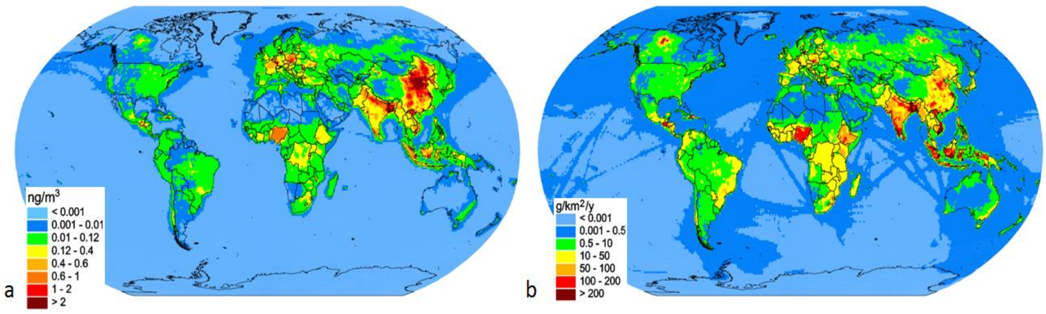

Figure. 5. Spatial distribution of global scale annual mean modelled air concentrations, ng/m^3 (a), and deposition fluxes, g/km^2/y (b) of B[a]P for 2016. Source: EMEP homepage, 3 March 2019.

Other important sources of hydrocarbons entering the ocean are shipping accidents, operational losses and illegal discharges from shipping. The global trend regarding shipping accidents leading to oil spills above 7 tons is, however, decreasing. According to ITOPF (2019), the annual average number of spills 2009–2018 was 6.4, compared with 35.8 for 1990–1999. The decrease of tanker spills is likely a result of improved safety measures in terms of the phase-out of single-hull tankers, which came into effect in 2003 (IMO, 2019), through an accelerated process following the disastrous accident involving the Erika tanker in1999. The Erika and Prestige (2003) accidents also marked the starting point for maritime vetting inspections as a possible measure for cargo owners to demand higher safety standards of primarily chemical and oil tankers (Powers, 2008). The declining trend in the number of tanker spills is even more pronounced taking into account the steady growth - close to an 80 per cent increase from 1990 to 2017 - in loaded crude, petroleum and gas shipping (UNCTAD, 2018).

During the last ten years, offshore oil production has remained at the same level, around 26–27 million barrels per day (mb day^{-1}) (IEA, 2018a), but its market share has shrunk as global oil production increased to approximately 95 mb day^{-1} in 2017 (IEA, 2018b). Beside oil spills, the main impact from offshore production of oil and gas is associated with the discharge of produced water, with global volume estimated to be up to 39.5 Mm^3 day^{-1}(Jiménez and others, 2018), and disposal of drilling waste (Bakke and others, 2013). Although several studies (e.g. Moodley and others, 2018) indicate sublethal effects from produced water on marine species, there is a general understanding that there is a low risk of long-term, widespread impact from produced water and disposal of drilling waste, but this cannot be verified from published literature (Bakke and others, 2013). However, the observed levels of DNA adducts in the liver of wild caught fish from regions with oil production in the North Sea above Environmental Assessment Criteria (EAC) raise concern regarding the effects of oil compounds on early life stages (Balk and others, 2011; Pampanin and others, 2017). There is a need for further studies on community and population level to advance the current knowledge based on single species toxicity data (Camus and others, 2015). This is also relevant for environmental risk assessment prior to new offshore exploration. If based on worst-case scenarios that are limited in their holistic validity, the risk assessment may be biased in the handling of associated uncertainties (Hauge and others, 2014). From the marine environment perspective, an increasing area of concern is the decommissioning of offshore platforms. In IEA (2018a), it is estimated that 2,500–3,000 offshore projects will probably need to be decommissioned, while today the annual average rate is 120 platforms per year. The costliest part of platform decommissioning is plugging and abandoning wells. In the North Sea, the removal of all topsides and substructures has been required since 1998, under the OSPAR Convention.[174] However, the Rig-to-Reef approach has been adopted in the United States of America and

South-East Asia, and allows for parts of the subsea structures to be left and converted to artificial reefs. In the Gulf of Mexico, there are already more than 500 such permanently converted decommissioned rigs (IEA, 2018a).

9. Other substances used on, and discharged from, offshore installations

Beyond environmental impact from hydrocarbons, produced water also contains elevated concentrations of metals, such as arsenic, cadmium, copper, chromium, lead, mercury, nickel, silver and zinc - some in the range of 10^2-10^5 times higher than background concentrations (Jiménez and others, 2018).[186] Naturally occurring radioactive material (NORM) originating from geological formations may also be present as dissolved solids in produced water. The most common NORM compounds are ^{226}Ra and ^{228}Ra and barium (Bou-Rabee and others, 2009).[187] To minimize negative environmental impact from produced water, efforts are being made (i) to use a small volume of water for the oil extraction process; (ii) to reuse the water; and (iii) to dispose of it at sea (Jiménez and others, 2018).

As concluded in WOA I, there are still knowledge gaps with respect to an assessment of large-scale impact from produced water (OSPAR, 2018a). In the North Sea region, the OSPAR Commission has worked hard to achieve phase-out of the most toxic chemicals used in the offshore production industry until 2017. Although the target was not entirely reached, at least the chemicals on the OSPAR List of Chemicals for Priority Action (LCPA) were not used at all on the Norwegian Continental Shelf (NCS) from 2014–2016. The total use and discharge quantity of chemicals on the NCS peaked in 2013, and there was a similar trend regarding discharge in the United Kingdom Continental Shelf (OSPAR, 2018b). The total quantity of chemicals used offshore was 398,158 tons in 2016. Seventy-one per cent (wt.) of the used chemicals were on the PLONOR list,[188] 28 per cent (wt.) were other non-substitution chemicals, and 1 per cent comprised substitution chemicals (i.e. chemicals that contain one or more substances which are candidates for substitution). In addition to the work on phasing out toxic chemicals, new technologies, for example advanced oxidation processes for remediation of produced water, have also been proposed (Jiménez and others, 2018).

10. Relationship to the Sustainable Development Goals (SDGs)

The atmospheric deposition of various pollutants on water (or land) is directly related to SDG 14 but is also relevant to most if not all SDGs,[189] as one of the prerequisites for life on earth is the supply of clean and healthy water (for example SDGs 2 and 6, or SDGs that might have an impact on air emissions, including SDGs 1 and 8).

The presence of POPs at concentrations likely to cause deleterious effects means that it is unlikely that SDG 14.1 will have been achieved by 2025. For many of the legacy POPs, such as the PCBs, emissions, discharges and losses are very low; the issue is re-emergence from the sediments due to the resistance of POPs to biodegradation. There also remains a clear need to increase scientific knowledge (SDG 14.a and other SDGs) around the cumulative impacts of the growing mixture of chemicals to which marine biota are being exposed.

[186] The potentially negative effects from metals are described in section 4 of the present Chapter.
[187] The potentially negative effects from NORM are described in section 5 of the present Chapter.
[188] OSPAR List of Substances Used and Discharged Offshore which are Considered to Pose Little or No Risk to the Environment.
[189] See United Nations General Assembly resolution 70/1.

SDG 3.9 will be hard to achieve in respect of POPs, metals, PPCPs and hydrocarbons specifically with respect to achieving a substantial reduction in water pollution. The impacts of POPs, metals, PPCPs and hydrocarbons on human health have not been evaluated in the present Chapter but it has been recognized that marine mammals are being impacted by POPs, with concentrations for some POPs and metals decreasing only slowly and increasing concentrations affecting top predators.

Achievement of SDG 2.1 will require more concerted monitoring programmes covering the edible portion of marine plants and animals to ensure the quality of marine food sources.

The available information on the impact of ionizing radiation from anthropogenic sources on the marine environment suggests that there is probably no significant problem from this quarter for achieving SDG 14.1. However, there are significant gaps in the information available on discharges of radionuclides in much of the world.

Relevant PPCPs should be included in already established long-term international, national and regional monitoring programmes to serve as a scientific basis for region specific “watch lists” for PPCPs, in particular in coastal waters. There should be no segregation of environmental regulation and legislation between terrestrial and marine ecosystems on national and international levels, with coastal areas treated as a transition zone in the “catchment-to-sea-continuum” and as the link between SDGs 6 and 14.

As the impacts of increased anthropogenically produced carbon dioxide become more significant in the ocean, it becomes more evident that marine biota is being exposed to yet another stressor ocean acidification. The pH decreases (see Chapter 9 of the present Assessment), along with the increase in temperature and decrease of dissolved oxygen there is a risk that biota already made vulnerable by their contaminant loading will succumb to the multiple stressors (see also Chapter 28) they are experiencing. It would be desirable to reduce the presence of multiple stressors in the ocean along with climate action.

11. Key remaining knowledge gaps

In WOA I, the need to work through a number of different organizations was highlighted as limiting the possibility of making clear comparisons between the environmental quality of different ocean areas because of the use of different measuring techniques and the very different ranges of the varieties of chemicals being observed. This situation remains.

The atmospheric deposition of various pollutants is heavily dependent on modelling approaches to increase the spatial coverage. To be able to model the deposition, there is a significant need for high quality data on emissions and deposition. These data need to be collected and used in regional and/or global modelling to facilitate the production of high resolution spatial and temporal deposition estimates. However, the availability of this kind of fundamental data is limited, especially for some ocean areas, which is quite evident from the present Assessment for which there is a lack of information for a large part of the ocean.

Changes in industrial production will result in changes in compartmental patterns as well as the point sources and substance mixtures. With the broadening of the Stockholm Convention,[169] there is a need for information on the concentrations of the compounds detailed in that convention that are found in the environment to permit the consideration of cumulative impacts (see Chapter 28 of the present Assessment) and the effectiveness of the processes aimed at eliminating the emissions and use of these compounds.

Critically, the biological effects and cumulative impacts of the chemicals detailed in the Stockholm Convention require considerable research to allow appropriate status assessments to be prepared, especially in cases where changes are due to the impact of increased atmospheric greenhouse gas concentrations (e.g. ocean warming, ocean deoxygenation, ocean acidification and changing rates of respiration).

Current GEOTRACERS efforts and ongoing time series will improve both global and regional resolution. However, significantly higher resolution is needed to improve estimates of trends with respect to trace elements and their isotopes. Time series in the South Atlantic and across the South Pacific are currently lacking for hazardous substances, as are data for the Southern Ocean. The extent of transboundary marine pollution is yet to be properly investigated. The mapping of contamination of coastal waters and sediments requires a more integrated effort, together with more globally targeted studies of biota such that effects can be determined on a larger (oceanic) basis.

It is necessary to coordinate spatial and temporal sampling for metals such that the data reflect a global strategy. This will require integrated efforts, possibly including the UNEP Regional Sea Conventions, with both coastal and open ocean sampling. As sampling resolution is optimized, such that changes in concentration can be detected with a known confidence, quality control/assurance guidelines, including inter-calibrations, will be required.

Very limited detailed information is published, outside the North-East Atlantic and its adjacent seas, of the levels of discharges of radioactive substances to the marine environment. It is known that substantial monitoring is carried out. There is, therefore, a case for restarting and extending the IAEA DIRATA database as a means to provide much wider publication of this information.

Likewise, the IAEA intention to repeat the studies carried out by the Agency in 1995 (MARDOS) and 2005 (WOMARS) on the levels of natural and anthropogenic radioactivity in fish and seawater in the different major fishing areas is welcomed. This would be an appropriate contribution to the United Nations Decade of Ocean Science for Sustainable Development (2021–2030).

A review of the studies of the impact of ionizing radiation on crustaceans concludes that there is poor coverage of data, particularly in the field, on this subject, and suggests that similar problems may exist with other phyla (Fuller and others, 2019). This implies that there is a need for further research on this subject.

The quite large number of PPCPs identified in marine ecosystems is primarily indicative of the capability of today's analytical method for the identification and quantification of these substances and their metabolites. This does not necessarily reflect the full range of PPCPs present in the marine environment. The ultra-trace concentrations of PPCPs in seawater, sediments and biota are still a significant challenge for existing analytical methods. However, technological developments and novel applications will further decrease limits of quantification and additionally lead to the identification of new and presently unidentified PPCPs (Kallenborn and others, 2018).

Both active and passive sampling strategies and analytical methodologies for analysis of PPCPs and their metabolites in the marine environment need to be harmonized. This will ensure common data quality and allow more effective data comparison between laboratories and geographic regions (Arpin-Pont and others, 2016).

Because PPCPs are mostly excreted unchanged or as metabolites, it is not appropriate to target only the parent compounds, but the major transformation products must be included in both the analytical procedures and the risk assessments (Rivera-Utrilla and others, 2013).

To date, there is no comprehensive data set available covering the worldwide occurrence of PPCPs in the coastal regions and the open ocean. This means that it has not been possible to conduct any potential assessment on the impacts of PPCPs on marine organisms. It would be desirable to create a database to support the risk assessment and modelling and provide information for the international management of PPCPs. Due to the lack of adequate data, especially for the different trophic levels in marine webs, a safety factor of 10,000 needs to be applied, which results in a high uncertainty of the risk characterization of these compounds (EMEA, 2018).

To further evaluate the ecotoxicity of the investigated PPCPs and to estimate whether the observed concentrations may have an effect on marine ecosystems, it will be important to improve the data on marine test organisms. This should focus on the impacts of chronic toxicity characterized by low dose exposure in long-term studies. This should include the behaviour of mixtures of chemicals (Deruytter and others, 2017).

12. Key remaining capacity-building gaps

The complex nature of the mixtures that comprise POPs and PPCPs, coupled with the fact that even at very low concentrations these compounds can be toxic, means that there is a need to develop the necessary analytical capabilities on a global scale.

Sampling, and subsequent analyses, in the open ocean and in coastal and shelf seas, need to be undertaken in a systematic, quality assured manner on a global basis, covering both the original and new POPs as detailed in the Stockholm Convention as well as metals, PPCPs, radioactive substances, NOx, SOx and hydrocarbons. Although significant analytical challenges are expected, this will permit precise spatial and temporal assessments to be made which will ultimately inform better management decisions with respect to utilization of POPs, PPCPs and other materials that may be deleterious to the marine environment.

POPs continue to accumulate in the polar regions and in top predators but neither present straightforward sampling opportunities. This requires that greater efforts be put into more harmonized monitoring plans such that the collection of samples for the determination of POP concentrations is integral to as many programmes as practicable, especially in regions known to be impacted by POPs. Furthermore, there needs to be a greater awareness and understanding of the movement of POPs through food webs. Development of trophic magnification factors should allow concentrations across food webs to be modelled, providing an indication of the probable concentrations of POPs in species that are difficult to sample.

Re-emergence is a significant source of POPs. This is contributing to the sustained elevated concentrations of, for example, PCBs. However, establishing a clear understanding of the routes and pathways through which contaminants enter our seas will enable better evaluation and targeting of measures, inform on issues of potential re-emergence, and potentially offer the possibility to predict recovery times. In addition, a major consideration for future assessments should be determination of the environmental realities due to multiple mixed effects, particularly, the impact on the environment not just by single substances or substance groups but the complex and potentially magnifying effects of numerous contemporary hazardous substances.

Over the many decades of analyses, the instrumentation has improved as has sampling methodology and sample preservation. However, in determining temporal trends, it is often the determined concentration that is given most attention, with less consideration given to the relevant limit of detection of the instrument for that sample. In this context, there is a need to consider the more technical and specific aspects of the analysis (Mangano and others, 2017). In addition, to support future assessments, it will be necessary to review and harmonize the threshold values utilized in the individual indicators, to ensure their relevance and application. Furthermore, gaining a comprehensive overview of novel sources of contaminants, particularly emerging from offshore activities, such as wind farms, will also be beneficial.

There is a need to develop laboratory facilities that can improve our knowledge of the toxicity of POPs and PPCPs in marine systems. Furthermore, it is essential that an infrastructure be put in place that will permit assessments of the contribution of POPs and PPCPs to the wider cumulative impacts of the multiple stressors to which marine species and habitats are being exposed, especially a changing climate and ocean acidification.

As with other monitoring of hazardous substances, there are major gaps in the capacities of most developing countries to monitor concentrations of POPs, metals, PPCPs and radionuclides in the marine environment.

The Minamata Convention on Mercury[190] entered into force on 16 August 2017 and includes articles to support parties thereto, including with respect to capacity-building and technical assistance, as well as health aspects, public awareness, education and monitoring. There are 113 parties to the Convention (as of July 2020).

Moreover, efforts should be made to reduce all the inputs sources of these hazardous substances to the ocean.

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Chapter 12
Changes in Inputs and Distribution of Solid Waste in the Marine Environment (other than Dredged Material)

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Keynote points

- Plastics now represent the major part of marine litter or marine debris.
- Most marine litter is from land-based sources, and results from poor waste management practices, especially in some rural and developing regions.
- Marine litter is present in all marine habitats, affecting the environment and marine organisms through entanglement, ingestion and rafting of invasive species.
- Amounts of marine litter are increasing in in remote and unpopulated areas.
- Time series data are needed to assess and monitor impacts of marine litter, including micro- and nanoplastics.
- Although a decreasing trend is observed, there is a need to harmonize reporting on dumping at sea.

1. Activities resulting in marine debris, including plastics, abandoned fishing gear, microparticles and nanoparticles, and estimates of the sources from land, ships and offshore installations

1.1. Introduction

The term "marine litter" refers to any persistent, manufactured or processed solid material discarded, disposed of or abandoned in marine and coastal environments (GESAMP, 2019) and covers an extremely wide variety of materials, ranging in size from mega litter (> 1m), to macro (>25mm), meso (>5mm), micro (> 1µm) and nano (<1µm). It is classified by the nature of the material, such as plastic, metal, glass, rubber, or wood, or by sources or uses, such as fishing gear, industrial pellets, sanitary items, single-use plastics. Plastic, defined as polymers synthesized from hydrocarbon molecules, or biomass with thermo-plastic or thermo-set properties, comprises the main component of marine litter and exhibits a wide range of properties, shapes and compositions (GESAMP, 2016). In 2018, approximately 348 million metric tonnes (MT) of plastic waste had been generated worldwide (PlasticsEurope, 2019), with annual amounts entering the ocean in the range of 4.8 to 12.7 million MT, based on data from 2010- (Jambeck and others, 2015).

Marine litter is most obvious on shorelines, where it accumulates from current, wave and wind actions and river outflows. However, marine litter, mainly plastic, also occurs on the ocean surface in convergent zones (ocean gyres), in the water column, on the seafloor and in association with marine biota, where it can cause harm (Barnes and others, 2009).

This section provides a robust description of changes in the state of marine litter, including key region-specific features, and describes the consequences of these changes to human communities, economies and well-being.

1.2. Situation recorded in the First World Ocean Assessment (WOA I)

The First World Ocean Assessment (WOA I) (United Nations, 2017b) contained only limited understanding of the sources, fate, transport, degradation and impacts of marine litter. Economic impacts and reduction measures were not considered in depth, due to a lack of information and knowledge on marine litter, including its spatial and temporal extent. A consideration of remote or ultra-deep areas, specific sources and fluxes for specific types of marine litter (riverine inputs, wastewaters, atmospheric inputs of microplastics, etc.) was not included, and impacts were not discussed. More recently, however, discussions have begun in ernest, as a result of the increased numbers of surveys and extensive studies that highlight that, for example, that more than 1,400 species had been affected by marine litter by 2019 (Claro and others, 2019).

Similarly, there was little discussion on microplastics, which are polymer particles of less than 5 mm (upper limit) and larger than 1 micron, as defined by GESAMP (2019), with reference only to primary microplastics, crafted to be microplastics, and the fact that larger pieces of plastic break up into smaller pieces (secondary microplastics).

1.3. Description of the environmental changes (between 2010 and 2020)

Marine litter is present in all marine habitats, from densely populated areas to remote regions (Barnes and others, 2009), from beaches and shallow waters to deep-ocean trenches (Pierdomenico and others, 2019). Most originates from land-based sources (GESAMP, 2016 .& 2019), wastewaters, combined sewer overflows, onshore recreational uses, solid waste disposal, inappropriate or illegal discharges and dumping, mismanaged waste dumps and runoffs (Figure 1). It is estimated that more than one million ton of plastic waste enter the ocean every year from rivers, with the top 20 polluting rivers, mostly located in Asia, accounting for a large percentage of the global total (Lebreton and others, 2017, Van Emmerick et al., 2019, Schmidt et al., 2017). Plastic pollution also enters the marine environment due to deficiencies in waste management infrastructures with microplastics from wastewater treatment plants that may reach up to 10 million particles/m3 (SAPEA, 2019). Inputs from extreme events and natural disasters such as hurricanes, floods, earthquakes and tsunamis, along with accidents, may reach millions of tons every year and match the magnitude of regular inputs from land (Murray and others, 2018).

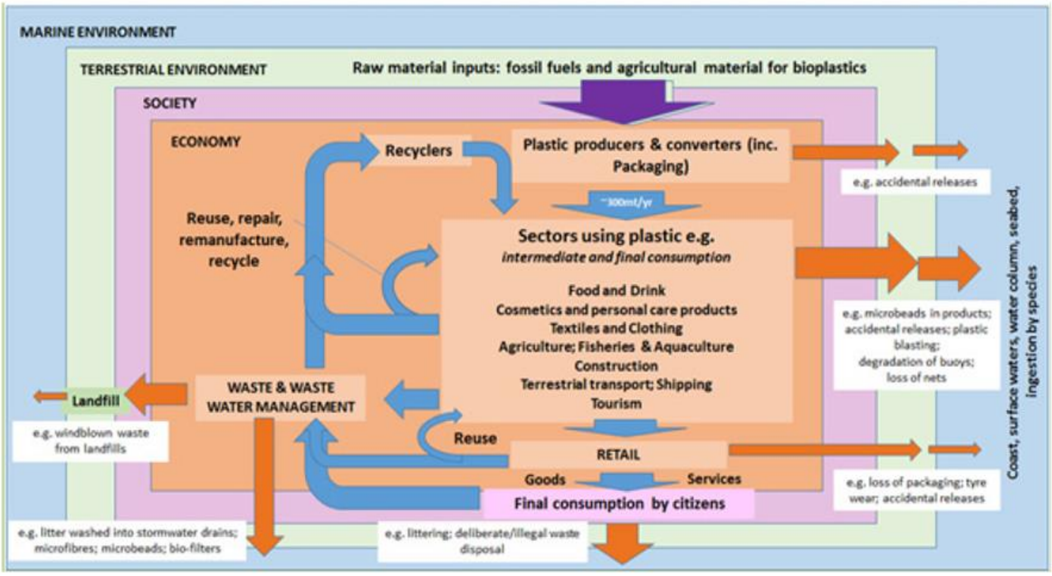


Figure 1. Plastics: production, use by sectors, end use by citizens, and flows back into the economy or into the environment (UNEP, 2017b).

Single-use plastic items are the biggest contributors to marine litter (European Commission, 2018). It is estimated that 1 to 5 trillion plastic bags are consumed worldwide each year (UNEP, 2018). The remaining sources of marine litter can be attributed to maritime transport, industrial exploration and offshore oil platforms, fishing and aquaculture (GESAMP, 2016 & 2019), as well as loss and purposeful disposal of, for example, containers, ballast weights and cargoes. In commonly used fishing grounds, large marine litter is 100 per cent composed of abandoned, lost or otherwise discarded fishing gear (ALDFG) (Pham and others, 2014). The amount of ALDFG is not well known, although some estimates are available (e.g. 640,000 tons per year, according to Macfadyen and others, 2009), and about 70 per cent (by weight) of floating macro-plastics in the open ocean is fishing related (Eriksen and others, 2014). It is also estimated that 5.7 per cent of all fishing nets, 8.6 per cent of all traps, and 29 per cent of all lines are lost around the world each year (Richardson and others, 2019).

Primary microplastics such as microbeads or industrial granulated pellets enter the marine environment directly, while secondary microplastics are derived from weathering, abrasion and fragmentation of single-use plastics (cutlery, trays, straws, cigarette butts, caps/lids, plastic bottles and shopping bags, etc.), synthetic textiles and clothing, coatings and paints, and tyres (Figure 2). Recent studies suggest that atmospheric transport and deposition of microplastics may also be an important pathway (Rochman, 2018).

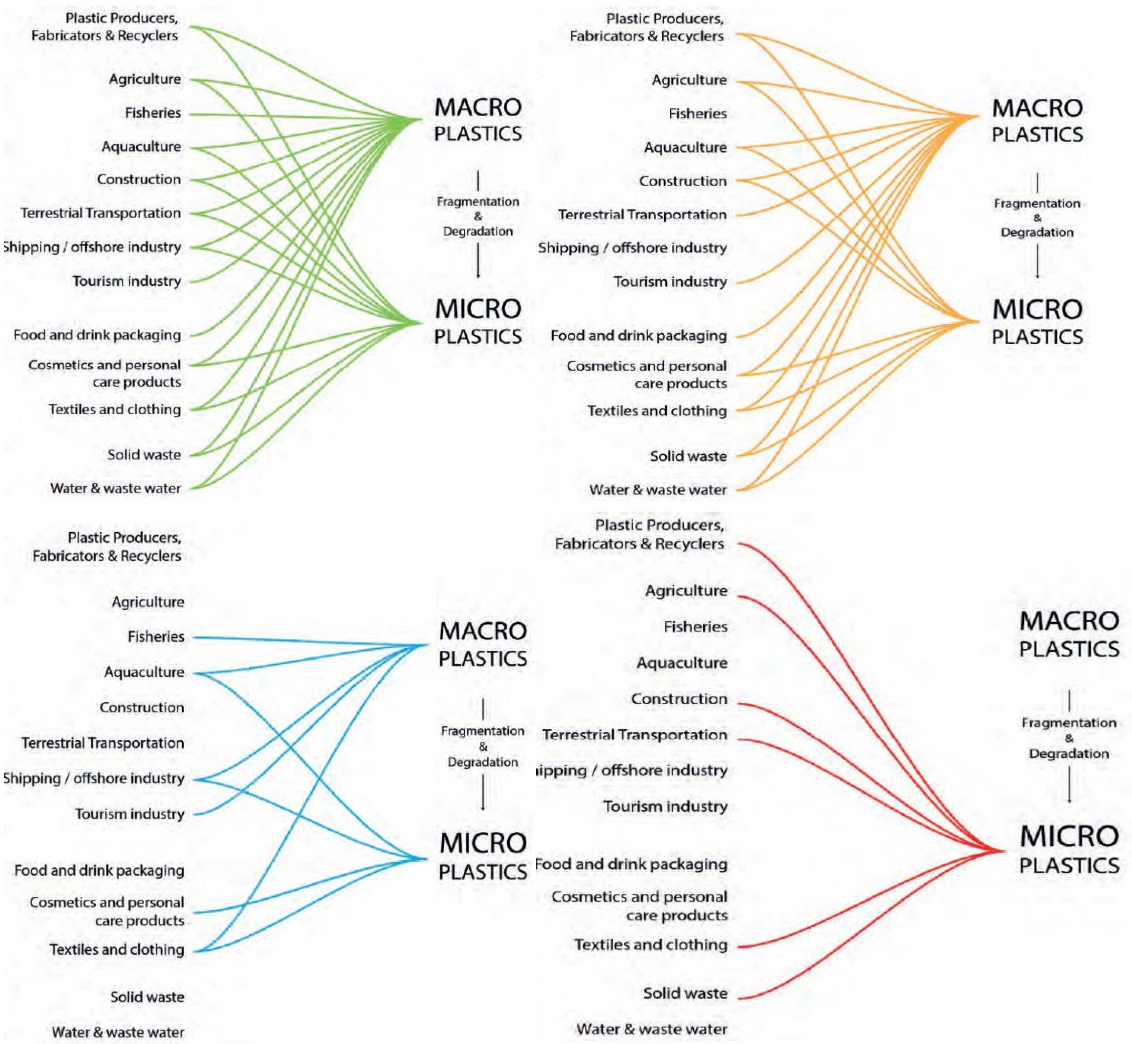


Figure 2. Sources of plastic entering via rivers (green), coastlines (orange) and direct inputs (blue), and through the atmosphere (red) to the marine environment. Adapted from GESAMP (2016).

The most common impacts of marine litter on marine life include entanglement and ingestion of plastic marine litter (GESAMP, 2016 & 2019). Entanglement poses a threat mainly to larger marine animals, such as top predators. Ingestion is common in a wider range of marine organisms, including marine mammals, turtles, sea birds, fish and invertebrate species, as plastics occur in various sizes. Other impacts of plastic marine liter include changes to marine communities, with structures acting as new habitats (Reisser and others, 2014), across several levels of biological organization (Rochman and others, 2018), or by infestation of the marine environment by non-indigenous species, harmful algal blooms and pathogens, dispersed via anthropogenic flotsam (Carlton and others, 2017, Viršek and others, 2017).. As a result, it can increase genetic exchange of bacteria and the spread of antibiotic resistance (Arias-Andres and others, 2018).

Plastic marine litter also smothers and damages benthic organisms. The potential impact is not only at the level of organisms, but also at population and ecosystem levels (Rochman and others, 2016). The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019) also confirmed the negative impact of plastics on biodiversity, with possible imbalances/disruptions in ecosystem diversity. After the 2011 tsunami in Japan, 289 species of macrofauna and macroflora were rafted to northern America in just six years (Carlton and others, 2017), a very uncommon scheme, with potential long-term changes (Murray and others, 2018).

Aside from being a physical contaminant, plastics and microplastics often contain chemical additives, such as phthalates and brominated flame retardants (see Chapter 11 of the present Assessment) and capture other contaminants. Laboratory studies demonstrate that microplastics can harm organisms and populations at higher concentrations than those found in nature. However, the best available evidence suggests that microplastics do not as yet pose a widespread ecological risk (as opposed to a risk to individual organisms), except in some coastal waters and sediments (SAPEA, 2019).

Human health is a main concern, despite a rather limited knowledge of impacts such as injuries and accidents or through possible contamination after a potential release of chemicals (SAPEA, 2019) or due to the presence of microplastics in seafood, and there are few appropriate risk assessment studies. These concerns may cause people to change their behaviour (tourism habits, reduction in the consumption of seafood, and so forth).

Since WOA I, more data are available and, as a consequence, modelling studies, assessments of riverine inputs, new technologies such as automated sensors, including aerials and satellites, and new ecosystem approaches like risk assessment for marine species and communities (Everaert and others, 2018) are improving understanding of how marine litter, plastics and nano- and microplastics in particular can cause harm.

To better support assessments and monitoring, new technical approaches, using tools such as drones, remote systems or automated sensors (Maximenko and others, 2019), and new indicators, may support implementation of harmonized monitoring of marine litter trends, and improve efficiency of global approaches and measures (GESAMP, 2019). Remote-sensing technology is the only approach that can be used to monitor large coastal or open sea areas in several spatial resolutions, and thus help in meeting requirements of indicator 14.1.1 of the United Nations Sustainable Development Goals (SDGs).[191] Space agencies are considering both optical and remote-sensing methods for testing and possible application in regular monitoring (Topouzelis and others, 2019; Martínez-Vicente and others, 2019). In terms of understanding the effects of plastics on wildlife and the environment, risk assessment is also a promising tool, by helping to model interaction between animal species and plastic. This approach is becoming more widely used, though more work needs to be done on quantifying the effect of the interaction, particularly in terms of lethality and sub-lethality (i.e. changes to feeding, reproduction, growth, etc.) of ingested plastics (Schuyler and others, 2016; Wilcox and others, 2018)

1.4. Key region-specific changes and consequences

Many Regional Seas Programmes have developed thematic strategies or plans for marine

[191] See United Nations General Assembly resolutions 70/1 and 71/313, annex.

litter. The Regional Seas Indicator Working Group has been established under the United Nations Environment Programme (UNEP) Regional Seas Conventions, Protocols and Action Plans, and has developed a core set of 22 regional seas indicators on marine litter. Work is ongoing to develop common methodologies for these indicators, building upon monitoring programmes in each region (GESAMP, 2019). Some Regional Seas Conventions instruments or bodies (for example, the Coordinating Body on the Seas of East Asia, the Oslo and Paris conventions and the UNEP/Mediterranean Action Plan) have updated or are considering updates to action plans to include port reception facilities to better manage administrative and legal matters, and to enforce, control and monitor systems, infrastructure and alternatives for collecting and treating ship-generated waste. Table 1 provides an overview of the state of knowledge in different basins of the world ocean.

Table 1. Overview of the state of knowledge of marine litter in the different basins of the world ocean.

	Sources/ distribution	**Importance**	**Circulation**	**Impacts**
Arctic Ocean	Plastic and microplastics in sea ice, surface and deep waters, deep-sea sediments and biota (Kanhai and others, 2018; Peeken and others, 2018).	Low quantities of marine debris; microplastics several orders of magnitude higher in sea ice (Cózar and others, 2017; Barrows and others, 2018). High prevalence of ghost fishing gear and impact in fishing grounds	Debris transported to the north via surface branch of the thermohaline circulation.	Low concentrations of microplastics in polar cod (*Boreogadus saida*), bigeye sculpin (*Triglops nybelini*) (Kühn and others, 2018; Morgana and others, 2018) and in 11 species of benthic invertebrates (Fang and others, 2018). Plastic accumulated by Greenland shark (*Somniosus microcephalus*) (Leclerc and others, 2012; Nielsen and others, 2014).
North Atlantic, Baltic Sea and North Sea	Litter and microparticles in all components of the marine environment; monitoring data since 1988 in the North-East Atlantic (OSPAR, 2017) and since 2005 along the coast of the United States of America.	Beaches in OSPAR[192] area have litter in the range of hundreds of items per 100 m (maximum at 6,090). Litter is widespread on the sea floor (Maes and others, 2018); abandoned and lost fishing gear is the most important type of litter in the Baltic sea.	Surface litter from populated areas of North East Atlantic transported to the Arctic. Litter from South-Eastern Atlantic travel through the equatorial current to the Western Atlantic and from North-West Atlantic to	Many species with ingested litter or microplastics; 94% of birds in the North Sea have pieces of plastic in their stomach; Entanglement (seals, sea turtles, birds, invertebrates, etc.) is a common pattern in the North Atlantic.

[192] Convention for the Protection of the Marine Environment of the North-East Atlantic; United Nations, *Treaty Series*, vol. 2354, No. 42279.

			the North Atlantic gyre (Van Sebille and others, 2015).	
Mediterranean Sea and Black Sea	Amount of municipal solid waste from 208 to 760 kg/capita/year; 250 billion particles are afloat (Collignon and others, 2012); highest concentration worldwide for floating microplastics (64 million items/km^2, (Van der Hall and others, 2017)) and sea floor debris (1,3 million items/km^2 (Pierdomenico and others, 2019); Black Sea beaches and seabed largely affected by abandoned or lost fishing gear.	Mediterranean Sea is one of the most affected areas worldwide (Ioakeimidis and others, 2017); five types of single-use plastics (cutlery/trays/straws, cigarette butts, caps/lids, plastic bottles and shopping bags), more than 60% of total type of marine litter.	Mediterranean and Black Seas are closed basins, with important large rivers (Nile, Po, Danube) (Lechner and others, 2014; Lebreton and others, 2017); touristic destinations, with high volume of maritime traffic.	All types of impacts described in the Mediterranean Sea, including ingestion by many species, entanglement, release of chemicals, rafting of various species.

South Atlantic Ocean	All types of litter in South Atlantic due to highly populated areas and large rivers; pelagic plastics restricted to Tropical Atlantic Ocean (Eriksen and others, 2014); in all islands (Ivar do Sul and others, 2014) hard plastic fragments, plastic films, paint chips, fibres, and strands; deep sea floor litter with high densities in south-east (Woodall and others, 2015), dominated by single-use items and microplastics.	Litter at very high concentrations, locally, but basin not the most affected area. In the islands of the Caribbean Sea, higher densities of macroplastics as compared to other islands in the Atlantic Basin; sources more related to human occupation than to fisheries (Ivar do Sul and others, 2014).	Besides general circulation scheme, linked to geostrophic currents and the presence of the South Atlantic gyre, transport to remote islands is an important driver (Monteiro and others, 2018).	Despite a lack of data from eastern part, all types of impacts described in South Atlantic, including ingestion by many species, entanglement, release of chemicals, rafting of various species.
Indian Ocean	South-East Asia and India are main sources of marine debris (Jambeck and others, 2015, Lebreton and others, 2017). Available data very recent or from South Africa and India.	Indian Ocean has greater surface particle count and weight of plastic, a large part of which is in Gulf of Bengal and central part of the basin, than South Atlantic and South Pacific combined (Eriksen and others, 2014); deep-sea floor litter at high densities far from coasts (Woodall and others, 2015), dominated by fishing gear, but with patchy distribution in South-Eastern part (Woodall and others, 2014); plastic and	Because of nature of currents, marine litter dumped anywhere is transported to southern Indian ocean gyre (Van Sebille and others, 2015), but also to western part by the residual circulation (Veerasingham and others 2016), thus reaching remote and unpopulated islands; West Indian Ocean and Arabian Sea	Data limited; impacts described include ingestion by many species (fish, invertebrates, sea turtles, etc.), entanglement (sea turtles, birds), release of chemicals, rafting of various species.

		microplastics also in adjacent seas of Indian Ocean, including Red Sea (Arossa and others, 2019); in Persian Gulf, low density polyethylene and polypropylene, in seawater and sediments (Abayomi and others, 2017).	heavily trafficked by commercial shipping and fishing vessels, loss of fishing gear and dumping of garbage prevalent (Woodall and others, 2015).	
North Pacific	Besides the Mediterranean Sea, the North-West Pacific is the most affected region (Chiba and others, 2018); shores of Pacific Ocean and East Asian marginal seas are surrounded by countries with rapid economic expansion; and high inputs from countries such as China, Indonesia, the Philippines, and Vietnam (UNEP and GRID-Arendal, 2016).	North Pacific disproportionately affected by plastic (Eriksen and others, 2014) from land-based sources and often sea-based sources in highly populated islands (Filho and others, 2019). ALDFG represents 46% of mass of debris larger than 5 cm, which accounted for one third of total mass of floating litter (Lebreton and others, 2018). Densities of marine debris reach millions of items/km^2 (Eriksen and others, 2014; van Sebille and others, 2015), with plastic as predominant material - 90 % of small pieces.	Beside the general circulation scheme, linked to geostrophic currents and presence of North Atlantic gyres, natural disasters, like tsunamis or earthquakes act as drivers in generation of litter.	All types of impacts, including entanglement and ingestion by marine organismsincluding birds, sea turtles and mammals, detected in the deepest invertebrates of the Mariana Trench (Jamieson and others, 2019). In some regions, because of fisheries (Alaska) or drifting litter (Hawaii), entanglement seriously affects marine ecosystems, such as coral reefs or animal forests, or untargeted populations, such as pinnipeds (Claro and others, 2019).

South Pacific	Compared to other ocean basins, there is relatively little new information on plastic concentrations data are mainly from Chile and Australia.	Highest concentrations of debris on beaches (239.4 ± 347.3 items/m^2, max 671.6 items per m^2) on Henderson Island (Lavers and Bond, 2017); in Isla Salaz y Gómez, close to the centre of the South Pacific Subtropical Gyre (SPSG) debris levels are significantly lower (<1 item/km^2) (Miranda-Urbina and others, 2015); highest recorded floating plastics in SPSG - more than 390,000 items/km^2 (at a maximum of 50,000 items/km^2) (Miranda-Urbina and others, 2015; Eriksen and others, 2018).	Different oceanographic models and empirical data sets suggest that marine debris counts and concentrations in SPSG are lower than other subtropical gyres in the Northern Hemisphere (Van Sebille and others, 2015). Locally, rivers may also play an important role in the distribution of marine litter (Gaibor et al., 2020)	Ninety-seven different species of animals, including turtles, fish, seabirds, mammals, and corallimorphs, either ingested or became entangled in plastics (Thiel and others, 2018; Markic and others, 2018); evidence of ingestion rates closer to subtropical gyres (Thiel and others, 2018); microplastics ingested in ultra-deep amphipods (Jamieson and others, 2019).
Southern Ocean	Lowest densities of plastic litter in the world, due to small-scale human activity; marine debris on a very local scale; potential input of approximately 44–500 kg of microplastics per decade (Waller and others, 2017); microplastics generated from macroplastic degradation or transferred across the limit of the Polar region (Polar Front).	Microplastics in intertidal sediments from a sub-Antarctic island (Barnes and others, 2009) in deep sea sediments in the Weddell Sea (Van Cauwenberghe and others, 2013), in surface waters of the Pacific sector (Waller and others 2017; Isobe and others, 2015 & 2017) and in shallow sediments and macroalgae at sites on King George Island near scientific research stations (Waller and others 2017); concentrations of 0.100–0.514 g/km^2 in South Polar Front and ranging from 46,000–99,000 particles/km^2 south of latitude 60ºS, with higher concentrations	Transfer of litter from northern waters to Antarctica is common.	Macroplastic and fishing debris on beaches and in seabird colonies at Bird Island Research Station since austral summer 1992/93 (Barnes and others, 2009); plastic particles ingested by 12 species of seabirds, the majority in association with wandering and grey-headed albatrosses and recently in penguins (Bessa and others, 2019); encounters between marine mammals and marine debris - mainly Antarctic fur seals entangled in plastic packaging bands, synthetic line and fishing nets; incidents have significantly reduced

		in coastal regions of the Ross Sea (Cincinelli and others, 2017; Cózar and others, 2014; Isobe and others, 2017); plastics in sediments from Terra Nova Bay, total of 1,661 items (3.14 g) with fibres the most frequent type (Munari and others, 2017); in surface trawls in the Antarctic peninsula, debris estimated at 1,794 items/ km^2, an average weight of 27.8 g/km^2, not originated from latitudes lower than 58°S; paint fragments 30 times more abundant than plastics (Lacerda and others, 2019).		since introduction of legislation in the late 1980s prohibiting disposal of plastics overboard, and improvements in disposal of packaging bands (Barnes and others, 2009).

1.5. Trends

Understanding the factors associated with changes in the quantities and impact of marine litter and the magnitude of such changes remains difficult because of the lack of standardization of methods for collection and analysis. Thus it is difficult to accurately compare counts or levels from different locations and/or over time. Moreover, reports often address a specific component of the marine environment, such as types of litter and impacts, without attention to natural environmental variability (GESAMP, 2019), which impairs complete understanding of the state of and possible changes in marine litter densities and impacts.

Table 2 summarizes the available information on beach, sea floor, floating and ingested marine litter worldwide. Additional information can be obtained from the online portal for marine litter.[193] While several modelling studies predict increasing trends (Kako and others, 2104; Everaert and others, 2018; Lebreton and others, 2018), that may be potentially balanced by reduction measures. most of the work based on regular surveys did not demonstrate any trend, other than in specific cases like remote islands in the Antarctic (Barnes and others, 2009), ingested plastic in south Atlantic petrels (Petry and Benemann, 2017), or specific features like converging currents above the Arctic Circle (Tekman and others, 2017). This increase in remote areas could be interpreted as a long-term transfer from affected areas to regions where human activity is either extremely reduced or non-existent. Decreasing trends were demonstrated in certain cases, like ingestion of debris, especially in respect of industrial

[193] Available at https://litterbase.awi.de/litter.

granules. Brandon and others (2019) and Wilcox and others (2019) also suggested an increase in sediment microplastics in California and floating microplastics in the North Atlantic, in relation to plastic production worldwide. The challenge now is to better understand how plastic is cycled through marine ecosystems, where it goes and how it degrades.

Table 2. Marine litter trends in various locations and components of the marine environment (compilation of data from reports and scientific literature)

Location	**Compartment/ species**	**Period (duration)**	**Methods**	**Trends**	**Observation**	**Reference**
East Greenland	Ingested microplastics (little auks, Alle alle)	2005 and 2014	Collected from live birds in nests	No evident temporal trend		Amélineau and others, 2016
East Greenland	Subsurface microplastics	2005 and 2014	WP-2 net, vertical tows -50m to surface	Significant increase		Amélineau and others, 2016
North Atlantic/ Arctic Circle, Fram Strait	Deep sea floor, two stations at #2500m, 79–79°35' North	2002–2014	Towed camera	Clear increase in litter densities and small-sized plastics abundance	Possible spreading from Europe to North and Arctic Basin	Tekman and others, 2017
North-East Atlantic	78 beaches	2001–2011	OSPAR/ MSFD* protocol	No large-scale trends	Hydrodynamics /climate-related drivers for local short -term changes	Schultz and others, 2013
North-East Atlantic (Rockall Trough)	microplastics ingestion in deep-sea benthic invertebrates (> 2000m)	1976–2015	Epibenthic sled/ Agassiz trawl	No trends between overall abundance or polymer types	2 species	Courtene-Jones and others, 2019
North Atlantic	Floating/ subsurface	1957–2016	Debris trapped in towed CPR,** 16,725 tows	Increase since 1957, no trend since 2000, no change in Arctic waters	6.5 million nautical miles	Ostle and others, 2019

North Sea, UK waters	Seabed, 17–150 stations/year	1992–2017	MSFD* classification system	No detectable trend	Unit: presence of plastic	Maes and others, 2018
North Sea/ Netherlands	Birds (fulmars, 973 samples stranded)	1979–2012	OSPAR regular protocol (mass and number)	Increase to mid-1990s; stable in the last decade; significant decrease of pellets		Van Franeker and Lavender Law, 2015
Irish waters	Cetaceans (stranded and bycatches)	1990–2015	Stomach content	No trend for ingestion of litter and entanglement		Lusher and others, 2018
Baltic Sea	2377 hauls/53 cruises	2012–2017	MSFD/BITS	Last 2 years, increase in plastics; no trend for litter from fishing	Plastic - 35% of litter	Zablotski and Kraak, 2019
Baltic Sea	245 stations; floating/ingested microplastics - Atlantic herring and sprat (814 samples)	1987–2015	Plankton samples and trawling, stomach content	No change in floating or ingested microplastics		Beer and others, 2018
North Atlantic Subtropical Gyre	Floating microplastics	1986–2008	6,136 surface Neuston nets, 335-µm mesh	No trend	Sea Education Association, archived plankton samples	Lavender Law and others, 2010
North Atlantic Subtropical Gyre	Floating plastics (2,624 tows)	1987–2012	Surface Neuston nets, 335-µm mesh	No significant change in user plastics, highly significant decrease of industrial plastics	Extension of the work from Lavender Law and others (2010)	Van Franeker and Lavender Law, 2015
North-East Adriatic Sea	Seabed, 67 stations	2011–2016	Otter trawl	Decrease in total litter; no trend for plastic	50% of plastic is from fishing/ aquaculture	Strafella and others, 2019

France, Mediterranean Sea	Sea floor/shelves and canyons	1994–2017	Trawling, 1,902 hauls, MSFD* classification system	No regular increase but higher levels in 1999-2001 and since 2012	Plastic is up to 62%	Gerigny and others, 2019
Spain/ Mediterranean	Seabed Shelves, 1323 hauls	2007–2017	Trawl, MSFD* classification system	No temporal trend, decrease in Alboran Sea	Medits project	García-Rivera and others, 2018
Western Mediterranean	Ingested debris/ sea turtles	1995–2016	MSFD classification system*	Slight decrease	195 samples	Domènech and others, 2019
Balearic Islands	Floating	2005–2015	Onshore/ offshore cleaning boats	No trend (all types of debris); increase in summer	From cleaning operations	Compa and others, 2019
Southern Brazil	Birds (white-chinned petrels, 122 samples, stranded)	1990–2014	Stomach content	Increase of fragments and pieces; decrease of virgin pellets		Petry and Benemann, 2017
North Pacific Subtropical Gyre	Floating microplastics	2001–2012	2,500 surface Neuston nets, 335-µm mesh	No evident temporal trend,	Confounded spatial and temporal variability	Lavender Law and others, 2014
Taiwan Province of China	Beach litter, 541 clean ups events	2004–2016	Clean ups	No temporal trend	Data from ocean coastal cleanups	Walther and others, 2018
China	National monitoring, beaches, surface and sea floor	2011–2018	State & Oceanographic Adminsitration (SOA) protocols	No trend		MEE/PRC, 2019
China	23 sites (beaches and adjacent waters; floating and seabed)	2007–2014	North West pacific action Plan (NOWPAP)/ SOA protocols	No clear trend	Percentage of plastic increasing in seabed litter	Zhou and others, 2016

Chile	Beaches (all coasts); 3 surveys, 69 beaches	2006–2016	Participative science, main categories	No trend	Three sampling years	Hidalgo-Ruz and others, 2018
Ecuador	Beaches (26 sites)	2018-2020	Participative science (400 volunteers)	No trend	One year sampling	Gaibor and others, 2020

*MSFD: Marine Strategy Framework Directive; **CPR: continuous plankton recorder.

1.6. Consequences of the change on human communities, economies and well-being

The most significant impact of the use of plastic in products and packaging is marine pollution (UNEP, 2014) but it is important to emphasize that it is difficult to quantify the economic impact of marine litter. Based on 2011 figures, the economic costs of marine plastic, as related to marine natural capital, are conservatively conjectured at between USD 3,300 and USD 33,000 per ton per year (Beaumont and others, 2019). While the input of plastic to the ocean is limited in European coastal areas (Jambeck and others, 2015), the estimated costs of cleaning up marine litter in coastal areas can amount to up to 630 million euros per year (Crippa and others, 2019). More recently (MacilGorm and others, 2020) a 9 fold increase in direct economic costs of marine litter was found from 2009 to 2015, reaching 10.8 billion USD.

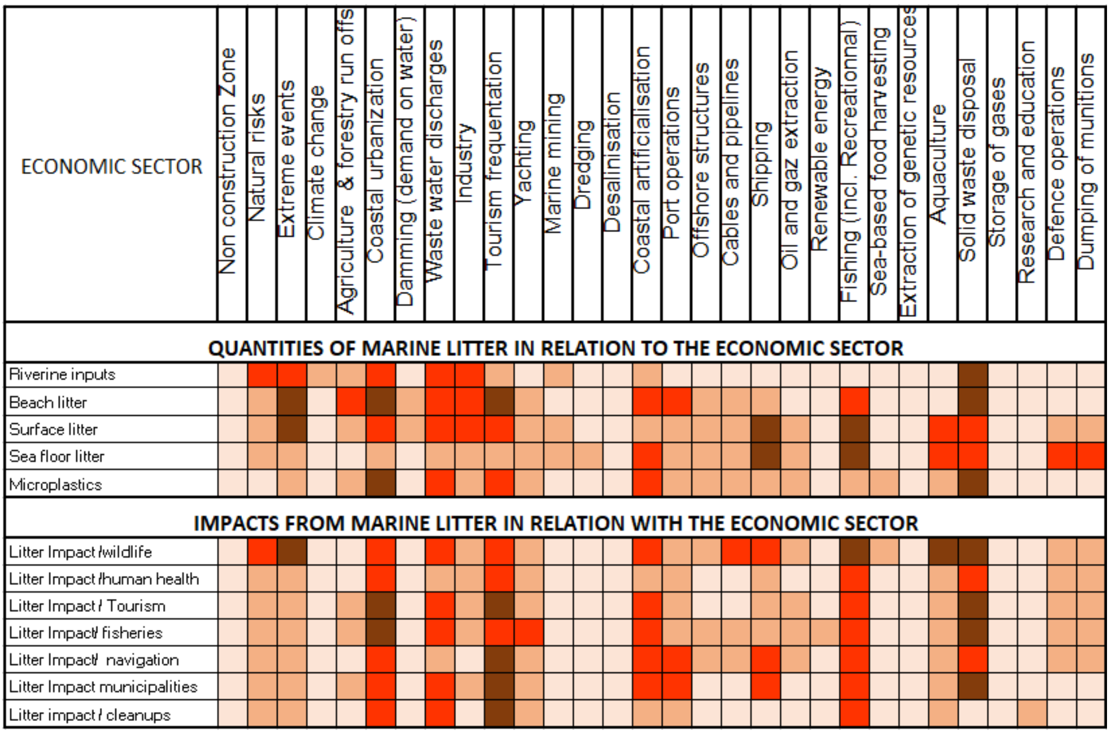
Beside indirect impacts (i.e. impact on biodiversity and ecosystems), beach litter is perhaps the most visible direct impact and affects the patrimonial value of coastal areas that can be translated as the financial expenditure of cleaning up (UNEP, 2019). Damage and costs to marine ecosystems and services must be considered in the future despite an actual limited understanding of the detrimental impacts on the marine ecosystem structure and functioning.

Marine litter can also result in increased costs for the shipping sector and recreation activities, including yachting (fouled motors, entangled propellers, lost output and repair costs) (Hong and others, 2017), but the damage and associated social costs also extend to other sectors such as aquaculture and fisheries. The removal of 10 per cent of derelict fishing pots alone would provide estimated additional revenues of 831 million USD annually for the global crustacean fishery industry (Scheld and others, 2016).

Most microplastics found in marine organisms are in their digestive system, which people do not ordinarily consume, with the exception of shellfish and small fish that are consumed whole. Beside accidents and injuries, there is no evidence that microplastics concentrations have a negative impact on fish and shellfish health or commercial stocks (Barboza and others, 2018). Links to human health are not sufficiently addressed, and gaps in knowledge are even greater when it comes to nanoplastics (less than 1 micron), particularly their absorption and behaviour (GESAMP, 2016, see also chapter 8) and how they may pass through biological barriers via different mechanisms (Wright and Kelly, 2017). As relevant toxicity data are absent, the European Food Safety Authority (EFSA) concluded that it is currently not possible to evaluate the human health risk of nanoplastics and microplastics (EFSA CONTAM, 2016). Moreover, there are indications that microplastic fibre ingestion by humans via the consumption of contaminated seafood is only a minimal contribution to the microplastic contamination of the total food basket (Catarino and others, 2018).

The socioeconomic impact of marine litter and the potential cost for key sectors and activities in or depending on the marine and coastal environment have not been well assessed, resulting in mispricing of ecosystem values and externalization of pollution costs. Approaches for giving value to marine litter are not well known either. Efforts need to focus on assessing the environmental and socioeconomic costs of the damage caused by marine litter and the cost/benefit of marine litter prevention/reduction measures (Table 3).

Table 3. Marine litter in relation to: economic sectors; sources, amounts and impacts; colour shading increases with the importance of impact (UNEP, 2019).



1.7. Relevance to the United Nations Sustainable Development Goals (SDGs)[194] and other frameworks

Global commitments on marine litter have been made in the context of the United Nations General Assembly and Environment Assembly, as well as the Convention on Biological Diversity,[195] and in recent Group of Seven (G7, Action Plan to combat marine litter) and Group of 20 (G20, Marine Litter Action Plan) declarations (UNEA-4, 2019). In 2016, the

[194] See United Nations General Assembly resolution 70/1.
[195] United Nations, *Treaty Series*, vol. 1760, No. 30619.

United Nations Environment Assembly adopted resolution 2/11 to combat marine plastic litter and microplastics[196] and, in 2019, published the Guidelines for the Monitoring and Assessment of Plastic Litter in the Ocean.[197]

Marine debris is directly linked with SDG 14 on conserving and sustainably using the oceans, seas and marine resources for sustainable development. SDG Target 14.1 is currently classified as a Tier III indicator, on which no internationally established methodology or standards are available (UNEA-4, 2019). To advance measurements of SDG indicator 14.1.1,[198] more harmonized methods are proposed to encourage development and implementation of regional or global monitoring programmes and facilitate exchange of results. These will help to move SDG Indicator 14.1.1 from Tier III to Tier II (for which conceptually clear, established methodology and standards exist, but data are not regularly produced).

Micro-and nanoplastics also relate to SDG 12 on ensuring sustainable consumption and production patterns. SDG 11 should be also mentioned since plastic marine litter also originate from mismanaged waste of urban settlements, when solid waste ending in the ocean is directly related to SDG6, as plastic litter and microplastics are carried by mismanaged wastewater and stormwater.

In 2019, the G7 reviewed the ongoing activities within the Regional Sea Conventions and set priorities for further actions, ensuring effective coordination through United Nations bodies to address monitoring and the socioeconomic impacts and consequences on human health and biota; and the involvement of industry in developing and implementing responses on management of waste and prevention;. Also, in the framework of the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal,[199] the parties adopted amendments to the annexes thereto, to bring certain plastic wastes within the scope of that Convention, inter alia, to address the impacts of plastic on the marine environment.[200]

Beside many national plans, inter-regional policies, such as the European Union Plastic Strategy (2018) and its various legally binding directives (MSFD directive 2008/56/EC, PRF Directive, 2019/883/EU, Single-Use Plastics Directive 2019/904/EU)[201] constitute a good example of an approach to address marine litter, taking into account circular economy principles, with many measures that are now being implemented (e.g. new materials, wastewater treatment, bans, extended producer responsibility, etc.).

Many initiatives have been launched to include scientific, political, social and economic action in projects, from both the individual and the global system perspective. As an example,

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[196] See United Nations Environment Assembly of the United Nations Environment Programme, document UNEP/EA.2/Res.11.
[197] Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), Report and Studies No. 99.
[198] See United Nations General Assembly resolution 71/313, annex.
[199] United Nations, *Treaty Series*, vol. 1673, No. 28911.
[200] See United Nations Environment Programme, document UNEP-CHW.14-28. Also available at http://www.basel.int/TheConvention/ConferenceoftheParties/Meetings/COP14/tabid/7520/Default.aspx.
[201] Available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019L0904.

the online, free Massive Open Online Course (MOOC) on Marine Litter[202] aims to form a global network of actors actively involved in addressing marine litter challenges. New tools such as mobile applications also enable citizens to log data on the location and type of debris found on coastlines and waterways into scientific databases. Other effective tools, such as the publically available European Marine Observation and Data Network (EMODnet),[203] include digital maps of litter, thus providing a comprehensive tool for marine policy and society as a whole.

More than 60 countries have introduced bans and levies to curb single-use plastic waste (UNEP, 2018), often without data/metrics or monitoring in place to evaluate the effectiveness and consequences of these actions. Measures include a ban on certain items (such as plastic bags), the introduction of levies or deposit systems and voluntary agreements at the industry level.

A variety of existing measures have been implemented already (FAO, 2016), including gear marking; port-state measures; onshore collection; payment for retrieved gear; better location and reporting of lost gear; disposal and recycling; alternatives to single-use plastics, especially polystyrene fish boxes; and awareness-raising schemes.

Pursuant to the International Convention for the Prevention of Pollution from Ships (MARPOL),[204] efforts to address marine litter include the development of a port reception facility database as a module of the International Maritime Organization Global Integrated Shipping Information System.

1.8. Outlook

Management of marine litter pollution is exceptionally complex and requires an integrated approach, encompassing science, legislation, economics, ocean literacy, education, social participation and international cooperation regarding capacity building, technology transfer, as well as technical and financial support on multiple levels, from global to regional to local due to the diversity of the actors, sources, materials, socioeconomic aspects and regulatory frameworks involved. Without improved international policies and mobilization, plastic pollution will only worsen (Jambeck and others, 2015). It is estimated that, if current consumption patterns and waste management practices do not improve, there will be about 12 billion tons of plastic litter in landfills and the natural environment by 2050 (Geyer and others, 2017). The consequences will not be purely economic, and the environmental impact will be huge.

A variety of options exist to deal with critical levels of marine litter, some of which include options to address the issue, understanding that not all of them are applicable to or supported by every country, and some do not consider adverse impacts.: reduction of plastic consumption; support for eco-design/innovation (especially research into end of life plastic

[202] Available at https://sustainablehighereducation.com/2019/03/22/mooc2019/.
[203] Available at http://www.emodnet-bathymetry.eu/approach.
[204] United Nations, *Treaty Series*, vol. 1340, No. 22484.

issues and alternatives);"; resource efficiency and better management of waste and water; long-term efficient and viable recycling targets for municipal waste and packaging/plastic waste; greater use of policy instruments and control measures, including incentives, taxes, and other regulatory measures, for example bans or extended producer responsibility schemes; and the adoption of remanufacturing initiatives and coordination of policy investments in the waste sector (Ten Brink and others, 2018). There is also a need for a tight regulation and supervision of global waste trading, especially scrap plastic.

Plastic pollution is also a gateway to effective environmental education. The challenge is to change people's perception and understanding of this issue, so that people can see plastic pollution as a vector of education, awareness and literacy, as well as to find potential strategies to overcome political, economic and cultural barriers. Within the context of marine litter science, the objectives may be related to policy-relevant goals and thus increase the stimulus to citizens (GESAMP, 2019).

1.9. Key remaining knowledge and capacity-building gaps

For microplastics, major gaps in knowledge include quantification of microplastics in the marine environment using standardized methods and information on how plastic degrades in various components of the marine environment and on the presence and impact of nanoplastics. More research is needed into the role of plastic debris as a transport vector of pathogens, antibiotic resistance, chemicals and biotoxins and the potential for dispersing diseases among marine life and human populations. Finally, in many countries, the lack of adequate national/regional monitoring of quantities and impacts of marine litter, including plastics, is a major bottleneck for addressing the issue and for assessing effectiveness of already taken measures.

Recent programmes (Commonwealth Scientific and Industrial Research Organisation, CSIRO, University of Baltimore and MSFD) have been designed to answer some of the scientific questions around the factors governing the distribution of land-based litter and the quantity of litter that flows from land to sea. Outputs of these initiatives are expected to include data-driven estimates of leakage rates to the sea, but also to help countries to understand where best to target effective interventions to stop debris from entering the ocean. With different methodologies developed to measure plastic leakage into waterways and oceans, from either mismanaged waste or in the form of microplastics, there is a need for harmonizing these different approaches.

Most significantly, there are insufficient infrastructures and policies regarding recycling, wastewater and solid waste management (UNEP, 2017b). In addition, and although illegal stakeholders may be active in solid waste collection and recovery, legislation is weak and there are huge disparities between countries with informal sectors, illegal manufacturing and black markets, that are limiting the implementation of reduction measures in use, waste management and prevention (UNEP, 2019). There is, however, general agreement and a raft of initiatives from all stakeholders on implementing more sustainable patterns of production and consumption, including circular economy, which is aimed at eliminating waste and the continual use of resources, by promoting reuse, sharing, repair, remanufacturing and recycling to create a close-loop system.. The recent actions taken at the United Nations Environmental Assembly (UNEA-4, 2019) largely support this approach with resolutions on sustainable consumption, production and business practices, waste management and single-use plastic products.

Additional gaps include weak enforcement, separate collection, strong regional disparities between urban and rural areas, and poor storm-water management. Essential measures include those aimed at securing landfills, developing port waste management, promoting best practices for the fishing industry and improving maritime transport to limit container losses or primary microplastics spills.

Understanding that the reduction in plastic consumption should lead to a reduction in plastic waste generation, barriers in tackling marine litter and microplastics may be related to unsustainable patterns of consumption and production. Collaboration with the private sector and industry is needed to promote a shift towards sustainable solutions. Insufficient economic incentives may be an underlying reason for challenges related to changing behaviours. Finally, the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances, is of particular interest for both producers and users of plastic.

Table 4. Summary of knowledge and capacity-building gaps.

Knowledge gaps
Incomplete knowledge about root causes of marine litter. Research is not focusing on the sources and fate of plastic pollution
Microplastics: and nanoplastics accurate accounting methods and analytical tools related to throughput, detection limits, precision and quality are limited
Polymer identification is complex and time consuming for micrometre range particles
Fragmented scientific knowledge (scale of plastic pollution, microplastics, scientific/technical basis for monitoring, coordination on data, toxicity of plastics, risk assessment, fate)
Unknown effects on human health of ingestion of plastic-contaminated seafood
Little knowledge of the contribution and impacts of ALDFG and aquaculture-related marine litter
Knowledge of the degradation of plastics and the leaching of additives or other chemical classes in different environments remains limited
Scope and granularity of computational models are insufficiently developed
Knowledge gaps regarding economic impacts of plastics on fisheries, tourism, maritime transportation. Links between marine litter fluxes and regional economy poorly understood
The impact of marine plastic litter on climate change through extremes events, and the possible release of emissions or by limiting the oceans ability to act as carbon sink has to be studied further
Extended Producer Responsibility (EPR) is difficult to implement in some countries, especially archipelagic

countries
Lack of public awareness, behaviour change and circular economy models, with differences in educational levels depending on the countries
Capacity-building gaps
Monitoring not in place in many parts of the world
Technical difficulties in locating accumulation areas and specific types of litter (ALDFG)
Technological shortcomings. (i.e. deficiencies in waste management infrastructures). Solid policies must relate to environmentally sustainable and efficient waste management, recycling capacity, and materials substitution
Economic evaluation methodologies need to incorporate costs of plastic in the environment
Lack of integrated decision-making on different levels and coordination in the establishment and implementation of programmes including measures targeting regional priorities
Weak enforcement of measures
Insufficient/inefficient waste treatment infrastructures and policies; inexistent waste management in many parts of the world
Strong regional disparities between urban and rural areas
Poor storm-water management
Inadequate infrastructures for waste collection, management, recycling, port reception
Recyclability must be improved
Collaboration and coordination with the private sector and industry needed to reduce/transform the production, demand and consumption of plastic.
Awareness, information and education must be improved

2. Dumping at sea (including garbage from ships and sewage sludge)

2.1. Introduction

Dumping is any deliberate disposal of wastes or other matter from vessels, aircraft, platforms or other man-made structures at sea, according to Article 1, para. 5 (a) (i), of the United Nations Convention on the Law of the Sea (UNCLOS),[205] the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972 (the London Convention, LC), and the 1996 London Protocol (LP) thereto.

Dumping of substances such as dredged material, sewage sludge, industrial waste, fish waste,

[205] Ibid., vol. 1833, No. 31363.

discharges from vessels and human-made structures, organic and inorganic chemicals, radioactive material, war explosives and military chemicals has impacted the marine ecosystems and created environmental challenges (OSPAR, 2010b, IMO, 2018). In addition to UNCLOS, to counter the environmental challenges resulting from waste dumping, London Convention and London Protocol provide provisions for controlling unregulated dumping and incineration of wastes at sea. These regulatory requirements have been amended on several occasions (IMO, 2018). Additionally, many countries have developed regional initiatives and approaches to control and assess waste dumping activities. Initiatives have also been taken under the framework of the Stockholm[206] and Basel[207] Conventions to address the control of transboundary movements of hazardous wastes and their disposal, as well as to protect human health and the environment from persistent organic pollutants.

2.2. Situation recorded in WOA I

Chapter 24 of WOA I on solid waste disposal (United Nations, 2017a) outlined the regulatory system relating to dumping and important international milestones, such as the adoption of the London Convention and London Protocol. An overview of the regulatory techniques and the waste streams covered under both instruments was provided, as well as efforts made to understand the quantity and nature of waste and other matter being dumped. WOA I (United Nations, 2017b) also identified concerns about under-reporting by many Contracting Parties to the London Convention and London Protocol, leading to difficulties in deriving a clear picture for assessing regime implementation and understanding waste dumping status.

2.3. Changes in the state of dumping at sea

The LP prohibited all dumping of waste, except for a limited number of categories such as: (a) dredged material; (b) sewage sludge; (c) fish waste, or material resulting from industrial fish processing operations; (d) vessels and platforms or other human-made structures at sea; (e) inert, inorganic geological material; (f) organic material of natural origin; (g) bulky items primarily comprising iron, steel, concrete and similar non-harmful materials for which the concern is physical impact and (h) sub-seabed sequestration of carbon dioxide streams in sub-seabed geological formations (IMO, 2018).

Changes in the overall waste dumping status can be understood by reviewing waste dumping data published and permits issued under the London Convention and London Protocol (IMO, 2019). The following sections provide an overview for each of the solid waste dumping categories.

2.3.1. Sewage sludge dumping

Sewage sludge dumping impacts sediment quality, benthic assemblages, aquatic flora and fauna and, in general, the whole marine ecosystem. Excessive nutrient loads from sewage

[206] Ibid., vol. 2256, No. 40214.
[207] Ibid., vol. 1673, No. 28911.

discharges can lead to a reduction of oxygen content in water, cause marine life mortality and destroy entire habitats and ecosystems (see Chapter 10 of the present Assessment). A total of 13 Contracting Parties reported disposal of sewage sludge for the period from 1976–2016, with a total amount of 393 x 10^6 tonnes (IMO, 2019). Figure 3 shows that dumping has declined dramatically to the point that many Contracting Parties prohibit the activity and very few report disposal operations. In 2011, a total of 0.6 million tonnes were dumped while, in 2016, it reduced to only 0.00041 million tonnes.

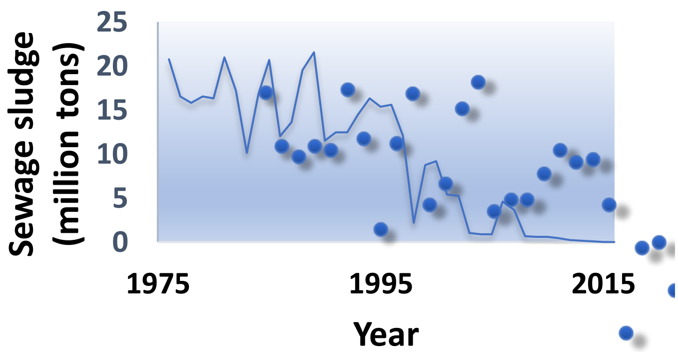

Figure 3. Amount of sewage sludge dumped (IMO, 2019).

In 2016, the International Maritime Organization published a report of the current state of knowledge regarding marine litter in wastes dumped at sea under the London Convention and London Protocol. It aimed to review whether sewage sludge or dredged material contained marine litter, according to litter types, properties and quantities. The review concluded that such an assessment was currently difficult due to an overall shortage of data, differences in methodology and reporting and the lack of systematic sampling in space and time (IMO, 2016a).

2.3.2. Disposal of vessels at sea

Approximately 22 Contracting Parties to LC and LP reported disposing of 758 vessels from 1976–2010 (IMO, 2016a). Some of these vessels have been disposed of to create reefs (Hess and others, 2001) but in other cases, LC and LP parties only permit the dumping of vessels when no land-based disposal options exist and dumping of these vessels are in deeper waters and not for reefs purposes Other disposal vectors from vessels include material for scientific experiments (IMO, 2016b).

2.3.3. Dumping of organic and inorganic wastes

Organic and inorganic wastes have long been disposed of at the sea, primarily loaded from land and transported offshore and disposed of at sea from vessels and platforms. Many nations continue to use the ocean as an ongoing depository for certain wastes generated within their borders. A total of 15 Contracting Parties to the London Convention and London

Protocol reported disposing of inert, inorganic geological material at sea for the period from 1983–2010, with a total amount of 315,227 x 10^6 tonnes (Figure 4) (IMO, 2016a). In 2011, 3.82248 million tons were dumped, with 1.453, 725 million tons in 2013 and 1.229620 million tons in 2016 (Figure 4).

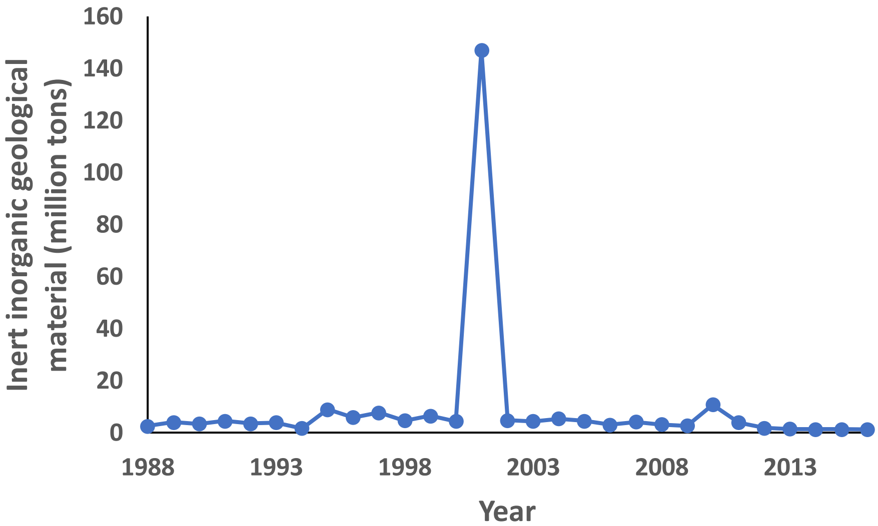

Figure 4. Amount of inert, inorganic geological material licensed (IMO, 2019).

Also, a total of 17 Contracting Parties to the London Convention and London Protocol reported disposing of organic material of natural origin at sea for the period from 1977–2010, with a total amount, including spoilt cargo (consisting of organic material of natural origin), of 37,628 x 10^6 tonnes (IMO, 2016a). Spoilt cargo was reported as disposed of at sea (total amount of 31,833 x 10^6 tonnes) by seven Contracting Parties from 2003 to 2010 (IMO, 2016a).

2.3.4. Dumping of industrial wastes and war chemicals

Twenty-three contracting parties reported disposal of industrial wastes at sea from 1976 to 1995 (232 x 10^6 tonnes). These wastes included scrapped vessels, waste explosives in concrete, sludge, waste acids or alkali, cattle industry waste, glass dust, industrial dust, ceramics, ammunition, concrete pipes, demolition rubble, sodium hydrosulphite, sludge containing heavy metals and fluorides, titanium oxide production waste, chlorophenol production waste, chromate production waste, gunpowder, fly ash, fermentation waste and potassium mining waste (IMO, 2019).

War explosives and military chemicals dumped at sea since the first world war still present significant risk to the marine ecosystem and for various users of the sea (Figure 5). Environmental samples typically show low concentrations of munitions compounds in water and sediments (in the order of ng/L and µg/kg, respectively), and ecological risk appears generally low (HELCOM, 2013, OSPAR, 2010a). Nonetheless, recent work demonstrates the possibility of sub-lethal genetic and metabolic effects in aquatic organisms (Beck and others, 2018).

Figure 5. Global distribution of documented marine sites with munitions dumped at sea (www.nonproliferation.org/chemical-weapon-munitions-dumped-at-sea/)

Moreover, the catching of munitions in fisher nets, the interaction of explosives with submarine infrastructure or offshore installations, as well as related material floating to the surface, can lead to accidental burning or explosions (OSPAR, 2010a).

2.3.5. Incineration at sea

Incineration at sea is the disposal of waste at sea, by specially designed incinerator ships, by burning organochlorine compounds and other toxic wastes that are difficult to dispose of. Amendments to the London Convention which entered into force in 1994 banned the incineration at sea of industrial wastes but incineration did not end until 2000 (IMO, 2016a).

2.4. Factors associated with changes

The present section looks at various factors that led to changes in dumping practices, namely, (i) factors that triggered increased dumping activities in the past, and (ii) sustained actions taken to mitigate this grave environmental issue. For centuries, communities have disposed of wastes in the ocean and seas, assuming that they are convenient and safe dumping grounds for diverting land-based pollution. Factors such as ignorance, negligence and a lack of proper waste disposal systems played an important role in these harmful waste dumping practices, as did the lack of strict regulations and monitoring.

Improved scientific understanding, awareness amongst scientific communities and increased government participation, along with growing global concerns, increased the need for international instruments to regulate the dumping of waste in the ocean (IMO, 2018). In addition to UNCLOS, the regulatory measures undertaken within the London Convention and London Protocol were important factors in improving the dumping situation.

Generic and comprehensive guidelines have been developed for all wastes that may be considered for dumping at sea (OSPAR, 2016b; IMO, 2018). Also, guidance on the national implementation of the London Protocol has been developed and updated and provides an outline of the types of action that States should consider at the national level. Based on the under-reporting issues highlighted in WOA I, Contracting Parties to the London Protocol and London Convention took further action to address the situation, including the adoption a strategic plan (IMO, 2019).

2.5. Impacts of changes on/interactions with other components of the marine system

The impacts of discharged materials on the marine ecosystem are the crux of the global solid waste dumping issue. Due to the dynamic nature of the ocean, determining the fate of various dumped materials is a challenging task. Also, the existence of different pollution sources and the complexity associated with tracking down specific contaminants, make it difficult to establish the extent to which ocean dumping contributes to observed ecological effects and impacts. In general, dumping effects depend upon the type, quantity and quality of waste materials as well as the characteristics of impacted areas of the ocean. In addition, the duration of the extended time period of dumping practices contributes to these ecological effects. To comprehend the dynamics, it is necessary to understand the possible impacts of major waste categories on marine components, as well as how changes in dumping practices are alleviating these problems (IMO, 2018).

Solid waste dumping in the ocean and seas can have varied impacts on the marine ecosystem, flora and fauna, as well as human beings relying on saline water sources. These may include, inter alia, chemical pollution (see Chapter 11 of the present Assessment), nutrients pollution and eutrophication (see Chapter 10), water quality degradation, depletion of water oxygen levels, suffocation of marine creatures, decreased submerged vegetation, poisoning and death of oceanic plants and animals and human health hazards. While different pollution pathways and associated sources exist, solid waste dumping actions carry their share of responsibility for the burden on the ocean and seas (IMO, 2018).

2.6. Ecosystem and socioeconomic consequences of continued changes in the system

In the ocean, undesired shifts between ecosystem states are caused by the combination of external forces impacting on and the internal resilience of the system. As resilience declines, the ecosystem becomes vulnerable and, as a consequence, progressively smaller external events can cause shifts. Thus, anthropogenic actions leading to perturbation increase the likelihood of undesired regime shifts (Scheffer and others, 2001).

Just as there is limited knowledge of socioeconomic consequences, the same holds true when assessing the consequences of continued change in the system. Ecosystem state shifts can cause large losses in terms of ecological and economic resources. Restoring a desired state may depend on the degradation affecting the system and require drastic and expensive intervention. One estimate suggests that removing litter from South Africa's wastewater streams would cost about 279 million United States dollars per year (Lane and others, 2007). With regard to other dumping activities, there are significant gaps in knowledge of socioeconomic consequences and of market-based instruments.

2.7. Relevance to the United Nations Sustainable Development Goals (SDGs)[194]

The issue of waste dumping is closely connected to SDG 14, in particular, Targets 14.1 and 14.c. In the context of the present Chapter, the relevant objectives of SDG 14 are also linked with SDG 12 on ensuring sustainable consumption and production patterns, as well as SDG 11 on making cities and human settlements inclusive, safe, resilient and sustainable. There has been a considerable amount of work undertaken to further support integration of the SDGs among sectors, which might have a spill-over effect on dumping at sea. Most notably, the Global Partnership on Waste Management (UNEP, 2010) is an important convergence and integration nexus, particularly as its six thematic areas include integrated waste management, marine litter and waste minimization. Pursuant to LC efforts to address marine litter include the development of a port reception facility facility database as a module of the International Maritime Organization Global Integrated Shipping Information System.

2.8. Outlook

Drivers for change in reference to dumping are associated with modifications to production and consumption patterns of the materials that are currently dumped in the ocean. Whereas different and distinct wastes streams are covered under the London Convention and London Protocol, each stream is associated with separate industries and drivers that might lead to change. Therefore, changing production and consumption patterns need to be inclusive of different stakeholders from a diverse set of industries.

The Strategic Plan, adopted in 2016 at the thirty-eighth Consultative Meeting of Contracting Parties to the London Convention and eleventh Meeting of Contracting Parties to the London Protocol, provides some indication of near- to medium-term development with regard to dumping (IMO, 2018). The plan outlines four strategic directions. Strategic Direction (SD) 1 aims to promote ratification of or accession to the London Protocol and outlines a target substantially to increase the rate per year of new ratifications or accessions thereto. SD 2 aims to enhance effective implementation of the London Protocol and London Convention through provision of technical assistance and support to Contracting Parties, the development of guidance and measures to support implementation by addressing regulatory, scientific and technical barriers, encourage and facilitate improved compliance, including reporting, as well as encourage and facilitate participation of Contracting Parties in the work of both instruments. SD 3 aims to promote the work of the London Protocol and London Convention externally, and SD 4 aims to identify and address emerging issues in the marine environment within the scope of both instruments. To that end, several graded targets have been formulated, whereby, by 2030, 100 per cent of Contracting Parties should be meeting their reporting obligations and should have a national authority in place and appropriate legislative or regulatory authority to implement LC and LP.

Future goals under both LC and LP are the regulation of ocean fertilization and geoengineering and a review of the impacts of new marine “geoengineering” technologies. Further work is envisaged on the basis of IMO-LP/UN/GESAMP collaboration on mine tailings, habitat destruction/restoration and marine litter, in order to address gaps in the international legal framework. Also, easy online reporting will be introduced, a database established, and monitoring activities reviewed. Lastly, the environmental effects of the legacy of chemical munitions dumped at sea in the past will be addressed.

2.9. Key remaining knowledge and capacity-building gaps

Since the adoption of UNCLOS and LC and LP, regulations for solid waste disposal at sea were introduced by coastal States significant progress has been made (IMO, 2018). However, due to substantial under-reporting by many Contracting Parties and a lack of published data, it is difficult to track implementation and understand the current extent of the challenge before us.

Knowledge gaps include:

- Scale of impacts of dumped fibreglass reinforced plastic (FRP) vessels.
- Socioeconomic impacts of all waste streams that are allowed to be dumped, including the legacy of dumping activities.
- Understanding of the impacts of relevant policies on dumping activities and marine environmental impacts (such as waste policies).
- Understanding of the extent and impact of marine litter
- Cumulative impacts of current and dumping activities and prevailing pollution from other sources.

Capacity-building gaps include:

- Monitoring (and reporting) of dumping activities.
- Understanding of the impacts of land-based activities on the amount of waste streams dumped in the ocean.
- New techniques to manage the risks associated with dumped munitions, the development of guidelines on encounters with munitions (such as individuals working in the fishing industry, techniques for safe removal and the monitoring of possible effects of dumped munitions.
- Development of sustainable alternatives to ocean-based dumping or prevention of the need for dumping by changing production patterns.

While the dumping of most allowable waste streams has been significantly reduced, other waste streams may increase. Distant areas of the world are also increasingly connected as consumption, production and governance decisions influence materials, waste, energy and information flows in other countries, which can generate aggregate economic gains while shifting economic and environmental costs. With over 60 per cent of the urban infrastructure expected to exist by 2050 yet to be built, understanding the role of dumping activities from urban construction and development activities is crucial. The land-ocean impacts of these activities on the marine environment need to be considered.

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Chapter 13
Changes in Erosion and Sedimentation

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Keynote points

- Coastal erosion can lead to coastal retreat, habitat destruction and loss of land, which result in significant negative ecological and socioeconomic impacts on the global coastal zones.
- Sediment budget and geology determine coastal morphology and dynamics, which influence the nature and health of the coastal ecosystems. Human activities affecting the sediment dynamics, both on the coast and on the land, modify the naturally occurring patterns of erosion and sedimentation.
- Globally, abstraction or interruption of sediment supplies to and along the coast has been increasing, through upstream dams, coastal and river sand mining, and coastal infrastructures. Reduced sediment supply enhances shoreline retreat.
- Distinct from sand or muddy coast, cliffs experience progressive erosion. This is largely caused by a combination of geotechnical instability, weathering on the upper cliff profile and wave action on the lower profile.
- Results of recent investigations reveal that, at approximately 15 per cent of all sandy beaches worldwide, the shoreline has been retreating with an average trend of 1 m/year or more over the last 33 years, while almost half of the world’s sandy beaches are currently stable.
- Many areas of the observed historical shoreline advance are related to reclamation and impoundment by coastal structures. These human activities modify the coastal dynamics, typically resulting in the downdrift erosion.
- Climate change impacts, including sea level rise and potential increases in the frequency and the intensity of severe tropical and extra-tropical storms, can accelerate coastal erosion. Human activities have the focused impacts on deltas and adjacent coasts, with potentially severe impacts on other coastal systems such as sand spits, barrier islands and wave-dominated estuaries.

1. Introduction

Chapter 26 of the First World Ocean Assessment (WOA I) (United Nations, 2017a) briefly discussed coastal erosion and subsequent damage to coastal properties. However, the chapter contained limited discussion of wider causes, geographic distributions and impacts of coastal erosion and sedimentation, effects of increased use of coastal protection structures, impacts of coastal erosion on coastal ecological systems, and capacity for modelling and forecasting coastal erosion and sedimentation.

The present Chapter addresses the above-mentioned gaps, with a particular focus on the trends and the changes to coastal erosion and sedimentation patterns over the period 2010–2020, following the baseline state described by WOA I (United Nations, 2017b). Aspects that have been considered include changes in river management that alter the sediment supply to the coasts; sand mining, dredging and disposal of dredged materials; changes in coastal infrastructures affecting coastal sediment transport processes; coastal erosion and sedimentation in respect of coastal and ocean ecological systems and social economics (natural resources/capital, livelihood and well-being); management practices for coastal erosion and sedimentation prevention; and advances in knowledge and capacity that have contributed to the evaluation of the changes in state.

2. Changes in state of coastal erosion and sedimentation

Factors that influence coastal erosion and sedimentation, encompass characteristics of coastal sediment, exchanges between the land, the coast and the shelf, and geomorphic responses to oceanic forcing. Human activities may both substantially influence and be affected by coastal erosion and sedimentation (Hapke and others, 2013; Angamuthu and others, 2018; Mentaschi and others, 2018).

Modern evaluation of the change to deltaic sediment supply was undertaken using satellite imagery approaches with consideration of sediment trapping on the floodplain or estuaries (Nyberg and others, 2018); relative distribution between the shelf and the coast; and fluvial sediment mobility compared with in situ material on muddy, sandy or rocky coasts. Factors that influence geographically variable shoreline responses to sediment availability, include underlying geological frameworks, wave action, tidal hydrodynamics, aeolian processes and ecomorphodynamic feedbacks such as for dunes or mangroves (Moore and others, 2018).

Widespread impacts due to human activities can occur if longshore sediment transport is disrupted by the installation of coastal structures or sand mining (Hapke and others, 2013; ICES, 2016). Further, low-lying coastal areas which are identified to be sensitive to the projected, rapid sea level rise, include coastal wetlands, barrier coasts, deltas and small islands (Nicholls and others, 1999).

Until recently, there has been no reliable global-scale assessment of the occurrence of sandy beaches or their rates of shoreline morphologic change. Exploiting the increased availability of satellite images, advanced image processing analysis techniques and computing resources, Luijendijk and others (2018a) presented an up-to-date global assessment of the occurrence and evolution of sandy shorelines using a fully automated analysis of 33 years (1984–2016) of satellite imagery. Their analysis showed that 31 per cent of the ice-free world shoreline is sandy, with the highest presence of sandy beaches reported in Africa (66 per cent), although the nature and characteristics of these beaches examined in the study vary substantially.

2.1. Changes in drivers

Human civilizations originated and thrived in the flood plains and the deltaic coastal zones of the world's large rivers, which are now inhabited by about 2.7 billion people (Best, 2019). The rapid increase in the demand for water, food, land and power has led to human interventions, such as the construction of large dams, deforestation, intensive agriculture expansion, urbanization, infrastructural construction, sand mining, etc. These human activities have placed these systems under immense stress, leading to large-scale and irreversible changes.

According to the International Commission on Large Dams (2018), globally, there are 59,071 dams with heights of more than 15 m and related reservoirs of more than 3 million cubic metres. The largest densities of hydropower dams are found in South America, South Asia and Northern Europe. The largest dams, including those were built, are under construction or planned, are located in the Mekong River Basin, the Amazon River Basin and the Congo River Basin (Kondolf and others, 2014; Warner and others, 2019).

The construction of dams and reservoirs can reduce the sediment supply to the coast by different degrees (Slagel and Griggs, 2008), and sometimes by more than 50 per cent (Besset and others, 2019), leading to the erosion of deltas and adjacent coasts. The reduction in sediment supply to the coasts is expected to increase largely in the twenty-first century (Dunn and others, 2018) with the value of 50 to 100 per cent (Kondolf and others, 2014; Besset and others, 2019). For example, in the Pearl River, China, the construction of two mega dams (Yangtan and Longtan) has reduced the fluvial sediment supply to the coast by 70 per cent over the period 1992–2013 (Ranasinghe and others, 2019). Kondolf and others (2014) found that 140 dams were built, are under construction or planned for the mainstream of Mekong River or its tributaries. Under a "definite future", if 38 dams that are planned or under construction, are actually completed, the cumulative sediment reduction to the Mekong Delta would be 51 per cent; and if all dams that are planned and under construction are completed, there would be a cumulative sediment reduction to the Mekong Delta of 96 per cent. This would lead to a serious decay of mangrove systems and as a consequence, the erosion of the coast and irreversible changes in the surrounding ecosystem. On the other hand, there are substantial efforts in States to remove large dams, such as the Elwha in Washington State (Warrick and others, 2015).

Sand mined from rivers, beaches and coastal seabeds is used for land reclamation, beach nourishment and industry (Bendixen and others, 2019). This removes significant amounts of sand that would otherwise contribute to the littoral transport, consequently resulting in a coastal sediment deficit (Montoi and others, 2017) and impacting the coastal morphology (ICES, 2016; Abam and Oba, 2018). Presently, coastal beach and seabed sand mining is common practice and sometimes illegal in many countries. Sand mining in general is known to take place in 73 countries on 5 continents,[208] although there is no reliable figure on the practice worldwide (Peduzzi, 2014; Jayappa and Deepika, 2018).

2.2. Changes in pressure

Economics and population growth commonly drive human occupation of the coastal zone, offset by socioeconomic costs of coastal management and adverse effects upon coastal ecosystem services. The balance between these pressures is commonly challenged by jurisdictional or economic divisions, with benefits and impacts are often separated geographically (e.g. updrift accretion and downdrift erosion affect different communities), or occurring over different time scales (e.g. building a seawall may defer the erosion pressure by a generation, but may effectively commit a community to subsequent construction of additional or larger works).

[208] See https://maritimereview.ph/2018/03/23/the-impacts-of-global-sand-mining/.

Secular changes to erosion and sedimentation may exceed the tolerance of coastal systems to adjust. For natural systems, these changes can lead to a loss of ecosystem services (Xu and others, 2019). Human activities may be intolerant of coastal dynamics, such as infrastructure that may be damaged or lose function due to changing shoreline or seabed position. The perceived need to respond to erosion or sedimentation generally depends on the nature of human activities in the coastal zone:

- Port facilities, including harbour basins and navigable access channels, typically extend across the bulk of the active coastal zone. Retention of port functions frequently requires coastal sediment management using breakwaters and dredging (see also Chapter 14 of the present Assessment).
- Substantial urban growth has occurred along the coasts since the 1950s, with the number of coastal cities with more than 100,000 inhabitants increasing from 472 in 1950 to 2129 in 2012 (Barragán and Andrés, 2015) (see also Chapter 14).
- Coastal management responses vary substantially, depending upon economics, legislation and social values; and are broadly classified into strategies of protection, accommodation, managed retreat, and sacrifice (Williams and others, 2018).
- Rural sensitivity to erosion and sedimentation is typically determined by the impacts to the drainage and flood mitigation structures (Hou and others, 2016). As these are commonly located in the supratidal zone, their sensitivity to coastal change is not always apparent.

2.3. Changes in state

Besset and others (2019) examined the coastal area changes of 54 selected deltas around the world over 30 years, based on literature and the analysis of satellite imagery. They found that 29 deltas are in overall retreat, 18 shorelines are advancing, and 7 do not show any significant change. Luijendijk and others (2018a), using Landsat images and supervised classification algorithms for shoreline detection, found that over the period 1984–2016, 24 percent of the world’s sandy beaches were retreating at a rate greater than 0.5 m/year, while 28 percent are advancing and 48 percent are stable. They also found that about 4 percent of the wold’s sandy beaches are retreating at rates exceeding 5 m/year while about 2 percent of global sandy shorelines are retreating at rates exceeding 10 m/year (Figure 1). Continental Australia and Africa are experiencing net erosion (0.20 m/year and -0.07 m/year, respectively), while all other continents appear to be experiencing net accretion. Globally, 8 percent, 6 percent and 3 percent of sandy beaches have accreted at rates of 3 m/yr, 5m/yr and 10 m/yr over the 1984 - 2016 period. Asia is the continent with the largest advancing rate (1.27 m/year), which is probably due to large land reclamation in the last few decades. Relatively high erosion rates are also seen at latitudes just south of the equator associated with large-scale land losses adjacent to the mouth of the Amazon River.

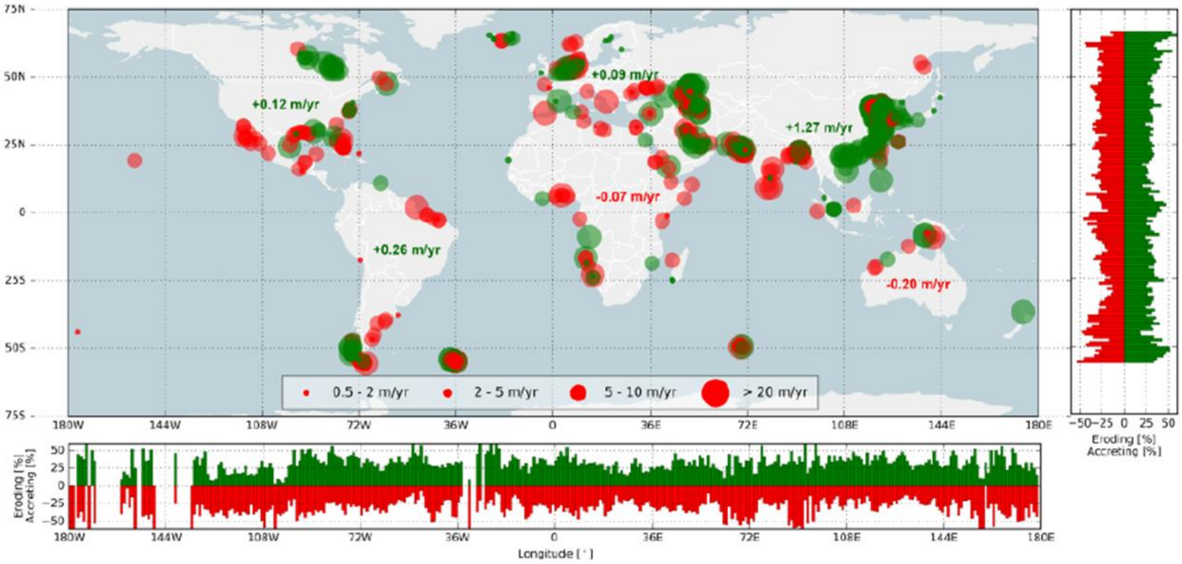

Figure 1. Global hotspots of beach erosion and accretion; the red (green) circles indicate erosion (accretion) for the four relevant shoreline dynamic classifications (see legend). The bar plots to the right and at the bottom present the relative occurrence of eroding (accreting) sandy shorelines per degree latitude and longitude, respectively. The numbers presented in the main plot represent the average change rate for all sandy shorelines per continent. Figure taken from Luijendijk and others (2018a), reprinted under the Creative Commons license (https://creativecommons.org/licenses/by/4.0/).

As a result of climate change, especially with the projected rise in sea level and increased frequency and severity of extreme waves, changes in coastal erosion and sedimentation patterns are likely to occur globally, as shown by several modelling efforts on projecting future evolution of shorelines at local, regional and global scales (Anderson and others, 2015; Antolínez and others, 2019; Castelle and others, 2014; Long and Plant, 2012; Ranasinghe and others, 2012; Splinter and others, 2014; Vitousek and others, 2017, Dastgheib and others, 2019; Bamunawala and others, 2020; Athanasiou and others, 2020; Vousdoukas and others, 2020). Recent, observations have also indicated an acceleration in coastal cliff erosion (Hurst and others, 2016; Sunamura, 2015; Castedo et al, 2017).

2.4. Changes in impacts

Coastal erosion and changes in sedimentation pose severe risks to coastal infrastructure, property, economic activities and ecological systems, and adaptation calls for significant investment. There is a tendency towards increasing damage from coastal erosion in specific locations which severely impact coastal socioeconomic activities and properties (Gopalakrishnan and others, 2016; Nguyen and others, 2018; Stronkhorst and others, 2017). The projection for risk and damage associated with coastal erosion and changes in sedimentation reveals a multiplication in the future (Dunn and others, 2019).

Ecosystem impacts from coastal erosion and changes in sedimentation can be substantial, particularly if there is a transformation from long-term accretion to erosion. Coastal wetlands are at significant risk, as many of these were developed during the relative mean sea level standstill of the late Holocene (Jones and others, 2019) and may not keep up with the rising seas in the future (Myers and others, 2019). Other geomorphic features sensitive to changing patterns of erosion and sedimentation include mangrove coasts, barrier coasts and small islands. There is a high risk of ecological disturbance for organisms that exclusively use the coastal zone for nesting or nurseries, with increased proliferation of human-occupied and modified shorelines also reducing the overall bioproductivity of the coastal zone (Rangel-Buitrago and others, 2018b).

Major socioeconomic impacts will occur at locations where erosion coincides with high population density. Existing problems have been identified adjacent to the Ganges-Brahmaputra, Mekong, Huang He, Yangtze, Volta and Mississippi deltas. For other parts of the coast, management of erosion hazards by engineering interventions requires long-term commitments to the maintenance, including the cost for upgrading of coastal defensive works, with potential risk to human safety and livelihoods if defences are subject to decline.

Local sea level rise and storminess may show significant differences between regions. Based on long-term satellite data, wave height shows an overall global increase (Young and Ribal, 2019), but large regional differences are reported; from large changes in the Southern Ocean to negligible effects in the North Sea (de Winter and others, 2012). These spatial variations are likely to result in regional variations in erosion and sedimentation (Brown and others, 2016).

2.5. Changes in response

Coastal erosion and sediment management practices have progressively matured from being almost wholly responsive to external changes, to arriving at recognition of the need for coastal resilience, using adaptive management and assessing the coast with a more holistic, longer term perspective (Rangel-Buitrago and others, 2018b).

The increase of larger, coastal-scale studies, an initial change from local-scale stabilization to regional assessment of erosion and accretion has been followed by the recognition that conditions may be variable, with potential for complex interactions between sedimentary coastal features (French and others, 2016; Psuty and others, 2018). Interconnections between coastal sediment supply and transport have been demonstrated over large scales and may occur over hundreds of kilometres and are likely to be further complicated by the potential impacts of projected sea level rise and other climate change-driven variations (Hapke and others, 2013). Therefore, changing modal conditions may introduce substantial uncertainty into future coastal change, leading to increased need for coastal resilience planning using adaptive design (Wright and Thom, 2019).

A major outcome of a large scale coastal system understanding has been demonstrated by changes in the applied scales of beach nourishment, for example, with the Sand Engine concept; which involves both onshore and nearshore placement of sediment, allowing natural hydrodynamics to redistribute sediment along the shore and over a sustained period of time (Stive and others, 2013; de Schipper and others, 2016; Luijendijk and others, 2018b).

Recent developments in coastal protection strategies have involved supplementing structural engineering approaches with “softer” or “greener” forms of coastal stabilization, which aim both to increase ecological co-benefits and to utilize resilient attributes of natural systems, such as adaptive capacity displayed by coastal dunes or disturbance-recovery behaviour demonstrated by coastal wetlands and mangrove forests (Narayan and others, 2016; Reguero and others, 2018).

There is also an emerging trend towards probabilistic analysis frameworks, instead of the traditional deterministic approach, which take into account the uncertainties associated with climate change impacts to facilitate risk-informed decision making (Wainwright and others, 2014; Jongejan and others, 2016).

3. Consequences of the changes on human communities, economies and well-being

Coastal erosion and changes in sedimentation continue to pose severe threats to the livelihood and well-being of coastal resource-dependent households, damage ecosystems and cause environmental stress. The closeness of human and ecological systems, and the risks created by problems of accelerated erosion and sedimentation changes, are evident in many areas all over the world (Jones and others, 2019). Further, erosion and changes in sedimentation have physical and chemical consequences for water quality and the health of fragile aquatic ecological systems (Prosser and others, 2018).

Coastal erosion and changes in sedimentation can have serious implications for achieving the integrated set of global priorities and objectives setting out under the 2030 Agenda for Sustainable Development, especially Sustainable Development Goal (SDG) 14 and SDG 15.[209] These processes may damage coastal infrastructure and habitats and increase risks to coastal communities, forcing adaptation and/or reallocation of coastal communities.

4. Key region-specific changes and consequences

4.1. North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean and North Sea

Coasts of the North Atlantic, Mediterranean and adjacent seas are densely populated and highly developed (Collet and Engelbert, 2013; Zhang and Leatherman, 2011; EU, 2013; Neumann et al. 2015). Areas highly sensitive to coastal change include the extensively reclaimed Netherlands shore, the subsiding Venetian coast and the barrier islands along the United States Eastern Seaboard, and the Gulf of Mexico coasts. The high economic value of the hinterland and coastal zone results in a low tolerance for erosion, and human interventions are common. Beach nourishment is the most common intervention along the Eastern Seaboard and Gulf of Mexico coastlines. Widespread erosion has been observed along the Gulf coast, associated with substantially reduced sediment load from the Mississippi River (Blum, 2009; Thorne and others, 2008). An extensive decline of fluvial sediment inputs has also been identified for major European river systems draining into the Mediterranean which support productive wetland areas.

4.2. South Atlantic Ocean and Wider Caribbean

The South Atlantic Ocean and Wider Caribbean regions have densely populated coastal cities, such as João Pessoa City, Brazil[210]; and important coastal ecological systems, such as Amazon mangrove forest; and sparsely populated coastal areas, such as the coasts of many states in Southeast Africa and the southern coast of Argentina (Zhang and Leatherman, 2011; UNESCO, 2009; Neumann et al. 2015). The input of sediments transported by rivers is

[209] See United Nations General Assembly resolution 70/1.
[210] http://atlasbrasil.org.br/2013/en/perfil_m/joao-pessoa_pb/

limited to areas near large basins such as the Amazon and Plata rivers. Reduction in sediment supply to the coasts by upstream dam construction and beach sand extraction has caused serious coastal erosion at various places, such as the coast of Ghana and many other places on the southwest coast of Africa and east coast of South America. Locally, many coastal sectors used and still prefer to use hard structures for erosion control which, in many cases, have exacerbated the problem, as in Colombia (Rangel-Buitrago and others, 2018b) and Brazil (Bonetti and others, 2018), for example.

4.3. Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

Indian Ocean coasts include the east coast of Africa, southern coasts of the Middle East, south Asia, the Indonesian archipelago, the west coast of Australia and Indian Ocean islands, including Madagascar and Sri Lanka. Deltas of major rivers include the Ganges-Brahmaputra, Indus, Ayeyarwady, Chao Phraya, Shatt-al-Arab, Zambezi and Limpopo, many of which are highly dynamic and adjacent to high population areas (Neumann et al. 2015). Africa, Australia and the Middle East have predominantly arid sandy coasts, with barrier lagoons, estuaries and, in some areas, extensive salt-flat coasts characteristic of the late Holocene sea level highstand that limit the transfer of fluvial sediments to the coast. Substantial coastal engineering projects, including construction of artificial islands through dredging and reclamation, have been undertaken along the west and south Gulf coasts, particularly along the coast of the United Arab Emirates (Peduzzi, 2014).

4.4. North Pacific Ocean

North Pacific coasts include the west coast of North America, the east coast of Asia and north Pacific islands, comprising the Philippines, Japan and Hawaii. Areas of high population density are found on the east coast of Asia and USA, and coincide with significant coastal interventions and declining sediment yield from major river systems of the Pearl, Yellow and Red Rivers, and rivers flow to the US West Coasts (Neumann et al. 2015). For example, in the US West Coast, the coastal erosion is caused by the reduction in fluvial sediment supply, coastal structures, climate change and variations, such as El Nino (Barnard and others, 2017; Hapke and others, 2009; Patsch and Griggs, 2007; Allan and Komar, 2006). North Pacific islands are highly sensitive to potential coastal change and impacts of severe events, including typhoons and tsunamis. Also, deforestation is resulting in the increased fluvial sediment delivery to the coast associated with the Fly River, Papua New Guinea.

4.5. South Pacific Ocean

South Pacific coasts include the east coast of Australia, the west coast of South America and shores of Pacific islands, including New Zealand, New Caledonia and numerous island and archipelagic States with different population sizes (Evans and others, 2016). The continental coasts are characterized by their geological structure and relatively low volumes of fluvial sediment reaching the ocean, resulting in compartmentalized coasts, with intermittent exchange related to along-shelf sediment transport (Thom and others, 2018). Changes to relative sediment supply are therefore most apparent at regional coastal sediment sinks and sources, with potential susceptibility of estuarine settings, barrier coasts and coastal wetlands to sea level rise. Coastal change impacts identified throughout the South Pacific are typically episodic, associated with extreme storms and tropical cyclones, with more widespread pressure during phases of elevated mean sea level.

Pacific island coasts include volcanic landmasses, seamounts, uplifted limestone and coral atolls. Sediment productivity is low, resulting in limited capacity for coastal adjustment to projected sea level rise (Nunn and others, 2015), particularly for low-lying reclaimed areas.

4.6 The Arctic Ocean and the Southern Ocean

Under the situation of climate change with rising air temperature, declining sea-ice extent, increasing wave action due to possible elevating storm intensity, storm induced tide and water surface area, permafrost coasts of the Arctic Ocean are now under severe erosion (Bull and others, 2019; Gibbs and Richmond, 2017; Tanski and others, 2016; Frederick and others, 2016; Fritz and others, 2015). The erosion rate of the Arctic coasts of the United States has doubled from 1950th to present, and appears to be accelerating; and especially, at Alaska's Beaufort Sea, the coastline is retreating with a rate of more than 30 m per year (Frederick and others, 2016; Wobus and others, 2011). The release of organic carbon to Arctic Ocean by coastal erosion can enhance global warming (Tanski and others, 2016). Ice sheet in Antarctica is also rapidly melting (Rignot and others, 2019; Gardner and others, 2018; Li and others, 2016).

5. Outlook

Human activities affecting the incidence of coastal erosion and sedimentation include the substantial growth in the number and scale of dams on major waterways, land-use changes leading to catchment deforestation and increased human occupation of the coastal zone, coincident with a proliferation of coastal structures (Rangel-Buitrago and others, 2018a, 2018c). Evaluation of global coastal change is not sufficiently mature to establish metrics for human-induced change to secular trends. However, identified hotspots of shoreline displacement, mostly associated with coastal erosion and accretion, are areas that are strongly linked to human activity, producing estimated 33-year trends exceeding 5 m/year for approximately 4 per cent of the world's coasts (Luijendijk and others, 2018a). Compared to our knowledge of preceding conditions, substantial coastal erosion has been observed for a majority of deltas due to a significant reduction in riverine sediment loads from 1970–2014 (Besset and others, 2019). Overall decreases in riverine sediment supply to the coast are expected to reduce the stability of adjacent, downdrift coasts and, for parts of the coast, will reverse long-term accretive trends. This will exacerbate the demand for coastal management works and reduce the effectiveness of existing works, particularly those which act to redistribute sediment supply. Further, this will increase the proliferation of coastal works, historically developed through increased coastal population levels and corresponding low tolerance for coastal change. As demonstrated by shoreline monitoring, increased manipulation of coastal dynamics and strict regulation of sand mining permit provide opportunities for substantial secular change to coastal trends, including both accretion and erosion (Williams and others, 2018; Bergillos and others, 2019). With sea level rise and an increase in the frequency and intensity of extreme climate events due to climate change, coastal erosion will be more serious for islands where riverine sediment does not exist.

6. Key remaining knowledge and capacity-building gaps

At present, significant knowledge has been accumulated on the interaction of coastal dynamic processes and sediment transport. However, the accuracy of models for sediment transport and coastal erosion/sedimentation is still limited, therefore more research is needed. Also, more information is needed on the extent of coastal erosion for identification of appropriate management strategies for coastal erosion and sedimentation, including alteration of riverine sediment supply and impacts of different management strategies such as protection, accommodation and retreat.

Although there have been substantial advances in data sets, particularly through satellite imagery (Besset and others, 2019; Luijendijk and others, 2018a; Shirzaei and Bürgmann, 2018), in many regions, especially developing States, the available data remain immature for local and regional decision-making, with many requiring substantial further interpretation and better worldwide spatial resolution. Better understanding of how to attribute driving processes, determine responses, and how this will change with sea-level rise and climate change, are required. Further, quantified erosion or sedimentation rates need to be placed in the context of thresholds for coastal ecosystems or morphologic systems. Interpretation of impacts both from changing fluvial sediment supply and application of coastal defence strategies requires improved understanding of the spatial dimensions associated with alongshore redistribution of available sediment supply, particularly in the situations where this occurs across international boundaries.

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Chapter 14
Changes in Coastal and Marine Infrastructure

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Keynote points

- Coastal and marine infrastructures are necessary for use, exploitation and protection of coastal and marine natural resources and environment for socio-economic development.
- In general, if well designed and built, coastal infrastructure development can be ecologically as well as economically and socially sustainable, and increase the resilience of the coasts and lead to sustainable economic growth.
- Infrastructures can influence natural systems and their use, and create pressures and conflicts or favourable conditions.
- Between the years 2010 and 2020, trends increased in newly developed, renovated, or upgraded marine and coastal infrastructure.
- The most significant changes are coastal and offshore land reclamation, especially in East Asian countries, for new coastal urban development, and roads, coastal defence structures and port and harbour and touristic facilities.
- Depending on the case, coastal and marine infrastructures may cause substantial damage or reduce damage to coastal and marine ecosystems.
- The new coastal infrastructure development approach, known as “blue infrastructure development” can harmonize coastal protection/development and habitat/ecological protection, thereby reducing ecological damage.
- Coastal and marine infrastructure development in general has created new opportunities for coastal dwellers and supported sustainable socioeconomic coastal development.

1. Introduction

1.1. Scope

The present Chapter covers changes in coastal and marine infrastructure during the period 2010–2020 from the baseline described in the First World Ocean Assessment (WOA I) (United Nations, 2017).

1.2. The First World Ocean Assessment (WOA I)

Chapters 17–19, 26–28 and 30 of WOA I cover coastal and marine infrastructures, including: waste receiving facilities at ports and their operation and impacts on the local marine environment worldwide and contribution to economic activity; knowledge gaps and capacity-building at ports, including improvement of operational skills; waste reception facilities; capacity to examine dredged material for safe re-deposition in the sea; the history, development and present state of submarine communications and power cables; the impacts of submarine communications and power cables on the marine environment; the threat to cables from the marine environment; capacity building on safe routing for submarine cables and resolving any conflicting demands with other parties; land reclamation, including present state, trend and socioeconomic and environmental impacts; tourism and recreation with relating infrastructures, such as roads, ports, harbours and airports, and other coastal infrastructures; sustainable tourism and capacity-building for tourism management; desalination and related coastal infrastructures; ocean and coastal scientific research facilities; and impacts of the coastal built environment on wildlife; and there is increasing financial investment in adaptation and mitigation strategies across sectors, from insurance to coastal protection.

It is clear from WOA I that issues relating to marine and coastal infrastructures need to be more systematically addressed. The present Chapter will fill in the gaps and provide additional data for evaluating the trends in marine and coastal infrastructures, particularly for the 2010–2020 period.

2. Documented change in state of marine and coastal infrastructures

2.1. Changes in land reclaimed from the sea

Coastal and marine land reclamation transforms ocean areas into land in many ways; infilling with dredged material or waste from land or building dykes. This is often for coastal and island cities with dense urbanization and a need for more space. Sengupta and others (2018) reviewed land reclamation from the mid-1980s to present day in 16 coastal megacities using Landsat TM satellite imagery. The total land reclamation area of these 16 megacities is 1249.8 km^2. Most of this was in China, whose policy changed in 2018. However, based on current trends, more land reclamation is to be expected in the near future globally.

2.2. Extent of new land defences against the sea, and extent of abandoned sea defences

Common strategies for adaptation to coastal erosion include hard/soft protection (hold/advance the line), accommodation, managed retreat and sacrifice (i.e. no active intervention) (Williams and others, 2018).

The most rudimentary method for coastal protection, using hard structures, has evolved from line protection to surface protection and, in addition to preventing storm surges and high tides, aims to protect sandy beaches where there is reduced sediment supply to the coasts. Typical coastal hard structure defences include seawalls, revetments, groins of various types, onshore and detached breakwaters and headlands, which protect beaches from wave attack or modify nearshore wave field and related sediment transport processes to create a new sediment balance at coasts that favours sedimentation instead of erosion.

Improperly designed or ageing coastal defence structures cannot function properly and may be abandoned or repaired. Causes of coastal defence structure degradation include damage due to corrosion; structure sinking due to foundation liquidation under wave action; toe scouring; wave overtopping; wave forces on structures; and sea level rise due to climate change. It is very difficult to make decisions about removing degraded coastal protection structures because they may already host endemic habitats with habitat value and the effects of removal are difficult to predict. Thus, in many cases, degraded coastal structures are just abandoned.

Nature-based solutions for coastal protection, including artificial wetlands or salt marshes, beach nourishment, oyster reef creation, mangrove re-establishment and protection etc., have the advantage of being able to grow with sea level and increasing CO_2 storage capacity (McKenna and others, 2015). However, at eroded coasts due to reduction in sediment supply, hard coastal defence structures can effectively prevent natural hazards while protecting the environment and natural habitats when being used in combination with natural barriers or natural systems, such as mangrove or coral reef. These structures can be called “blue infrastructures” (Kazmierczak and Carter, 2010; Edwards and others, 2013).

2.3. Extent of coastal development, including development for tourism: roads, town sites, tourism and recreation facilities, artificial beaches, and other coastal development structures

Coastal developments along estuaries and coastlines have become hotspots for population explosion and magnets for various industries as well as non-industrial activities such as residential, tourism and recreational development. Many coastal cities transform into megacities within a few years as a result of socioeconomic activities (Blackburn and others, 2013).

The demand for seafront living globally makes these areas develop into densely populated cities with road networks and businesses. Wealthier populations with coastal and marine tourism and recreation demands also lead to a rapid development of coastal tourism and recreation cities, such as on Asia-Pacific coasts and islands. Coastal tourism also demands the creation of many artificial beaches worldwide, such as Waikiki Beach in Hawaii, United States of America, and beaches in Singapore.

2.4. Adaptation strategies for coastal communities dealing with sea level rise

Climate change and sea level rise will increase the risks of natural hazards to coasts (IPCC, 2019). Adaptation strategies will have to determine risks and develop and implement management approaches to reduce to an acceptable level the risks to individuals, communities, societies and ecological systems at the coast and on the sea. Among common adaptation strategies mentioned in Section 2.2, accommodation and protection require the building or upgrading of present infrastructures, in many cases in combination with restoration of coastal habitats/ecological systems.

The upgrading of coastal infrastructure is also influenced by economic factor. For example, five of the top ten ports in the world that are most susceptible to sea level rise are located in the East and Southeast United States. While these ports are working to re-build infrastructure to higher standards, they must balance the requirements for predicted increases in international trade with the need to address both sea level rise and stronger and more frequent extreme weather events

2.5. Changes in port, harbour and marina installations and their management, including dredging

According to the United Nations Conference on Trade and Development (UNCTAD, 2018), container transport is rapidly expanding and, in 2017, at the rate of 6 per cent, or 42.3 million twenty-foot equivalent units (TEUs). Port competition also heightened, thus providing opportunities for shipping lines to improve management skills and increase bargaining power and influence.

World-leading regions in terms of container port volume are Asia (63 per cent) and Americas (16 per cent). Measured by total tons of all cargo handled, of the world's top 10 ports, 8 were in Asia, mainly China. Profit levels vary considerably between ports but averages across volumes suggest that only four United States dollars are earned for each tonne of cargo (UNCTAD, 2018). Employees are categorized across traditional lines that have yet to reflect the technological shift in working methods and skill sets. While few new large seaports are being planned or constructed, it was suggested that beyond 2020, 80 per cent of world trade will be conducted through seaports which will require additional facilities. Also, there is a growing interest in off-shore, deep water ports such as the Louisiana Offshore Oil Port.

Due to an increase in the global fishing fleets (Rousseau and others, 2019), there was an increase in the number of fishing ports in the past; but as world ocean fisheries resources are decreasing, this trend likely will not continue.

The global recreational boating market is also increasing. In 2009, the industry's total revenue was 18.12 billion dollars, increasing to 40 billion dollars in 2017, with a 2 per cent growth rate from 2015 to 2017, and with the highest increase rate in North America and the Asia-Pacific region (Value Market Research, 2017).

Dredging to maintain or create/increase navigation depth in existing (regular operations, renovation/expansion) or newly constructed ports, harbours and marinas is increasing in line with the global economic growth rate (IADC, 2018).

2.6. Changes in submarine cables and submarine pipelines

After a marked decline in production between 2006 and 2010, from 2010 to 2018 the number of kilometres of communications cables installed in all oceans has increased, at an average rate of over 70,000 km per year. As of early 2018, there were approximately 448 submarine cables with a length of over 1,000,000 km in service around the world. There has been a noticeable increase in Oceania and Southeast Asia. Also, the growth of cables between African States, as well as from Africa to Asia, Europe and South America, continued. Before 2009, only 16 African countries were connected to a submarine cable system. Currently, only one coastal country - Eritrea - has yet to be connected. Over 50 submarine projects have been proposed so far for the period 2019–2021, worth a total investment of around US7.2 billion dollars. About 30 per cent of the expected deployment will be in the Pacific region. This is followed by the Atlantic and Indian Oceans which are projected to receive about 21 per cent and 17 per cent, respectively, of investment planned for the coming years.

A new industry has emerged for the recovery of old cables for their scrap value. In the past ten years, some 62,000 km of cable has been recovered, with a projection of over 100,000 km contracted for recovery by the end of 2020.

Transmission power cable installations have seen a more modest growth. However, large numbers of power cables have been installed in association with marine wind farms.

Cable faults in the deep ocean below ~2000m water depth continue to be few, as there is little human disturbance in this area. For example, in the vast Areas Beyond National Jurisdiction, an average of four cable breaks are recorded annually, compared to ~150–200 breaks worldwide. However, deep-ocean mining is a potential future threat and is subject to ongoing discussions between the cable industry and the International Seabed Authority (ISA, 2018).

As discussed in WOA I, the seabed disturbance from cable installation is temporary, with natural restoration occurring over weeks to years, depending upon the vigour of wave/current action and the supply of sediment (Kraus and Carter, 2018). Because submarine landslides and sediment flows can be triggered by storms, as well as earthquakes and potentially tsunami, climate change may influence the hazard risk to telecommunication cables by affecting storm frequency and intensity (Gavey and others, 2017). New research (Gutscher and others, 2019) suggests that natural hazards, too weak to break a cable, may still deform glass fibres to produce a detectable signal, raising the possibility of using cables as environmental monitors and early warning systems for hazards.

3. Consequences of the change on human communities, economies and well-being

Development or improvement of coastal infrastructures, especially blue infrastructures, can bring huge benefits to coastal communities. Coastal and marine infrastructures are very important for disaster risk reduction, economic development, and coastal and marine science development. Coastal infrastructures support intermodal connections to maritime connections and critical global supply chains; provide public access to coastal recreation, tourism and other uses; and support access for developments. Coastal defence structures can help to minimize damage due to coastal erosion, flooding, high waves and storm surge, for example. Hotel and recreation infrastructures support tourism and recreation and generate employment. New cable connectivity brings the benefits of global communications, telemedicine and learning to otherwise isolated communities, and supports economic development, ocean science development and management implementation.

Coastal infrastructures have critical roles in achieving the Sustainable Development Goals (SDGs)[211] (Economist, 2019). The improvement of coastal and marine infrastructures contributes, in particular, to implementation of SDGs 1, 2, 6, 8, 9, 10, 13 and 14.[212] With regard to SDG 14, in particular, coastal and marine infrastructures may enable better observation, monitoring and surveys on coastal and ocean environment, ecological systems and biodiversity to provide better data for better management. On the other hand, however, the development of coastal and marine infrastructure may damage habitats and ecological systems, including their extent, structures and functions. Careful planning, with the aid of evidence-based marine spatial planning and functional analysis and use of blue infrastructures, can help to reduce negative effects. In the United States, for example, federally-approved state coastal management programs are required to consider all stakeholder interests related to the ocean-coastal interface.

4. Key region-specific changes and consequences

4.1. North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean and

[211] See United Nations General Assembly resolution 70/1.
[212] United Nations Sustainable Development Goals. See https://sustainabledevelopment.un.org/?menu=1300.

North Sea

4.1.1. North Atlantic Ocean

The coasts of the North Atlantic Ocean extend to the eastern United States of America, Canada and West European and West African countries. Levels of economic development of nations in those regions vary markedly, as do coastal defence and other infrastructure development. In Canada and the United States of America, coastal habitats are used as natural defence infrastructures (Elkin, 2017). In West Europe, due to limited land area, coastal defence and other marine infrastructures are developed for coastal protection. For Northwest Africa, there are numerous interrelated issues including severe coastal erosion, flooding, poverty and inadequate development of coastal infrastructures. In 2018, the Global Environment Facility and World Bank Group funded the West Africa Coastal Areas Resilience Investment Project with a budget of 210 million United States dollars to help to build the resilience of coastal communities in Benin, Côte d'Ivoire, Mauritania, Sao Tome and Principe, Senegal and Togo (WB, 2018).

4.1.2. Baltic Sea

The total length of coastline in the Baltic Sea is about 40,000 km and large flood-prone areas exist in Denmark, Germany and Poland. Therefore, the coastal infrastructure, for example, dikes, needs to be upgraded to better adapt to flooding. There is also considerable development of tourist-related infrastructure as well as, inter alia, ports, harbours, marinas, shipyards, wind farms, solar power stations, submarine power and communication cables.

4.1.3. Black Sea

The Black Sea coastline is 2,042 km long, with 1,228 beaches, and an area of 224 km^2. Some coastal parts are densely populated and are also popular for tourism, with many facilities, such as hotels, resorts and marinas. There are also ports and harbours. Coastal defence structures have been built to ameliorate severe coastal erosion and flooding.

4.1.4. Mediterranean Sea

The Mediterranean Sea has a 46,000 km coastline bordering 22 countries. As one of the busiest maritime regions in the world, there are many important ports. The densely populated Mediterranean coast also faces risks of erosion and flooding – a situation that will become more serious in the future due to climate change and sea level rise, and coastal infrastructure will need to be upgraded.

4.1.5. North Sea

The coastal and low-lying inland areas bordering the North Sea are at risk of flooding. As with other areas, coastal flooding risks will increase in the future due to sea level rise and more intense/frequent storms. Thus, new as well as upgraded coastal defence structures are needed to meet this challenge.

4.2. South Atlantic Ocean and Wider Caribbean

The South Atlantic Ocean and the wider Caribbean coasts encompass South American and Southwest African States. Southwest African coasts are generally in a natural condition. For example, some parts are protected by coastal ecological systems such as mangrove forests. Coastal infrastructures in the South Atlantic Ocean and the wider Caribbean coasts include coastal defence structures; tourism facilities; ports and harbours, but newly developed or upgraded structures are needed to adapt to climate change. Caribbean nations are also exposed to pronounced earthquake and volcanic activity. Natural infrastructures are used for coastal prevention and hazard protection, and researches (e.g. Powell and others, 2018) found that investments in natural infrastructure in the coastal zone can have measured value for coastal communities while increasing ecological persistence and resilience, but more research is needed for best practice development.

4.3. Indian Ocean, Bay of Bengal, Arabian Sea, Red Sea, Gulf of Aden and the Persian Gulf

The Indian Ocean and Bay of Bengal encompass many developing countries in Asia and Africa. Coastal natural hazards for countries bordering the North Indian Ocean include storm surge, sea level rise, earthquakes and tsunami. However, environmental degradation and exploitation by unsustainable economic activity resulted in reduced adaptive capacity of coastal communities, and this requires huge investments for adaptation infrastructures and sustainable economies. Perhaps the most feasible way forward for coastal States of the Indian Ocean is to restore degraded and damaged coastal habitats to create coastal blue infrastructures.

Coastal and marine infrastructures of the Arabian Sea, Red Sea, Gulf of Aden and the Persian Gulf, in general, are better developed than those in the Indian Ocean and the Bay of Bengal.

4.4. North Pacific Ocean

Like the coasts of the North Atlantic Ocean, developed countries such as the United States of America, Canada, Japan and Republic of Korea have high-quality coastal and marine infrastructures that not only protect coasts and reduce hazard risks but in some cases, also promote protection and conservation of coastal and ocean environments, habitats and biodiversity (Gillies and others, 2019). For many Pacific coastal States, there are the ever-present risks of major earthquakes and volcanic eruptions. However, the coastal and marine infrastructures in developing countries in the region are not so advanced (PEMSEA, 2018; Connell, 2018). To remediate the situation of underdeveloped coastal infrastructures in Asian developing countries, the Asian Development Bank has launched an ambitious action plan with a proposed investment of five billion United States dollars for healthy oceans, which includes developing or improving coastal infrastructure (ADB, 2019).

4.5. South Pacific Ocean

South Pacific coasts include the east coast of Australia, west coast of South America and shores of the Pacific Islands, including Papua New Guinea, New Zealand and New Caledonia. Coastal infrastructure in these nations is mainly to support economic development and prevent damage due to natural hazards, especially extreme storms and rising sea level, and to adapt to climate change. Major earthquakes, tsunami and volcanic eruptions are also a consideration.

4.6. The Arctic Ocean and Southern Ocean

The low population densities of these regions mean that coastal and ocean infrastructures are less developed than those of highly populated regions such as the circum-Pacific and Mediterranean.

4.6.1. Arctic Ocean

Coastal infrastructure development in the Arctic Ocean is faced with rapidly changing weather and ice conditions due to climate change. Declining sea-ice cover is leading to increased shipping and related infrastructure (U.S. Committee on the Marine Transportation System, 2018). Progress has been made with the installation of a 1,900 km fibre-optic communications cable off north Alaska with branch lines into six coastal communities (Submarine Cable Networks, 2017) and extensions of domestic networks in Greenland and Norway, among others (Quintillion, 2020).

4.6.2. Southern Ocean

Much of the Southern Ocean comes under the aegis of the Antarctic Treaty System including the Commission for the Conservation of Antarctic Marine Living Resources (ATS, 2019; CCAMLR, 2017, 2019). Nevertheless, there is a strong focus on scientific research into the roles played by Antarctica and the Southern Ocean in influencing global climate and ocean. Such research is supported by permanently occupied stations along Antarctica’s coast and on some subantarctic islands.

5. Outlook

5.1. Anticipated outlook for the state of the topic over the near to medium term (~10–20 years)

In the next 10 to 20 years, more upstream hydropower dams will be constructed and river sand mining will continue with increasing sediment deficit at coasts, leading to accelerated coastal erosion (See also Chapter 13) and more coastal protection structures. Coastal and offshore land reclamation, together with coastal erosion, will continue to damage or degrade important coastal and offshore shallow water marine habitats. There is also an increase in maritime tourism and associated infrastructure. At the same time and at many coastal places, socioeconomic development will lead to an increase in coastal populations and requirements for coastal and marine infrastructure. All these factors together with climate change, manifested by increasing ocean temperature, rising sea level and increase in the frequency and/or intensity of extreme weather events, increase risks to the coasts of maritime natural hazards. Thus, there is a need to develop new or upgrade existing infrastructure to mitigate risks and ensure sustainable development of the coasts and maritime economy.

Progress in knowledge and capacity anticipated in the future will contribute to evaluation of the change in the state and promote development of more effective and environmentally friendly marine and coastal infrastructures; and there will be an increase in the use of blue infrastructure or natural barriers to harmonize coastal and environmental protections.

5.2. Ecosystem and socioeconomic consequences of continued change in systems

In general, the development of marine and coastal infrastructures, especially coastal and offshore land reclamation, will damage coastal and marine habitats and ecological systems (Duan and others, 2016; McManus, 2017; Lin and Yu, 2018). Impacts of coastal structures on the ecology of coastal systems include obstructing animal access routes, destroying coastal habitats and ecological systems and changing the coastal environment (Hill, 2015). Coastal defence structures can modify sediment budget at the coast and thus change coastal morphology, with corresponding changes in coastal biotic communities but, on the other hand, in certain cases, coastal defence structures can protect coastal habitats that otherwise will be destroyed by coastal erosion (Schmitt and Albers, 2014). Coastal land reclamation may also help to create and restore coastal habitats for hazard prevention (Khalil and Raynie, 2015).

Researchers (e.g., Taormina and others, 2018) failed to show conclusively any influence of cable-based electromagnetic fields on the abundance and biodiversity of organisms, and confirm the generally low environmental footprint of telecommunications cables, especially in the deep ocean (depths >2000 m) (Burnett and others, 2013). Records of submarine cable breaks caused by landslides and sediment-laden currents, are important observations of these processes that transfer heat, carbon and nutrients from land to the deep ocean and hence may influence marine ecosystems (Pope and others, 2017).

During the past 10 years, there is a clear tendency towards alleviating or mitigating damages to coastal and ocean ecosystems from coastal and offshore development using a new development approach: blue economy development (PEMSEA, 2018). Blue coastal infrastructures can harmonize coastal protection and habitat/ecological protection; and promote carbon sequestration (Sutton-Grier and others, 2015; Wellman and others, 2017).

Coastal and marine infrastructures, in general, have a positive socioeconomic impact on coastal communities. Good infrastructure is the most important condition for coastal hazard risk mitigation, sustainable socioeconomic development and poverty eradication.

6. Key remaining knowledge and capacity-building gaps

In general, at the global level, not enough is known about the extent of coastal infrastructures, especially built coastal defence infrastructures, and their ecological and socioeconomic impacts. Also, scientific understanding of the interactions between coastal dynamics, sediment transport and the environment, and ecological processes with marine and coastal infrastructures is still lacking. The problems are especially serious for developing countries where little money is invested to undertake coastal and marine scientific research. A lack of proper knowledge and data also hinders proper design and construction and increases the environmental and ecological damage of coastal and marine infrastructures.

A science-policy interface is particularly important when considering decision-making related to the sustainable development of blue and nature-based marine and coastal infrastructures to optimize use of and minimum damage to coastal and marine infrastructures.

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Chapter 15
Changes in Capture Fisheries and Harvesting of Wild Marine Invertebrates

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Keynote points

- Worldwide, from 2012–2017, estimated landings in marine capture fisheries increased by 3 per cent to 80.6 million metric tons (MT) and estimated gross landed value increased by 1 per cent to 127 billion United States dollars (in 2017).
- Some of the world's capture fisheries continued to experience overexploitation, vessel subsidization, ineffective management, bycatch and discards, habitat degradation, abandoned, lost, or otherwise discarded fishing gear (ALDFG), and illegal, unreported or unregulated (IUU) fishing.
- In 2017, the World Bank estimated annual net losses to global capture fisheries of 88.6 billion dollars for the year 2012 (expressed in 2017 dollars) due to overfishing. If allowed to continue for the foreseeable future, such annual losses would constitute a lost natural capital asset worth trillions of dollars.
- The great majority of small-scale, artisanal or subsistence fishery (SSF) landings were destined for local human consumption, thus contributing vitally to food security and nutrition in developing States, but IUU fishing continued to pose risks to many people who depended upon fisheries for protein, exacerbating poverty, augmenting food insecurity, and potentially hindering efforts to achieve SDG targets.
- Promisingly, scientific stock assessments and management were shown to lead to more sustainable[213] outcomes, and management reforms were predicted to lead to rapid (decadal-scale) rebuilding of stocks. These were important lessons as the world began to look to unexploited and as-yet unregulated fisheries in the Polar regions and the deep ocean (the mesopelagic zone).
- The adverse effects of climate change on the oceans were expected to hinder sustainable outcomes, and fishery-dependent developing States, particularly their SSFs, were highly vulnerable to climate-related changes.

1. Introduction

Global landings of marine capture fisheries expanded significantly as of the 1950s (FAO, 2016a, 2018, 2019a) but have levelled off since the late 1980s, with a rate of growth of less than 1 per cent since 2010 (FAO, 2019a). Between 2012–2017, world marine capture fisheries production (mainly harvests constituting landings) remained flat, ranging from 78.4 MT in 2012 to 80.6 MT in 2017. From 2010 to 2017, capture fishery yields (inland and marine) increased slightly in both the developed world, from 24.1 to 24.8 MT (2.9 per cent), and the developing world, from 63.0 to 67.6 MT (7.3 per cent) (FAO, 2019a).

[213] In this chapter "sustainable", "biologically sustainable" and "maximally sustainable" are, accordingly to FAO definition, applied primarily to single stocks.

In 2017, the world price averaged over all fisheries was 1.57 dollars/kg, which translated into an estimated gross landed value for the world's marine capture fisheries of 126.8 billion dollars (FAO 2019a). Estimated annual net benefits from these landings were only 3 billion dollars (2012 data inflated to 2017 dollars) (World Bank and others, 2012; Tai and others, 2017; World Bank, 2017). Excessive fishing effort, leading to lowered biomass, resulted in estimated annual lost net benefits of 88.9 billion dollars. If allowed to continue, this would constitute natural capital asset losses (that is, the discounted or "present" value of future losses occurring annually at the same level as the 2012 estimate) in the range between 1.3 to 4.4 trillion dollars, when applying social rates of time preference of 7 to 2 per cent.

In the last decade, fish markets exhibited fast-paced globalization, thus increasing the vulnerability of SSFs to the depletion of some locally important stocks (Crona and others, 2015; Kramer and others, 2017). In 2017, about 38 per cent of global fish production entered international trade, either for human consumption or for fishmeal and fish oil (FAO, 2018b). In 2017, the export value of seafood was 156.5 billion dollars, of which 84.6 billion dollars (54 per cent) were attributed to exports from developing States.

Reported world landings and value suggested that little had changed since the publication of the First World Ocean Assessment (WOA I) (United Nations, 2017), which relied upon data up to 2012. Governance improved in some regions, however, including the rebuilding of some fisheries as a result of prudent management (FAO, 2018b; Hilborn and others 2020). The ecosystem-based approach to management has been recommended in the scientific literature as a helpful tool in the longer term, bringing commercial fisheries closer to the ideals expressed in the 1995 Code of Conduct for Responsible Fisheries (Long and others, 2015; Patrick and Link, 2015; FAO, 2018a; Marshall and others, 2018; see also Chapter 30 of the present Assessment).

There was extensive evidence that some of the world's fisheries were not managed sustainably (Sustainable Development Solutions Network, 2019), meaning that the targets of the 2030 Agenda for Sustainable Development and its Goals (SDGs),[214] particularly the fisheries-related targets under Goal 14, as well as others relating to food security, had not yet been met. Some progress was noted, however (United Nations Statistics Division, 2019). During the period from 2012 to 2017, the most salient issues were as follows:

- Of the world's marine capture fisheries for which data existed, about 60 per cent were "maximally sustainably fished" and this proportion has been increasing since 1990 (FAO, 2020). The combined sum of the proportions of maximally sustainably fished and "underfished" stocks comprised the indicator for SDG 14.4.1: the proportion of fish stocks within biologically sustainable levels (Figure 1). Equivalently, this indicator also revealed the growing proportion of "overfished" stocks since 1974 (see Figure 1; Sustainable Development Solutions Network, 2019; FAO, 2020a, 2020b; see also World Bank, 2017). While 66 per cent of fish stocks currently are either maximally sustainably fished or underfished, Figure 1 emphasizes the need to reverse a declining trend in the combined sum of these two categories by improving management approaches to the 34 per cent of fish stocks outside biologically sustainable levels.

[214] See United Nations General Assembly resolution 70/1.

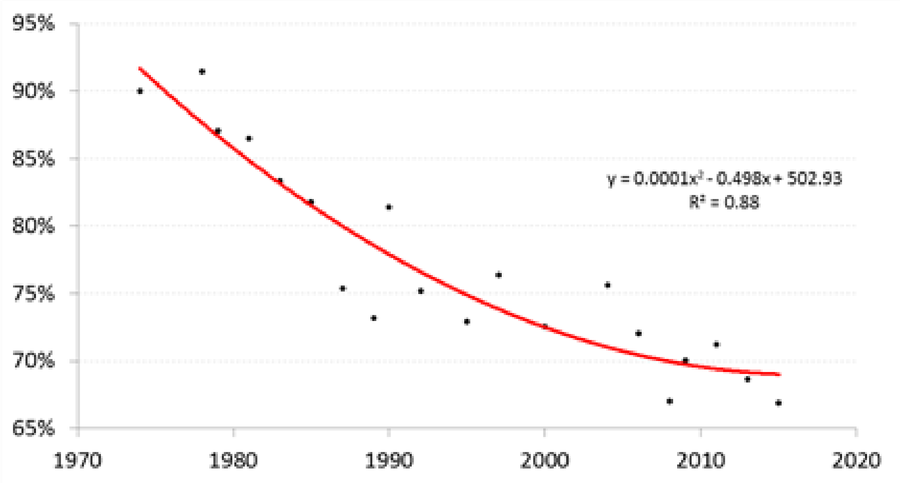

Figure 1. Proportion of fish stocks within biologically sustainable levels, SDG indicator 14.4.1. These data comprised the sum of the percentages of the world's marine capture fisheries that were considered to be either "maximally sustainably fished" (59.6% in 2017) or "underfished" (6.2% in 2017). Note that the percentage of fisheries that were maximally sustainably fished increased from 1990 to 2017. Alternatively, if subtracted from 100% in any year, the data comprised the growing percentage of the number of fisheries that were "overfished" (FAO, 2020a, 2020b).

- IUU fishing continued, thus weakening fisheries governance and leading to illicit trade in seafood (Macfadyen and others, 2019; Sumaila and others, 2020).
- Subsidization of fishing vessels continued (Sumaila and others, 2019a), including subsidies that contributed to overcapacity, excessive fishing, and stock depletion (Rousseau and others, 2019). Sala and others (2018) estimated that 54 per cent of high seas fishing grounds would be rendered unprofitable if subsidies were to be eliminated. Negotiations under the auspices of the World Trade Organization on eliminating IUU fishery subsidies and prohibiting certain other forms of subsidies continued at an accelerated pace, and agreement was expected during 2020 (WTO, 2020).
- Bottom trawling impacts to marine habitat continued, but measures were implemented by individual States or RFMO/As to mitigate these impacts on seabeds and seamounts, and progress was made on the development of indexes of seabed integrity to assess levels of impact (Eigaard and others, 2017; Hiddink and others 2017; Kroodsma and others, 2018).
- Fishing power in demersal and pelagic fisheries continued its steady—but often imperceptible—increase in efficiency (known as "technology creep") at 0.2% annually on average, necessitating compensating adjustments in management (Palomares and Pauly 2019).
- ALDFG continued to diminish ecosystem integrity, thus imposing costs for both industry and national authorities (FAO, 2018b).
- Some regional fisheries management organizations or arrangements (RFMO/As) covering the high seas were not effective enough in assessing stocks, enforcing catch limits, or providing observer coverage, to account for catches, bycatches or discards (Cullis-Suzuki and Pauly, 2010; Crespo and Dunn, 2017; ICES, 2018a), but States were increasingly motivated to achieve sustainable outcomes by increasing the effectiveness of RFMO/As, as exemplified by agreement on regional cooperative initiatives such as the 2017 Jakarta Concord for the Indian Ocean.[215]

[215] The Indian Ocean Rim Association, Jakarta Concord: Promoting Regional Cooperation for a Peaceful, Stable and Prosperous Indian Ocean (adopted March 7, 2017), https://www.iora.int/media/23699/jakarta-concord-7-

- Significant gaps remained in establishing and reaching consensus on management practices for sustaining healthy fish stocks, including: disputed jurisdictions in the Central Pacific and South-West Atlantic (Harrison, 2019); less than fully effective management of high-seas fisheries on deep ocean shelves and seamounts (ICES, 2018b); limited progress in conservation of potential fish stocks in the Central Arctic Ocean (a temporary 16-year moratorium on unregulated fishing awaited entry into force); and absence of management of prospective fisheries in the mesopelagic zone, where regulation was either nascent or non-existent (Priede, 2017; Hidalgo and Browman, 2019; Remesan and others 2019).

Notwithstanding these issues and gaps, recent scientific research suggested that, with appropriate governance, the median time required to rebuild overfished stocks could be less than ten years and, if reforms were to be implemented, 98 per cent of overfished stocks could be considered healthy by the middle of the century (Sumaila and others, 2012; Neubauer and others, 2013; Costello and others, 2016; Hilborn and Costello, 2018; Garcia and others, 2018). Little consensus existed among scientists, however, on whether recovered ecosystems and populations could assume their original functions (van Gemert and Andersen, 2018; Ingeman and others, 2019), and for some extremely depleted stocks, such as Atlantic cod *Gadus morhua*, potential recovery times were projected to be much longer (Neuenhoff and others, 2019).

Scientific assessment and management of fish stocks was shown to improve their sustainability (Hilborn and others, 2020). Scientists reasoned that management reforms, including rights-based approaches, had the potential to yield significant increases in annual catches (2–16 MT) and profits (31–53 billion dollars) (Costello and others, 2016). Scientists also maintained that increases in biomass and biodiversity concomitant with fishery management reforms would facilitate adaptation of ocean ecosystems to global climate change (Berkes and Ross, 2013; Armitage and others, 2017). Consequently, the rebuilding of fish stocks remained a high priority for States and international organizations (Delpeuch and Hutniczak, 2019).

Even with appropriate governance leading to stock rebuilding, the adverse effects of global climate change were expected to impede progress toward sustainability (see Chapter 5 of the present Assessment; Lam and others, 2016; Pentz and others, 2018; IPCC, 2019; Lotze and others, 2019). Despite a limited understanding of the extent to which changing conditions contributed to ecosystem shifts, scientists found that alterations in the structures and functions of marine ecosystems were more common than expected, and they contended that such changes could be hard to reverse (Selkoe and others, 2015; Samhouri and others, 2017).

The impacts of climate change also were expected to include increases in the intensity of natural hazards and their frequencies, thus affecting local distributions and abundances of fish populations (Barange and others, 2014; Bryndum-Buchholz and others, 2018). Scientists predicted that fishery-dependent developing States would be impacted the most severely, and, due to expected changes in species distributions and consequent increases in transboundary migrations of stocks, future international governance would need to account for such redistributions (Pinsky and others, 2018; Sumaila and others, 2019b).

2. Catch-landing disparities, SDGs and SSFs

march-2017.pdf

2.1. National jurisdictions

Between 2012 and 2017, global landings were stable, and the density of fishing effort continued to be highly concentrated in coastal oceans (Tickler and others, 2018). Catches by incoming distant water fleets were found to grow faster than catches by home States, and 78 per cent of trackable industrial fishing in the exclusive economic zones (EEZs) of lower income States was carried out by vessels flagged by high-income States (McCauley and others, 2018). In 2016, landings in tropical areas continued to grow strongly to 23.8 MT, they were flat in temperate areas at 38.9 MT, and in upwelling areas they exhibited high variability, declining to 14.5 MT (FAO, 2018b). Tables 1 and 2 depict national and regional variations in average landings between 2005 and 2014 compared to 2015 and 2016 (FAO, 2018b).

Table 1. Marine capture fisheries production by country. Source: FAO (2018)

MARINE CAPTURE PRODUCTION: MAJOR PRODUCER COUNTRIES

Country		Production *(tonnes)*			% Variation		Variation, 2015 to 2016 *(tonnes)*
		Average 2005–2014	2015	2016	2005–2014 (average) to 2016	2015 to 2016	
China		13 189 273	15 314 000	15 246 234	15.6	−0.4	−67 766
Indonesia		5 074 932	6 216 777	6 109 783	20.4	−1.7	−106 994
United States of America		4 757 179	5 019 399	4 897 322	2.9	−2.4	−122 077
Russian Federation		3 601 031	4 172 073	4 466 503	24.0	7.1	294 430
Peru	Total	6 438 839	4 786 551	3 774 887	−41.4	−21.1	−1 011 664
	Excluding anchoveta	989 918	1 016 631	919 847	−7.1	−9.5	−96 784
India		3 218 050	3 497 284	3 599 693	11.9	2.9	102 409
Japan[a]		3 992 458	3 423 099	3 167 610	−20.7	−7.5	−255 489
Viet Nam		2 081 551	2 607 214	2 678 406	28.7	2.7	71 192
Norway		2 348 154	2 293 462	2 033 560	−13.4	−11.3	−259 902
Philippines		2 155 951	1 948 101	1 865 213	−13.5	−4.3	−82 888
Malaysia		1 387 577	1 486 050	1 574 443	13.5	5.9	88 393
Chile	Total	3 157 946	1 786 249	1 499 531	−52.5	−16.1	−286 718
	Excluding anchoveta	2 109 785	1 246 154	1 162 095	−44.9	−6.7	−84 059
Morocco		1 074 063	1 349 937	1 431 518	33.3	6.0	81 581
Republic of Korea		1 746 579	1 640 669	1 377 343	−21.1	−16.0	−263 326
Thailand		1 830 315	1 317 217	1 343 283	−26.6	2.0	26 066
Mexico		1 401 294	1 315 851	1 311 089	−6.4	−0.4	−4 762
Myanmar[a]		1 159 708	1 107 020	1 185 610	2.2	7.1	78 590
Iceland		1 281 597	1 318 916	1 067 015	−16.7	−19.1	−251 901
Spain		939 384	967 240	905 638	−3.6	−6.4	−61 602
Canada		914 371	823 155	831 614	−9.1	1.0	8 459
Taiwan, Province of China		960 193	989 311	750 021	−21.9	−24.2	−239 290
Argentina		879 839	795 415	736 337	−16.3	−7.4	−59 078
Ecuador		493 858	643 176	715 357	44.9	11.2	72 181
United Kingdom		631 398	65 451 506	701 749	11.1	−0.4	−2 753
Denmark		735 966	868 892	670 207	−8.9	−22.9	−198 685
Total 25 major countries		**65 451 506**	**66 391 560**	**63 939 966**	**−2.3**	**−3.7**	**−2 451 594**
Total other 170 countries		**14 326 675**	**14 856 282**	**15 336 882**	**7.1**	**3.2**	**480 600**
World total		**79 778 181**	**81 247 842**	**79 276 848**	**−0.6**	**−2.4**	**−1 970 994**
Share of 25 major countries		***82.0%***	***81.7%***	***80.7%***			

[a] Production figures for 2015 and 2016 are FAO estimates.

Table 2. Fishing areas and capture production. Source: FAO (2018).

CAPTURE PRODUCTION: FAO MAJOR FISHING AREAS

Fishing area code	Fishing area name	Production (tonnes) Average 2005–2014	2015	2016	% Variation 2005–2014 (average) to 2016	2015 to 2016	Variation, 2015 to 2016 (tonnes)
21	Atlantic, Northwest	2 041 599	1 842 787	1 811 436	−11.3	−1.7	−31 351
27	Atlantic, Northeast	8 654 911	9 139 199	8 313 901	−3.9	−9.0	−825 298
31	Atlantic, Western Central	1 344 651	1 414 318	1 563 262	16.3	10.5	148 944
34	Atlantic, Eastern Central	4 086 427	4 362 180	4 795 171	17.3	9.9	432 991
37	Mediterranean and Black Sea	1 421 025	1 314 386	1 236 999	−13.0	−5.9	−77 387
41	Atlantic, Southwest	2 082 248	2 427 872	1 563 957	−24.9	−35.6	−863 915
47	Atlantic, Southeast	1 425 775	1 677 969	1 688 050	18.4	0.6	10 081
51	Indian Ocean, Western	4 379 053	4 688 848	4 931 124	13.9	5.2	242 276
57	Indian Ocean, Eastern	5 958 972	6 359 691	6 387 659	7.2	0.4	27 968
61	Pacific, Northwest	20 698 014	22 057 759	22 411 224	7.7	1.6	353 465
67	Pacific, Northeast	2 871 126	3 164 604	3 092 529	7.7	−2.3	−72 075
71	Pacific, Western Central	11 491 444	12 625 068	12 742 955	10.9	0.9	117 887
77	Pacific, Eastern Central	1 881 996	1 675 065	1 656 434	−12.0	−1.1	−18 631
81	Pacific, Southwest	613 701	551 534	474 066	−22.8	−14.0	−77 468
87	Pacific, Southeast	10 638 882	7 702 885	6 329 328	−40.5	−17.8	−1 373 557
18, 48, 58, 88	Arctic and Antarctic areas	188 360	243 677	278 753	48.0	14.4	35 076
World total		**90 302 377**	**92 655 917**	**90 909 868**	**0.7**	**−1.9**	**−1 746 049**

In 2018, new estimates of world fish catches, reconstructed (using 1950–2010 data) to include catches (and discards) missing from official statistics, suggested that world annual landings were underestimated by at least one third, and catches were declining faster than previously thought (Pauly and Zeller, 2016; Zeller and others, 2018). Using this method, a significant proportion of unreported fishing comprised discarded fish and catches by IUU vessels, recreational fishers, or SSFs. Reconstructed catches for the Food and Agriculture Organization of the United Nations (FAO) regions revealed especially large differences compared to recorded landings in the Western Atlantic, the Mediterranean and the Indian Ocean (Palomares and Pauly, 2019).

With regional variations, global fisheries employment of 40.4 million persons in 2017 exhibited a small increase compared to 2012 (less than 3 per cent) (FAO, 2019a). With respect to SDG Target 2.3, which promoted, inter alia, access by SSFs to productive resource services and markets (SDG Indicator 2.3.1), progress was noted in the development of targeted regulatory and institutional frameworks. More than 20 per cent of fishing States, particularly those in Oceania and South Asia, exhibited only low to medium levels of implementation of these frameworks, however (ECOSOC, 2019).

It was estimated that SSFs employed more than 90 per cent of the world's 120 million people involved in capture fisheries (about 50 per cent of whom were women) (World Bank and others, 2012; FAO, 2015, 2019a). Despite their significant contribution to global catches, SSFs were marginalized, with increasing pressure from both industrialized (and often subsidized) fleets and other ocean uses (Schuhbauer and Sumaila, 2016; Bundy and others, 2017; Ding and others, 2017; Willmann and others, 2017; Cohen and others, 2019). Climate changes were expected to impact SSF participants adversely, and adaptive strategies were identified, including the need for identifying alternative livelihoods (Shaffril and others, 2017).

Capture fisheries remained a key source of nutrition and employment for millions, but it was estimated that more than 820 million people were still undernourished (FAO, 2019c).

Between 90–95 per cent of SSF landings were destined for local human consumption, thus making a sizable contribution to food security and nutrition (World Bank and others, 2012; Golden and others, 2016; Basurto and others, 2017; Johnson and others, 2018).

The application of information technologies to help to expand SSF opportunities in areas such as safety, the sharing of local knowledge, capacity building and governance were outlined in the SSF Guidelines (FAO, 2015), which were considered central to the achievement of the fishery-relevant SDGs (Said and Chuenpagdee, 2019). Implementation was expected to take time, but a growing use of human rights approaches provided opportunities for SSF empowerment (Song and Soliman, 2019). Research efforts such as the "Too Big to Ignore" global partnership were organized to help to focus attention on SSFs (TBTI, 2020), and 2022 was proclaimed the International Year of Artisanal Fisheries and Aquaculture by the United Nations General Assembly.[216]

Subsidies exacerbated problems of overcapacity and overfishing, especially where IUU fishing was involved. Some subsidies in well-managed fisheries were beneficial, such as investments in stock assessments. In 2018, annual world fishery subsidies were estimated to be 35.4 billion dollars, compared to 41.4 billion dollars a decade earlier (2009 data expressed in 2018 dollars) but the decline was not considered significant (Sumaila and others, 2019a). Most subsidies were provided by developed States (Schuhbauer and others, 2017). Capacity-enhancing (detrimental) subsidies increased in proportion to the total, comprising 63 per cent of all subsidies (about 22 billion dollars) versus 57 per cent a decade ago (Sumaila and others, 2019a).

Progress was made in proposing guidelines for assessing fisheries and accounting for their contributions in data-poor environments (Cai and others, 2019). FAO introduced a methodology for a possible SDG indicator 14.7.1 on the contribution of a measure of sustainable fisheries to GDP (FAO, 2020c). A more comprehensive indicator to include IUU fishing, resource rents and trade in fisheries services also was under development.

2.2. High-seas fisheries

Many of the world's most valuable capture fisheries were those that focused on highly migratory apex predators that straddled adjacent EEZs or migrated among EEZs and the high seas (Sumaila and others, 2015). Fisheries for species groups such as tunas, billfish and sharks were targeted by national fleets within their own EEZs, by international fleets licensed to access foreign EEZs, or on the high seas. The use of ocean space by longline fisheries, for example, overlapped by more than 75% with the known spatial distributions of commercially valuable sharks (Queiroz and others, 2019). High seas capture fisheries landings grew from about 0.5 MT to 4.3 MT between 1950 and 2014 (Cheung and others, 2019).

Since the 1950s, industrial fishing expanded significantly, with increases in landings from inshore waters, the high seas (especially the large pelagics) and Polar regions (United Nations, 2017; Watson and Tidd, 2018). High seas yields peaked in 1989 at 5.2 MT but declined slightly in the past three decades. Although the high seas encompass 60 per cent of the world's ocean, capture fishery yields comprised only about 5 per cent of world marine yields of both fish and invertebrates. The contribution of high seas fisheries to global seafood supply was therefore of minor importance to food security during that time (Schiller and others, 2018).

[216] See United Nations General Assembly resolution 72/72.

Vessels flagged to high-income States comprised 97 per cent of industrial fishing vessels on the high seas (McCauley and others, 2018). Longline fishing was reported to account for 84–87 per cent of hours fished on the high seas (Crespo and others, 2018). More than 80 per cent of this effort was attributable to vessels from only five States. From 1950 to 2014, the distance fished from port by industrial fishing vessels more than doubled, but at the same time it exhibited a decline from 25 to 7 T/Mm in catch (metric tons) per distance (million meters) travelled (Tickler and others, 2018).

Nearly 95 per cent of total ice-free ocean areas were exploited by industrial fishing, but since their peaks in 1996, the total industrial catch declined by 18 per cent and the industrial catch per unit of area fished declined by 22 per cent (Tickler and others, 2018). Fishing intensity (effort per month) by longline vessels was found to increase in boreal regions during the summer months, with intensity linked to environmental predictors (Crespo and others, 2018).

3. Invertebrate landings

Marine invertebrate harvests grew from about 12.4 MT in 2012 to 12.5 MT in 2017, representing a growth rate of only 0.1 per cent per year. Marine invertebrate landings comprised a number of different types of organisms, including mollusks (squid, octopus, shellfish), crustaceans (shrimps, prawns, crabs, lobsters, krill), echinoderms (sea urchins, sea cucumbers) and tunicates, and yields of these groups represented about 15.5 per cent of world marine capture fisheries landings in 2017 (FAO, 2019a).

4. Levels of bycatch and side effects

There were few time series available to document trends in bycatch (ICES, 2018a). Due to regulatory restrictions or poor quality, non-target fish caught or damaged were often discarded. In 2019, it was estimated that global discard levels accounted for 10.8 per cent of world catches (2010–2014 data), which translated to 9.1 MT (ranging from 6.7 to 16.1 MT) (Pérez Roda and others, 2019). Policies and management measures are progressing so that they manage not only impacts on target species but also to include effects on other species (ICES, 2019).

5. Post-harvest fish losses

Post-harvest fish losses (PHFLs) were harvested fish that lost part of their value due to deterioration in quality, rendering them inedible or unmarketable (Diei-Ouadi and Mgawe, 2011). These losses were an issue primarily for SSFs, where storage capacity, processing and transportation modes were limited. The most recent global estimate of non-discarded PHFLs was 10-12 $MT \cdot yr^{-1}$ (Manning, 2010). More recent studies of PHFLs were limited only to local fisheries, especially in Africa and Asia, finding that losses were reduced for older fishers and for those exhibiting higher levels of education and from larger households (e.g. Adelaja and others, 2018).

6. Potential for fisheries enhancement

Fish stock propagation, more commonly known as fisheries enhancement, comprised a set of management approaches involving the use of aquaculture technologies, programs in marine ranching, the construction of artificial reefs, and egg and larval releases to restore fish stocks that exhibited depressed populations. The science was still in its infancy but showed some potential to increase fishery yields beyond those achievable by the exploitation of wild stocks alone, although an understanding of the ecological consequences was inchoate (Taylor and others, 2017).

7. Marine protein and oils in agriculture and aquaculture

Fishmeal was used as a feed, and fish oil was used as a feed additive for aquaculture and livestock. Whole fish as a raw material is "reduced" by cooking, pressing and heating to yield ratios of whole fish to fishmeal (~22-23 per cent) and fish oil (~4-5 per cent). Worldwide landings of whole fish for this purpose stood at 14.3 MT in 2016 (FAO, 2018b). In 2016, world production of fishmeal was 4.4 MT and fish oil was 0.9 MT. In 2016, 69 per cent of fishmeal and 75 per cent of fish oil production was used in aquaculture. In agriculture, 23 per cent of fishmeal was used for swine production, 5 per cent was used for poultry and 3 per cent was used for other purposes.

Aquafeed for shrimp or finfish culture (see Chapter 16 of the present Assessment) comprised fishmeal and fish oil, oilseeds (especially soybeans) and by-products from the processing of other fish products (Silva and others, 2018). Estimates of total aquafeed production were 40.1 MT in 2018 (Alltech, 2019), making the component attributed to fish reduction less than 15 per cent of the total. This proportion was expected to fall below 10 per cent by 2020 (Fry and others, 2016). In 2016, 19 per cent of world fishmeal production was derived from fishery by-products (IoA, 2016). This proportion was projected to increase to 38 per cent by 2025 (FAO, 2018b).

Commercial harvests of krill were undertaken in the Southern Ocean and a few other regions to supply fishmeal and fish oil (EUMOFA, 2018). Fisheries for mesopelagic fish were explored for the same end uses, but the costs of harvesting these fish were considered steep and the ecological consequences of exploiting them were not yet fully evaluated (Hidalgo and Browman, 2019).

8. Illegal, Unreported or Unregulated (IUU) fishing

IUU fishing weakened efforts to manage fisheries sustainably, increasing risks to 4.3 billion people who depended on fisheries for protein (FAO, 2016d), exacerbating poverty, augmenting food insecurity, and potentially hindering efforts to achieve some SDG targets (FAO, 2016b). In 2016, IUU fishing was thought to be responsible for annual catches of up to 26 MT, with a gross landed value of up to 23 billion dollars (FAO, 2016c). Several international legal instruments comprised measures relevant to eliminating subsidies for IUU fishing, and SDG indicator 14.6.1 tracked the implementation of these instruments by State, region, and the world (Figure 2). Across the world, the overall score for the degree of implementation of the applicable instruments was moderate (falling within Band 3). Negotiations on the use of international trade measures to eliminate subsidies for IUU fishing (and to prohibit certain other forms of subsidies) continued at the World Trade Organization, with the expectation of reaching agreement during 2020 (WTO, 2020).

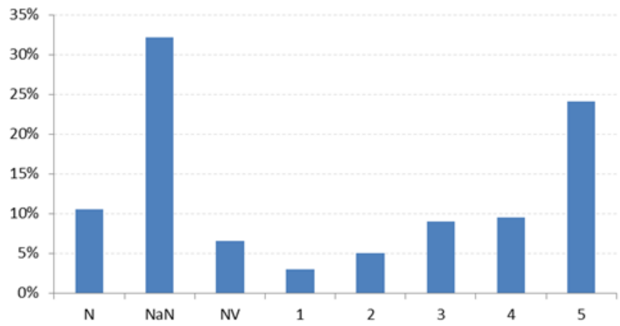

Figure 2. Indicator for SDG 14.6 which seeks, by 2020, to "prohibit certain forms of fisheries subsidies which contribute to overcapacity and overfishing, eliminate subsidies that contribute to IUU fishing and refrain from introducing new such subsidies, recognizing that appropriate and effective special and differential treatment for developing and least developed countries should be an integral part of the WTO fisheries subsidies negotiation." More specifically, this figure shows, as of June 30, 2020, the proportion of 199 FAO jurisdictions (mainly States) exhibiting varying degrees of implementation of international legal instruments aiming to eliminate subsidies that contribute to IUU fishing. Based upon responses to a questionnaire, the abscissa represents scores relating to the degree of implementation of applicable legal instruments, ranging from not applicable (N; e.g., in the case of a land-locked country), no response (NaN; or the calculation method was unknown), or not validated by a national statistical system for global reporting (NV) to very low (1), low (2), moderate (3), high (4), and very high (5). There were six applicable legal instruments; to determine the underlying scores attributed to each State, these instruments were assigned weights (by FAO) that depended upon their relevance to SDG 14.6. Source: FAO (2020d).

Where IUU vessel catch led to illicit trade in seafood, significant economic and social consequences ensued. For example, the diversion of fish from legitimate trade led to estimated worldwide annual losses in economic contributions to States of 26–50 billion dollars and tax revenue losses to States of 2–4 billion dollars (Sumaila and others, 2020).

Illegal fishing also was linked to seafood fraud (Miller and Sumaila, 2016) and found to be associated with both drug and human trafficking and forced labour (United Nations, 2017; Tickler and others, 2019). The ILO estimated that a substantial proportion of the world's 21 million people trapped in forced labour were involved in the world's fishing industry, including aquaculture, although the exact numbers were difficult to determine (FAO and ILO, 2013; ILO, 2016; Cavilli and others, 2019). Forced labour in developed State fisheries was thought to be rare, but consumers in developed States were found to have purchased seafood from producers who utilized forced labour (Tickler and others 2019).

In June 2016, the Agreement on Port State Measures (PSMA) to Prevent, Deter and Eliminate Illegal, Unreported and Unregulated Fishing,[217] which was the first binding international agreement to target IUU fishing specifically, entered into force. The effective implementation of the PSMA was expected to contribute to the long-term conservation and sustainable use of living marine resources and marine ecosystems (FAO, 2016b). Worldwide, as of June 30, 2020, there were 61 State Parties to the PSMA. The PSMA's main objective was to prevent, deter and eliminate IUU fishing by preventing vessels engaged in IUU fishing from landing catches in the State Parties' ports. The agreement is therefore expected to reduce the incentives of such vessels to continue to operate and also to block fishery products derived from IUU fishing from reaching national and international markets.

9. Outlook

Empirical evidence, along with modeling advances in fisheries science, demonstrated that

[217] Food and Agriculture Organization of the United Nations, document C 2009/REP and Corr.1–3, appendix E.

effective management could improve fish stocks, increasing yields and resource rents, and providing increased food security in developing States. The absence of effective and enduring governance in some of the world's fisheries, however, showed that they continued to be affected adversely by overexploitation, ongoing subsidization, IUU fishing, illicit trading, bycatches and discarding, habitat damage due to bottom-trawling, post-harvest fish losses, and gear abandonments. While the proportion of the world's marine capture fisheries characterized as "maximally sustainably fished" continued to grow, so did the proportion of those considered to be "overfished."

Significant efforts, including international negotiations under the auspices of the World Trade Organization, continued to be made to prohibit certain fishing vessel subsidies and to eliminate subsidies for IUU fishing. Further, the PSMA was finalized to mitigate landings of IUU catches, but its adoption by States was incomplete.

Global climate change has led already to shifts in distributions and abundances of fish populations, and these were expected to continue or accelerate. Even with appropriate governance leading to stock rebuilding, scientists expected the adverse effects of climate change to impede progress toward sustainability in marine capture fisheries.

10. Key knowledge gaps

Alterations in the structures and functions of marine ecosystems as the consequence of anthropogenic forcings were becoming more common, including overfishing, nutrient pollution, and climate change. Especially with respect to the latter, understanding was limited of the extent to which a changing climate contributed to the redistribution of commercially important stocks or led to potentially irreversible shifts in marine ecosystem structures and processes. Developing States that depended upon fisheries for food security, nutrition, and exports were expected to be impacted more severely than States with more diversified economies, but this hypothesis needed closer study.

A better understanding was needed for the potential for commercial stocks to migrate into the Central Arctic (see Ch. 7) and about commercial values and ecological significance of other as-yet-unexploited stocks in deep sea environments, such as in the mesopelagic.

Improvements in fisheries governance, including applications of effective management tools, were predicted by scientists to result in increases in biomass and biodiversity, thereby potentially allowing ocean ecosystems to adapt to global climate change, but there was little scientific consensus yet on whether recovered ecosystems could assume their former roles.

11. Key capacity-building gaps

The rebuilding of fish stocks remained a high priority for States and international organizations, but financial resources for undertaking scientific stock assessments and administering effective conservation and management measures needed further support and reinforcement in many fisheries, especially those of developing States. With appropriate governance, however, the most sanguine studies concluded that the median time required to rebuild overfished stocks could be less than a decade, and, if reforms were to be implemented, thereby comprising sustainable management, a large proportion of overfished stocks could be considered healthy by midcentury.

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Chapter 16
Changes in Aquaculture

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Keynote points

- Global aquaculture production in 2017 (animals and plants) was recorded as 111.9 million tonnes, with an estimated first sale value of 249.6 billion United States dollars. Since 2000, world aquaculture no longer enjoys the high annual growth rates of the 1980s and 1990s (11.3 and 10.0 per cent, respectively). Nevertheless, aquaculture continues to grow faster than other major food production sectors. Annual growth declined to a moderate 5.8 per cent during the period 2001–2016, although double-digit growth still occurred in a small number of countries, particularly in Africa, from 2006 to 2010. Fish produced by this rapidly growing sector are high protein, and contain essential micronutrients, sometimes essential fatty acids, which cannot easily be substituted by other food commodities.
- The United Nations predicts that the global population will reach 8.5 billion in 2030. This will inevitably increase the pressure on food sectors to increase production and reduce losses and waste. Production increases must be able to ensure sustainability, given the context in which key resources, such as land and water, are likely to be scarcer and in which the impact of climatic change will intensify. Aquaculture is no exception. Success in achieving the long-term goal of economic, social and environmental sustainability of the aquaculture sector, to ensure its continued contribution of nutritious food to keep the world healthy, will depend primarily on continued commitments by governments to provide and support a good governance framework for the sector. As the sector further expands, intensifies and diversifies, it should recognize relevant environmental and social concerns and make conscious efforts to address them in a transparent manner, backed by scientific advice.

1. Current status and major improvements

The present section provides an assessment of major global changes and improvements in the aquaculture sector over the past decade and outlines its current status.

1.1. Production and species

Aquaculture grows faster than other food production, although no longer at the growth rates of the 1980s and 1990s (11.3 and 10.0 per cent, respectively, excluding aquatic plants). Average growth declined to 5.8 per cent during the period 2000–2016, although higher growth occurred in several countries, particularly in Africa, from 2006 to 2010 (FAO, 2018a). Global production in 2016 included 80 million tonnes of food fish, 30.1 million tonnes of aquatic plants and 37,900 tonnes of non-food products. Food production included 54.1 million tonnes of finfish, 17.1 million tonnes of molluscs, 7.9 million tonnes of crustaceans and 938,500 tonnes of other animals. China, the major producer in 2016, has produced more than the rest of the world combined since 1991. The other major producers in 2016 were India, Indonesia, Viet Nam, Bangladesh, Egypt and Norway. Aquatic plants (28 million tonnes) included seaweeds and a much smaller volume of microalgae. China and Indonesia were the major producers of aquatic plants in 2016 (FAO, 2018). Ornamental fish and plant species are not included in this review.

1.2. People and nutrition

Global official statistics indicate that 59.6 million people were engaged in the primary sector of capture fisheries and aquaculture in 2016, with 19.3 million people in aquaculture and 40.3 million in fisheries (FAO, 2018b). In addition to the primary producers, many people are engaged along the aquaculture value chain. The sector supports livelihoods, including family members, of 540 million people, or 8 per cent of the world population (FAO, 2017a), of which 19 per cent were women in 2014 (FAO, 2016).

Aquaculture's contribution to human nutrition has been fully recognized (Chan and others, 2017; HLPE, 2014). Aquaculture improves nutrition of rural poor, especially mothers and young children (Thilsted and others, 2016), although there are concerns that growth of the sector and intensification of production methods may result in decreased availability of certain fatty acids and micronutrients (Bogard and others, 2017). Considering the increasing global population and the importance of a healthy diet, Béné and others (2016) stressed that access to fish is a key issue in creating healthy populations, especially among the rural poor, worldwide.

1.3. Inputs resources

Land and water are the most important resources for aquaculture development. Gentry and others (2017) estimated that 11,400,000 km^2 of the coastline are suitable for fish, and over 1,500,000 km^2 could be developed for bivalves. The challenge is to secure suitable land and water resources for the development of aquaculture at national levels.

Good quality seed and optimal feed are essential. Most animal species are cultured with external feeds and feeding the ever-expanding aquaculture sector has been a concern. In 2016, about 55.6 million tonnes of farmed fish (including Indian carps) and crustaceans depended on external feeds (fresh ingredients, farm-made or commercially manufactured feeds) (FAO, 2018b).

In 2005, aquaculture consumed about 4.2 million tonnes of fishmeal (18.5 per cent of total aquafeeds by weight). By 2015, this had been reduced to 3.35 million tonnes (7 per cent of total aquafeeds by weight). Even with globally increasing production, the use of fishmeal for aquafeeds will decrease further to 3.33 million tonnes by 2020 (5 per cent of total aquafeeds by weight for that year). Efforts toward making sustainable feeds by replacing fish meal and fish oils with plant-based feed can impact levels of Omega-3 fatty acids and nutritional value of farmed fish. The industry can make strategic use of fish oils in fish feed by feeding these essential compounds to farmed fish at key life stages (Hamilton and Others, 2020) Nevertheless, for aquaculture to grow, aquafeed production is expected to continue growing at a similar rate, to 69 million tonnes by 2020 (Hasan, 2017). Considering past trends and predictions, aquaculture sustainability is more likely to be closely linked with the sustained supply of terrestrial animal and plant proteins, oils and carbohydrate sources for aquafeeds (Troell and others, 2014). The aquaculture sector should, therefore, strive to ensure sustainable supplies of terrestrial and plant-based feed ingredients, including algae and processing waste that do not compete directly with use to feed people directly.

1.4. Biosecurity

Diseases continue to challenge global aquaculture and are one of the primary deterrents to aquaculture development of many species. Thus, investment, and a focus on biosecurity and health, have been on the increase worldwide (Subasinghe and others, 2019). Biosecurity in aquaculture consists of practices that minimize the risk of introducing an infectious disease and spreading it to the animals at a facility and the risk that diseased animals or infectious agents will leave a facility and spread to other sites and to other susceptible species. These practices also reduce stress to the animals, thus making them less susceptible to disease.

The long list of aquatic diseases/pathogens includes acute hepatopancreatic necrosis disease (AHPND), which recently devastated shrimp aquaculture in Asian countries (e.g. China, Malaysia, the Philippines, Thailand). The causative agent is a virulent strain of *Vibrio parahaemolyticus*, a bacterium commonly found in coastal waters. Revenue loss due to AHPND in South-East Asia has been estimated at over 4 billion dollars. Countries must monitor other emerging diseases, such as *Enterocytozoon hepatopenaei* in shrimps and tilapia lake virus (TiLV) in tilapias, which has the potential to severely impact the sector if not addressed in a timely manner (FAO, 2017a). New molecular diagnostic tools are now being applied to the identification of disease agents and their distribution patterns in hatchery, farmed and wild fish throughout the world. A recently developed microarray has also been used to look at impacts of pathogen carrier status (sea lice and the infectious haemopoietic necrosis virus) on wild salmon.

While research aimed at finding vaccines is progressing, the emerging issue that countries face is the misuse and abuse of antimicrobials and other drugs because of residues and resistant pathogens. Prudent use of antimicrobials, better understanding of the role of good husbandry management and microbiota in the culture systems are important to reduce antimicrobial use and resulting welfare implications in aquaculture production. Following the approval by the World Health Organization of the Global Action Plan on Antimicrobial Resistance (AMR),[218] countries are encouraged to develop national action plans on aquatic AMR and to integrate them into the global action plan (FAO, 2017a).

1.5. Technology

Remarkable improvements have been made in genetics and breeding, both in finfish and shrimp. Specific Pathogen Free (SPF) and Specific Pathogen Resistant (SPR) shrimp (*Penaeus monodon* and *P. vannamei*), Genetically Improved Farmed Tilapia (GIFT), some carp species with better growth performance, and commercial-scale production of various species of grouper, pompano and cobia could be classed as success stories (FAO, 2017a). Technological improvements in feeds, nutrition, health management and disease control are contributing to intensification, expansion, and sustainability (FAO, 2017a). Adoption of genetic improvement programmes is slow, even for some major aquaculture species. Such programmes are expensive to initiate but there is evidence that public–private partnerships can be effective in building and sustaining long-term programmes (FAO, 2019). Potential negative environmental and socio-economic impacts should always be considered along with potential for developing native species culture, when deciding to introduce a species for culture (Wurmann, 2019)

Over the past few years, SPF *P. monodon* and *P. vannamei* have been more available in Asia and Latin America. However, the use and misuse of the term SPF has been and will continue to be a concern among aquaculture stakeholders (Alday-Sanchez and others, 2018). Life cycles of important crab and lobster species have been experimentally closed but commercial production of their seed is still rudimentary.

Attempts have been made to use recirculating aquaculture systems (RAS) for salmon, with some positive outcomes. RAS is becoming the standard for smolt and post-smolt production in Norway and Chile. The approximate investment cost is 60 million dollars for a complete

[218] World Health Organization, document WHA68/2015/REC/1, annex 3.

system (FAO, 2017b). Other emerging technologies that help minimize disease and reduce wastes are closed and semi-enclosed cage systems, currently being developed and deployed for salmon farming in Norway (Nilssen and others, 2017).

The transgenic AquAdvantage Atlantic salmon has been under review by the United States Food and Drug Administration (FDA) for more than a decade. After an exhaustive and rigorous review, the FDA has determined that AquAdvantage salmon is as safe to eat as any non-genetically engineered Atlantic salmon, and as nutritious. Approval for production and consumption was finally granted in November 2015 in the United States of America and for sale in Canada by Health Canada in 2016.

2. Aquaculture and environment

Many countries emphasize environmental sustainability and social responsibility. In addition to laws and regulations, and voluntary codes aimed at ensuring environmental integrity, some of the means of achieving this goal include innovative, less-polluting techniques, proposed by the ecosystem approach to aquaculture which emphasizes management for sustainability (FAO, 2010), and provides a planning and management framework effectively to effectively integrate aquaculture into local planning (Brugère and others, 2018). Although efforts in intensification have resulted in decreased use of land and fresh water per unit of fish produced (FAO, 2017a), they have also led to an increase in the use of energy, feed and pollution per unit of farmed fish (Hall and others, 2011).

Although aquaculture has been accused of negative environmental and social impacts (Bushmann and Fortt, 2005; Mercedes and Others, 2016) and suffers from a biased perception from the public, aquaculture has, from an ecological efficiency and environmental impact point of view, clear benefits over other forms of animal food production for human consumption. Life-cycle assessment is useful to determine environmental impacts and ensure environmentally sustainable development (Bohnes and Laurent, 2019). Farmed finfish are similar in feed conversion efficiency to poultry, and much more efficient than beef. Recent estimates indicate that demand for feed crops and land use would be less than for alternative food production systems, even if over one third of protein production comes from aquaculture, by 2050 (Froehlich and others, 2018). Filter-feeding carp and molluscs are even more efficient producers of animal protein, as they require no human-managed feeds and can improve water quality. Because aquaculture is relatively new, it offers great scope for innovation to increase resource efficiency (Waite and others, 2014). Where resources are stretched, the relative benefits of policies that promote aquaculture over other forms of livestock production should be considered.

In general, the environmental performance of aquaculture has improved significantly over the past decade. If aquaculture doubles its production by 2030, for growth to be sustainable, the sector must improve its productivity and environmental performance (Waite and others, 2014). In order to achieve “sustainable intensification”, aquaculture must: (a) advance socioeconomic development; (b) provide safe, affordable, nutritious food; (c) increase production of fish relative to the amount of land, water, feed and energy used; and (d) minimize environmental impacts, fish diseases and escapes (FAO, 2017a).

3. Aquaculture and society

The importance of fish and fishery-based activities to food security in less-developed countries is particularly prominent. In 2016, 85.7 per cent of the global population engaged in fisheries and aquaculture was in Asia (FAO, 2018a), a greater than one per cent increase since 2014. More than 19 million people (32 per cent of all people employed in the sector) were engaged in fish farming, and 95.9 per cent of all aquaculture engagement was in Asia. The statistics clearly indicate the important and increasing contribution of aquaculture to Asia’s regional food, nutrition security and socioeconomic development.

There are several major reviews on the subject (World Bank, 2007; Allison, 2011; Béné and others, 2016). Fish provides more than 4.5 billion people with at least 15 per cent of their animal protein intake. The nutritional properties of fish make it important to the health of consumers in developed and developing countries. Fish are efficient converters of feed into high quality food and its carbon footprint is lower than other animal production systems. Fisheries and aquaculture value chains contribute substantially to the income and employment and therefore to the indirect food security of more than 10 per cent of the world population, essentially in developing countries and emerging economies (FAO, 2017a).

The 80 million tonnes of aquatic animals produced in 2016 contributed 46 per cent to total aquatic animal production and a little over 54 per cent to total fish consumption in the same year. Per capita food fish consumption was estimated as 20.3 kg in 2016, compared to 19.5 kg in 2013 (FAO, 2018b). An estimated 18.7 million people were employed in aquaculture in 2015 (FAO, 2017a).

The culture and use of small indigenous fish species with high nutritional value in human nutrition is recognized and being practiced (Castine and Others, 2017). However, with the intensification of aquaculture production methods, and with the increasing use of plant-based feedstuffs, care must be taken to ensure that the nutrient contents of farmed aquatic animal products are as high as possible (Beveridge and others, 2013; Bogard and others, 2017).

4. Key remaining knowledge gaps

The rapid growth of intensive aquaculture, in some cases not well planned, has caused concern about environmental impact, human health and social issues. Although the lion's share of production originates from Asia, opposition to aquaculture development is strongest in the Western world (Froehlich and others, 2017), where aquaculture is still a relatively new industry competing with well-established activities. Our knowledge on the impact of climate change on aquaculture need to be improved. Further research and investigations are necessary to improve seed, feed and health management. The increasing dependence of developed countries on farmed seafood imports from developing countries and insecurity regarding product environmental, social and safety credentials have initiated considerable public debate. Scientific uncertainties and conflicting information on the issues concerning seafood consumption have further confused the public. The establishment and application of third-party certification systems, covering the environmental, social and food safety concerns of seafood, have begun to ease this situation. More research is needed to communicate the nutritional and health benefits of increase consumption of seafood. Determination of the nutritional profiles of cultured fish and wild caught products and quantifying health benefits from socioeconomic improvements through aquaculture need further attention.

With a growing world population, annual supply from the aquaculture sector must surpass supply from capture fisheries and reach 62 per cent in 2030 in order to maintain current consumption levels. This presents tremendous challenges to the sector, to policy makers and to the aquaculture community at large. Improving perceptions will be instrumental in achieving this goal (Vannuccini and others, 2018). Better information and exchange thereof would help in clearing concerns, myths and ambiguities. To improve public awareness of aquaculture, the industry needs a more open, broader dialogue that will increase transparency. To communicate the benefits of aquaculture more effectively, it must collaborate more with stakeholder groups viewed as credible by the public. While important social and environmental issues are still to be addressed, it is important to put aquaculture in a wider perspective by comparing its costs and benefits with other animal production systems and with its potential contribution to sustainable food security, given forecasted demographic pressures. However, a holistic view, with a balanced evaluation of the risks and benefits of aquaculture, has been lacking, thus impeding the development of policies that reflect production realities (Bacher, 2015).

5. Key remaining capacity-building gaps

Capacity development is an integral part of aquaculture development. The Fisheries and Aquaculture Department of the Food and Agriculture Organization of the United Nations (FAO) has been conducting training in many aspects of capacity development in member countries for years. Sustainable development requires, inter alia, decent infrastructure, technology, policies and training. While technology to improve the efficiency of production systems is essential, the development of human resources, both in terms of quality and quantity, is pivotal to sustaining the industry, all the more so in view of the changing paradigms that are affecting the sector. Some of the key trends and challenges reflect an ever-increasing global call for sustainable development that is socially and environmentally acceptable, irrespective of the economic status of the nation.

To boost sustainable aquaculture development, countries must improve extension services. The training of extension workers must be modified to incorporate and reinforce information delivery methods and mechanisms, as well as practical farming techniques, which will help them better to help farmers to improve their production systems and practices to improve production and profit. New models and players are needed in the extension field as information technology and media, farmer associations, development agencies, private sector suppliers and others will probably enjoy greater prominence, thus broadening training experience. The goal should be to improve extension services and ensure a more effective use of resources.

Numerous donor and development agencies have helped to expand aquaculture capacity in developing countries in the past five years. Many developing and developed countries have allocated resources to improve national aquaculture capacity. Numerous governments have provided basic aquaculture extension support and some limited research and development services. However, the level of State support is inadequate in many countries. By contrast, private sector engagement in capacity development in aquaculture has been improving, with noticeable success in many countries.

6. Outlook

The major growth in aquatic production is expected to originate from aquaculture, and is projected to reach 109 million tonnes in 2030, an increase of 37 per cent over 2016 levels. However, it is estimated that the annual growth rate of aquaculture will slow down from 5.7 per cent in 2003–2016 to 2.1 per cent in 2017–2030, mainly because of a reduced rate of growth in Chinese production, in part compensated by an increase in production in other countries (FAO, 2018a). The share of farmed aquatic animal species in global fishery production (for food and non-food uses), which was 47 per cent in 2016, is projected to exceed that of wild species in 2020 and to grow to 54 per cent by 2030.

Over 87 per cent of the increase in aquaculture production in 2030 will originate from Asian countries. Asia will continue to dominate world aquaculture production, with an 89 per cent share in 2030. China will remain the world's leading producer, but its share in total production will decrease from 62 per cent in 2016 to 59 per cent in 2030. Production is projected to continue to expand on all continents, with variations in the range of species and products across countries and regions (World Bank, 2013).

Millions of people engaged in fisheries and aquaculture are struggling to maintain reasonable livelihoods. These are the people who are most vulnerable to certain climate change impacts, such as extreme weather conditions, storms, floods, sea level rising, etc., and particular attention needs to be paid to them when designing adaptation measures if the sector is to continue to contribute to meeting global goals of poverty reduction and food security (FAO, 2018a).

The 2030 Agenda for Sustainable Development[219] emphasizes people, planet, prosperity, peace and partnership. The 2030 Agenda and its Sustainable Development Goals (SDGs) are

[219] See United Nations General Assembly resolution 70/1.

highly relevant for policy making, planning and management for the sustainable development of aquaculture. When developed appropriately, aquaculture will contribute to the achievement of many SDGs, including SDG 14, and in particular, target 14.7, which aims, by 2030, to increase the economic benefits to Small Island Developing States and Least Developed Countries from the sustainable use of marine resources, including through sustainable management of fisheries, aquaculture and tourism.

A recent analysis shows that most of the available international guidance focusing on aquaculture development broadly meets the expectations of the SDGs. Existing international commitments and calls for sustainable aquaculture development, such as in the FAO Code of Conduct for Responsible Fisheries and its associated Technical Guidelines, the 2000 Bangkok Declaration and Strategy and the 2010 Phuket Consensus, and the FAO Blue Growth Initiative for SIDS,[220] which includes the ecosystem approach to fisheries and aquaculture, are generally well aligned with the 2030 Agenda and will support delivery of the SDGs (FAO, 2017a).

If there is no concerted effort is made to increase the rate of growth of aquaculture, FAO forecasts an apparent fish supply-demand gap in the early to mid-2020s. The study by Golden and others (2017) suggests that aquaculture is unlikely to contribute substantially to human nutrition in nutritionally vulnerable nations. We have already discussed the need for more integrated efforts to develop policies addressing both fisheries and aquaculture for human well-being. These mean that we need to rethink and redesign our strategies towards future aquaculture development worldwide.

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[220] See www.fao.org/3/a-i3958e.pdf.

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Chapter 17
Changes in Seaweed Harvesting and Use

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Keynote points

- As of 2012, about 80 per cent of seaweeds were either consumed directly such as kelps or processed for phycocolloids such as carrageenan, for use in the food industry. The rest were used widely in pet food, industrial cosmetic and medical applications. World production of seaweeds has steadily risen over the five-year period (2012–2017) at a rate of about 2.6 per cent annually or about 1.8 million tonnes (wet weight) per year due to demands mostly from farming or aquaculture with an estimated value of about 12 billion United States dollars.
- China remains the top supplier, followed by Indonesia. The Philippines is still the world’s third largest producer of seaweed, despite being frequently visited by typhoons every year, the Filipino seaweed farmers have become resilient and can revive their farming operations immediately. The Republic of Korea ranks fourth and has made a concerted effort to increase production to North America through marketing campaigns.
- Major species farmed are still the carrageenophytes, *Kappaphycusalvarezii* and *Eucheuma* spp. (85% of world's carrageenan production) that are being grown in Indo-Pacific region, while the alginate-producing kelps (*Saccharina* and *Undaria*), cold water species, are the major species harvested.
- Emerging applications of seaweeds in agriculture include the reduction of methane production in farmed animals, but still incipient because of issues dealing with bromoforms, which can have environmental consequences.
- Production has been affected negatively in typhoon-vulnerable areas.

1. Introduction

The present Chapter deals only with seaweed harvesting, uses by human society and ecosystem services. The taxonomy and ecological role of seaweeds and how they are affected by other components of the marine environment are covered in the present Assessment in Chapter 6G on marine plants and macroalgae.

Seaweeds are macroalgae belong into three main groups: red (Rhodophyta), brown (Phaeophycaea) and green (Chlorophyta). They are of economic importance for many countries as food for direct human consumption or as food in the aquaculture of commercial species, for the production of phycocolloids (e.g. agar, carrageenan, alginates), and are used in the manufacture of different products of commercial interest, mainly in the processed food and pharmaceutical industries (see Buschmann and others (2017), Kim and others (2017); Park and others (2018) for a historical review).

According to the baseline review of status, as provided in Chapter 14 of the First World Ocean Assessment (WOA I) (United Nations, 2017), red, brown and green seaweeds were harvested in commercial quantities, from the wild, in about 37 countries and farmed in more than 27 countries. About 96 per cent of the total production worldwide, amounting to around

26 million tonnes (wet weight) in 2012 and valued at about 6 billion US dollars, came from mariculture. China was the top producer by volume, and supplied at least 50 per cent of the total world production from 2003 to 2012, only in 2007 the Philippines was overtaken by Indonesia as the second largest producer. Since 2007 up to present, Indonesia still holds the second spot as the world's largest producer of seaweed due to the vast farming areas and improved farming technology. Chile was the top supplier from wild stock harvests, followed by China, Norway and Japan. As of 2012, about 80 per cent of seaweeds were either consumed directly such as kelps or processed for phycocolloids such as carrageenan, for use in the food industry. The rest were used widely in pet food, industrial cosmetic and medical applications. Seaweeds were also used as animal feed additives, fertilizer, water purifiers and prebiotics in aquaculture. The top species farmed were the red seaweeds, *Kappaphycusalvarezii* and *Eucheuma* spp. as sources of carrageenan, accounting for 33 per cent of the production; while 20 per cent was contributed by alginate-producing brown seaweeds called kelps (such as *Laminaria* from wild harvesting).Seaweed harvests from wild stocks were reported to be considerably affected by over-harvesting and climatic changes. The kelps were reported to be most affected by surface seawater heating and abrupt changes, since reproduction will not occur above 20°C. Kelp die-backs were reported in Norway and France and along other European coasts. Seaweed farming has been seriously affected by the bacterial "ice-ice" disease, so named because it causes the seaweed body to become translucent. It specifically targets *Kappaphycusalvarezii*. The increase in diseases has been attributed to low genetic diversity and mono-crops of cultured stocks. Reported environmental and ecological impacts of commercial-scale seaweed harvesting include habitat destruction, damage to substrata and changes in particle size distribution in sediments, disturbance to birds and wildlife, disruption to food webs and localized faunal and floral changes in biodiversity, often affecting fishers' harvests. Direct effects on seaweed populations include increased growth rates and the covering of available substrata by algae other than kelps.

In terms of the socioeconomic impacts of seaweed farming, small-scale farmers appear to benefit most as it offers substantial employment opportunities relative to other forms of aquaculture. However, small-scale farmers were found to be disadvantaged as compared to large-scale growers due to their lack of farm/financial management skills and their dependence on processors for their materials.

2. Documented change in the state of seaweed production and uses (2012–2017)

World production of seaweeds has steadily risen from the 2012 WOA I baseline (United Nations, 2017), mostly as a result of farming or aquaculture (Figure 1). From more than 24.6 million tonnes (wet weight) in 2012, farmed seaweed production rose to close to 32 million tonnes (wet weight)in 2017 (FAO, 2019), thus accounting for 96.6 per cent of total world production or an annual increase of about 1.8 million tonnes (wet weight). This is now valued at 11.85 billion US dollars (FAO, 2019).

China remains the top supplier, with an increasing production of about one million tonnes per year, now accounting for more than 54 per cent of world production. This represents a steady 1 per cent increase every year since 2012. Indonesia ranked second and, although its production jumped 66 per cent in 2013, it remained more or less steady through 2017. The Philippines is the world's third largest producer of seaweed, next to China and Indonesia. Despite the Philippines being hit by typhoons every year, the Filipino seaweed farmers have become resilient and can revive their farming operations immediately. Trono and Largo, 2019 reported that apart from typhoons, the steady decline in seaweed production was caused by epiphytism, loss of genetic diversity due to culture methods used, and political unrest in the main farming areas in Southern Philippines. Recent data of edible seaweed from USA were generated by Piconi and Veidenheimer (2020). The Korean government has made a very concerted effort to grow new markets in North America.

The carrageenan-producing *Kappaphycus alvarezii* and *Eucheuma* spp. continued to be the major species farmed,with an increase in production from 8.3 million tonnes (wet weight) in 2012 to 12.3 million tonnes(wet weight) in 2016. Kelp production also increased from 5.7 million tonnes (wet weight) in 2012 to 8.4 million tonnes (wet weight) in 2016 (Figure 2).

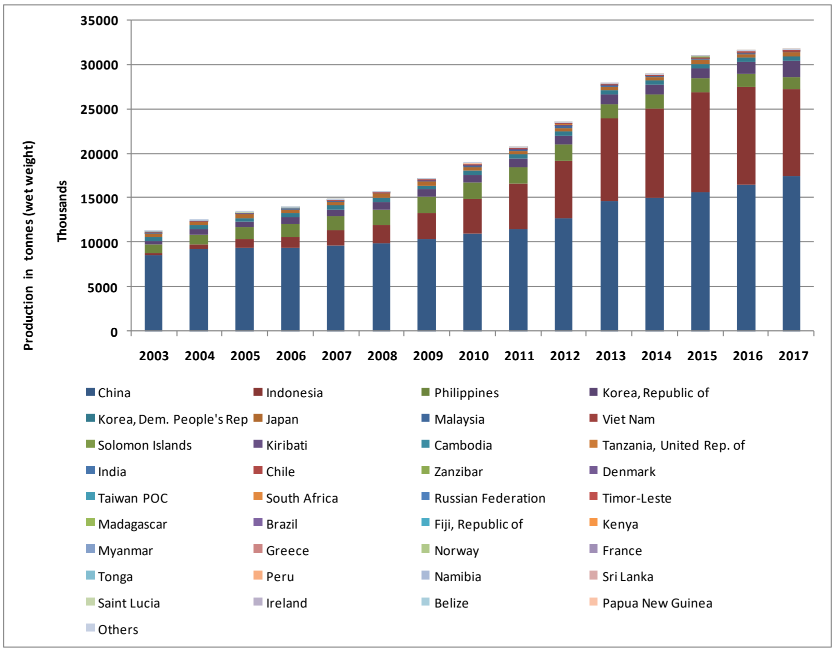

Figure 1. World seaweed production from aquaculture, 2003–2017 by country/territory in tonnes (wet weight). Data from 2003–2012 were retrieved from FAO (2014). Data from 2013–2017,according to FAO (2019).

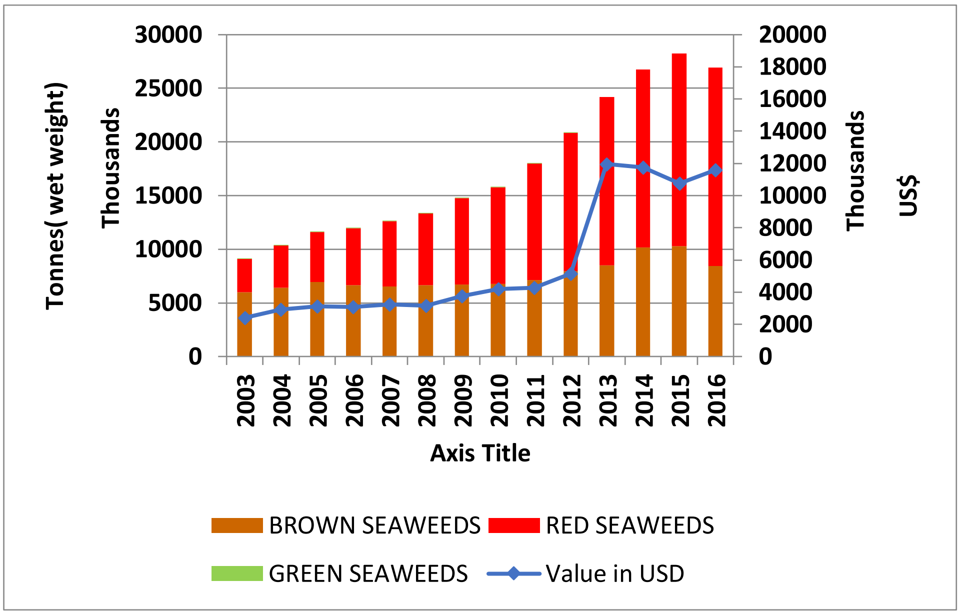

Figure 2. Total world seaweed production, by major grouping for the period 2003–2017 in tonnes (wet weight) and valued in US dollars. Data from 2003–2012 were retrieved from FAO (2014). Data from 2013–2016, according to FAO (2018). Monetary values for 2013–2016 are from FAO (2019).

Papua New Guinea has increased production over the last seven years, from 100 tonnes (wet weight) in 2010 to 4,300 tonnes (wet weight) in 2017. New producers include Cambodia, which posted production of 2,000–2,200 tonnes (wet weight) in 2015–2017, and Norway, which recorded 51–149 tonnes (wet weight)in 2015–2017.

The trend in production from harvesting of wild stocks has been more or less the same over the five-year period since the 2012 baseline (Figure 3), with Chile, China, Norway and Japan still the top four producers, in that order. Indonesia replaced France in fifth place with an increased harvest that was six times that of 2012 (from 7,600 tonnes to about 50,000 tonnes).

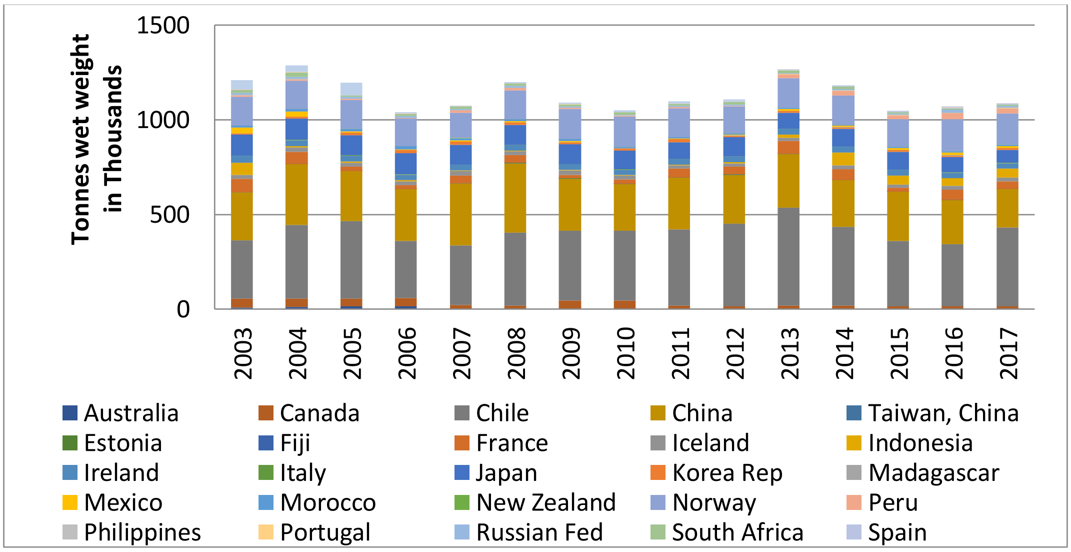

Figure 3. World seaweed production from wildstocks 2003–2017, by country/territory in tonnes (wet weight). Data from 2003–2012 were retrieved from FAO (2014), while production data from 2013–2017, according to FAO (2019).

3. Consequences of the changes on human communities, economies and well-being

Buschmann and others (2017) have predicted that seaweed (as well microalgae) production could provide 18 per cent of the global alternative protein market share or 56 million tonnes of protein by 2054.

There is increasing domestic consumption of seaweed and seaweed-based products worldwide, thus augmenting local incomes. This is due to new innovations in dining such as gourmet restaurants and bakeries featuring seaweed-enhanced dishes, new health trends for people with different food needs, such as vegans, diabetics and athletes looking for foods high in vegetable protein, soluble fibre and a high amount of minerals, essential amino acids and vitamins (Bradford, 2014; Ibáñez and Herrero, 2017; Kim and others 2017).

In areas where capitalization is a main factor in large-scale production, such as Brazil, as well in the southern Atlantic coast, the increase in seaweed production partly depends on associations and cooperatives. Nearshore seaweed farms, however, can often be beset with problems such as coliform contamination, siltation and other anthropogenic activities that impact coastal regions.

4. Key region-specific changes and consequences

Although seaweed production is concentrated in three major regions, namely, the Indian Ocean, the North Pacific and the South Pacific, production is increasing in other regions. In the South Atlantic, for example, specifically Brazil, *Kappaphycusalvarezii* and *Gracilaria* spp. are cultivated on a family scale, as promoted by Government agencies and international organizations, for agar extraction for the commercial market (Simioni and others, 2019). Wild harvesting of *Sargassum* for agricultural purposes occurs in some regions.

In the South Pacific, Chile (unlike Argentina, Brazil and Mexico which have only small-scale processing plants for the production of algae), is the only country in the region where the harvesting, cultivation and processing of seaweeds occurs on a commercial scale. Most of the *Gracilaria* it produces (50 per cent of global production) is acquired by Chinese processors (Ramírez and others, 2018). Changes in the conduct of the trades based on the introduction of new markets and the opening of nations to international circuits has brought seaweeds from marine products of relatively low economic value (i.e. commodities) into the category of export goods with a high trading value in the market. New legislation for the conservation of marine resources and restricting wild harvesting, and management policies granting unions and cooperative rights to sea plots in order to promote cultivation, have provided for a transformation at the national level to governance promoting sustainability. This has been particularly important for the artisanal sector in social and economic matters (Gelcich and others, 2015; Gallardo and others, 2018).

5. Outlook

With regard to the Sustainable Development Goals (SDGs)[221] in general and SDG 14, in particular, seaweed farming and harvesting are relevant to: SDG 14.1, on reducing marine pollution, since it has no fertilizer inputs and recycles nutrients;14.2 on better marine and

[221]See United Nations General Assembly resolution 70/1.

coastal ecosystems; 14.3 on reducing ocean acidification - by absorbing atmospheric carbon dioxide; 14.4 on reducing overexploitation of fisheries - by taking fishers out of capture fisheries; 14.5 on conservation of marine and coastal areas; and target 14.b[222] -by supporting small-scale artisanal fisheries; and contribute to achieving the other SDGs, including but not limited to SDG 3 on achieving food security and SDG8 on sustained and inclusive economic growth, especially that women and children are involved.

Bjerregaard and others (2016) discussed the seaweed aquaculture focused on food security, income generation and environmental health in Tropical Developing Countries. Buschmann and others (2017) state that seaweeds could be the "ultimate sustainable crop" which would lead to the growth of the aquaculture industry required to sustain the world's food supply. Without the constraints of arable land (since the sea covers 75 per cent of the planet's surface), fertilizer and freshwater inputs, coupled with "new aquaculture" technologies, mariculture of seaweeds or "phyconomy" (see Hurtado and others, 2019), could provide the 14 per cent year growth rate required of the industry to secure global food security by 2050. Seaweeds not only supply food for human consumption but also supply raw materials for feeds, nutraceuticals and pharmaceuticals, and provide a carbon sink to help to combat climate change.

Apart from the projected continuing increase in seaweed production for traditional and current uses, emerging applications in agriculture could help cattle-producing countries to reduce global warming. For example, the red alga *Asparagopsis*, if added to cattle feed, has been observed to considerably reduce methane "belching" in cattle by about 26 per cent (Roque and others, 2019).

Seaweed farming is pursuing eco-friendly certification for sustainable production. The Seaweed Standard will contribute to the health of the world's aquatic ecosystems by promoting environmentally sustainable and socially responsible use of seaweed resources.

6. Key remaining knowledge and capacity-building gaps

Cottier-Cook and others (2016) discussed the safeguarding the future of the global seaweed aquaculture industry. Duarte and others (2017) discuss how may seaweed farming play a role in climate change mitigation and adaptations. Further scientific approaches will be necessary to answer these questions.

Buschmann and others (2017) identified many knowledge gaps with regard to large-scale production, economics and climate change. The biology of many seaweed species is still unknown and, even for those which are already harvested or farmed, there are aspects of their biology which are still not well understood. Advanced production models need the above phyconomic information and, for offshore farms, information on climate change effects are especially important. The establishment of offshore farms will need long-term data on typhoons, sea-surface temperatures and oceanographic information. Large-scale, phyconomic production would also need phyconometric information to generate appropriate economic and financial models, such as new applications, markets and "externalities". Artisanal farmers and harvesters still face the age-long problems of capitalization, the lack of healthy and vigorous planting materials, and pricing variabilities.

[222]See United Nations General Assembly resolution 71/313, annex.

Currently, institutions in five countries are working together to address some of these knowledge and capacity-building gaps, with focus on safeguarding the seaweed industry, especially in developing countries[223].

7. Information and data used in the assessment

	Description	**Data Source**	**Reference**
Figure 1	World seaweed production from aquaculture, 2003–2017	2003–2012	FAO, 2014
		2013–2017	FAO, 2019 (Tables 5 and 6)
Figure 2	World seaweed production by group, 2013–2016	2003–2012	FAO 2014
		2013–2016	FAO, 2018
	Monetary values for 2013-2016	2013–2016 US$ values	FAO, 2019 (Tables 5 and 6)
Figure 3	World seaweed production from wild stocks, 2003–2017	2003–2012	FAO, 2014
		2013–2017	FAO, 2019 (Tables A-6)

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Chapter 19
Changes in Seabed Mining

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Keynote points

- The present Chapter updates Chapter 23 of the First World Ocean Assessment (WOA I) (United Nations, 2017b) in terms of shallow-water aggregate, placer deposits, iron sands, and phosphorite. Exploration licenses for deep-water seabed mineral resources have increased significantly since WOA I and are the focus herein.
- New technologies to reduce the impacts on the marine environment are now envisaged for exploitation of placer deposits, traditionally mined by dredging. Prospects for mining phosphorite deposits have faced opposition from stakeholders and are waiting to become a reality.
- Seabed mineral deposits addressed here--polymetallic sulphides, polymetallic nodules, and cobalt-rich crusts--are being considered for mining, with 30 contracts for exploration given by the International Seabed Authority (ISA).
- One driver for these activities is that deep-water seabed mineral resources contain diverse rare and critical metals that would support the implementation of Sustainable Development Goals adopted by the United Nations in 2015.
- Environmental impacts from exploitation of these seabed mineral resources are a scientific community focus and regulations are now being developed by the ISA.
- A lack of information on biodiversity, connectivity, and ecosystem services exists and a robust collection of baseline ecological data is necessary for predictions related to the future deep-water seabed mining activities, given the risk of irreversible damage to deep sea ecosystems.
- The ISA has considered different financial models for commercial mining of polymetallic nodules. Metal prices are difficult to predict, which can create significant risk that may delay commercial mining.
- Deep-water seabed mineral resources are typically located far from human communities and social impacts may be less than for terrestrial mining. However, significant concerns exist about loss of biodiversity and ecosystem services, including the role of the deep ocean in climate regulation. These legitimate concerns constitute the basis for a “social license to operate”.

1. Introduction

1.1. Links to the First World Ocean Assessment (WOA I)

Chapter 23 of the First World Ocean Assessment (WOA I) focused on marine mining, and particularly on established extractive industries, which are predominantly confined to near-shore areas, where shallow-water, near-shore aggregate and placer deposits, and somewhat deeper water phosphate deposits are found (United Nations, 2017a). At the time of publication, there were no commercially developed deep-water seabed mining (DSM) deposits but an assessment of mining leases and exploration activity was included. Since WOA I, the number of deep-water (depths greater than 200 m below the ocean surface) seabed exploration licenses has increased both within national jurisdictions of coastal, island and archipelagic States, and beyond in the Area (the seabed, ocean floor and subsoil thereof beyond the limits of national jurisdiction) under the administration of the International Seabed

Authority (ISA). For the first time, in 2017 deep-water seabed test-mining was carried out by Japan at a water depth of 1,600 m within its exclusive economic zone (EEZ) (METI, 2017). The update in the present Chapter will focus on the nascent deep-water seabed mining industry and mineral deposits. Hereafter, we use seabed for deep-water seabed.

Environmental issues focused on impacts from dredging activities and a list of references for some mining operations were provided. However, WOA I could not provide an environmental baseline for DSM and considered that environmental, social and economic aspects were often not adequately understood with available data. Data on potential environmental impacts are still scarce and can differ greatly between mineral extraction from near-shore and seabed mining sites. Information on economic benefits, and to some extent social impacts, of mining is becoming progressively more accessible due to several initiatives promoting an increase in transparency of extractive industries.

In 2015, the 2030 Agenda for Sustainable Development was adopted by all United Nations Member States.[224] It includes 17 Sustainable Development Goals (SDGs) to be addressed on the basis of a global partnership. DSM activities may have implications for the achievement of SDGs 1, 5, 7–10, 12–14, and 17.

1.2. Drivers, challenges and opportunities for seabed mining

Many drivers, challenges and opportunities exist for DSM, and have been discussed in many scientific papers and popular media (Hein and others, 2013; Banerji, 2019; Koschinsky and others, 2018). One key issue related to drivers is where will the critical materials come from to support infrastructure development and goods for an expanding middle class in developing societies and transition to urbanization in those societies. In addition, the question is how will rare and critical materials, which are abundant in seabed mineral deposits, be sourced to support green technologies (e.g. wind turbines, electric vehicles, solar cells), viewed by some stakeholders as solutions for a low-carbon future and global climate change (Graedel and others, 2015; Kim and others, 2015; McLellan and others, 2016; Zweibel, 2010; World Bank, 2017a). DSM has been suggested as offering a potential partial solution to these important issues (World Bank, 2017a).

Many unique characteristics of future seabed mines have been pointed out as additional drivers for this new industry (Hein and others, 2013; Petersen and others, 2016). These include: the high grades (concentrations) and tonnages of rare and critical metals in seabed mineral deposits; the fact that marine-based mine sites will not have roads, seafloor ore transport systems, water and electrical transport systems, buildings, waste dumps and other infrastructure on the seafloor; and, most importantly, no overburden will need to be removed before mining can take place because the deposits of interest are exposed at the seafloor. All of these could lessen environmental impacts.

However, there are many challenges to DSM. The most significant challenge is obtaining a sufficient understanding of the various ecosystems that characterize seabed mineral deposit environments, as well as knowledge needed to avoid, mitigate and reduce the environmental impacts of resource extraction. Other challenges include social license, which can be addressed through transparency and communications. Challenges for the industry include how to improve mining engineering and environmental safeguards, and development of green metallurgical processing technologies. The ever-present volatility of metal prices and markets, and competition with land-based mines, will also entail significant challenges.

DSM is being heavily regulated even before extraction has begun. This offers an opportunity right from the start to apply a precautionary approach and adaptive management, supported by real-time

224 See United Nations General Assembly resolution 70/1 (https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf)

monitoring.

1.3. Overview

Marine aggregate exploitation is still the major offshore mining activity, namely as an alternative to mitigate the huge negative impacts of both legal and illegal beach and onshore sand mining (Torres and others, 2017). An update of this activity is considered first in section 2. Updates of other near-shore shallow-water deposits follow on, including iron sands, placer diamonds, placer tin, and phosphorite deposits, before seabed deposits are considered. Those of current economic interest are seafloor massive sulphide (SMS) (or polymetallic sulphide) deposits, polymetallic nodules, and cobalt-rich ferromanganese crusts (see Figure 1). The marine environment and the need to gather sufficient data and information on the environmental impacts that may arise from their exploitation will be addressed in section 3. Envisaged economic and social impacts related to DSM are discussed in section 4. Section 5 briefly identifies the major capacity-building needs.

2. Changes in scale and significance of seafloor mining

WOA I emphasized the state of active marine mining, which was and still is limited to near-shore, shallow-water deposits. Provided below are a few updates, although little has changed since WOA I in this field of activity.

2.1. Current state of changes

2.1.1. Aggregate, sand and gravel update

WOA I presented a thorough overview of aggregate mining and identified the large negative impacts of beach sand exploitation, especially concerning coastal vulnerability and resilience to flooding, storm surges, tsunamis and rising sea levels. All of these impacts have led to an increasing global interest in offshore aggregate exploitation as an alternative.

Since the conclusion of WOA I, aggregates continue to be the most mined materials in the marine environment, generally at water depths of less than 50 m. In 2016, the Netherlands led marine aggregate extraction (12.5 million tonnes), followed by the United Kingdom of Great Britain and Northern Ireland (11.9 million tonnes), Germany (10 million tonnes), France (7 million tonnes), Denmark (6.6 million tonnes) and Belgium (6.6 million tonnes) (UEPG, 2018). In Belgium, no gravel was exploited from the continental shelf in 2017 and changes in marine sand and gravel legislation in 2014 specified the maximum amounts of sand that can be extracted from some areas, with an annual decrease of 1 per cent between 2014 and 2019 (ICES, 2018). In Finland, there was no marine extraction in 2017, but permits have been issued to extract 8 million m^3 of sand up to 2027 off the shore of Helsinki, and from the mouth of the Iijoki River (ICES, 2018). Since WOA I, the United States sand and gravel extraction, used as a source material for storm damage coastal restoration projects, has increased particularly along the Atlantic and Gulf of Mexico coasts. For the United States North Atlantic region alone, 2018 total aggregate extraction was 17.45 million m^3, 97% of which was used for beach replenishment (coastal restoration) public sector projects (ICES,2019). China identified abundant marine aggregates along its continental shelves, mainly in the East China Sea, the Taiwan Strait, and the northern continental shelf of the South China Sea, which have been roughly estimated to be 1.6×10^{12} tons (Qin and others, 2014). Other countries already identified in WOA I with significant offshore aggregate mining activity include, India, Japan, the Republic of Korea, and the Republic of Kiribati.

Current development trends indicate that sand demand will increase further in the coming years at an accelerated rate, associated largely with rapid urban expansion, putting additional strain on the limited sand deposits and causing conflicts worldwide (Torres and others, 2017). Therefore, a need exists for technological innovation to minimize impacts on the environment (Gavriletea, 2017), and also for integrated studies to better understand the marine environment and the time of recovery from aggregate mining impacts (e.g. Gonçalves and others, 2014), especially the impacts on benthic and planktonic ecosystems.

2.1.2. Placer diamonds update

Placer diamond mining was well covered in WOA I, although a few updates are warranted. About 75 per cent of the diamond production in Namibia is from its offshore placer deposits. Debmarine, a 50/50 joint venture between De Beers and Namibia, is in the process of building a new mining vessel (SS Nujoma) that will increase the offshore production by about 500,000 carats per year.[225] This custom-made ship will be ready for operation in 2022 with new technologies that will provide higher efficiency and productivity. Placer diamond mining off Namibia has now reached water depths of up to 200 m.

2.1.3. Placer tin update

Placer deposits in riverbeds, valleys and on the seafloor make up nearly 80 per cent of the world’s tin resources (Kamilli and others, 2017). The most extensive area for onshore and offshore placers is in the enormous tin belt of Southeast Asia. In 2017, Indonesia became the second largest producer of tin in the world, mined both onshore and offshore in subequal amounts, and is the largest producer of offshore tin. Based on the 2018 annual report of the PT Timah Tbk mining enterprise,[226] total tin production in Indonesia increased from 24,121 tonnes in 2016 to 33,444 tonnes in 2018, the highest level of production since 2012. Indonesia’s reserve of 800,000 tonnes is second only to that of China which stands at 1,100,000 tonnes (USGS, 2019), and Timah estimates that Indonesia’s tin resource totals 1,043,633 tonnes. Timah’s offshore mining is exploring the use of borehole mining technology, which the company thinks can increase tin-ore production with a much lower environmental impact. This is significant because offshore placer tin deposits are mined by dredging methods, which have an environmental impact on benthic, midwater and pelagic ecosystems.

For comparison, in 2018, mine production for Malaysia was only 4,000 tonnes but the estimated reserves are 250,000 tonnes (USGS, 2019). Historically, Malaysia has produced 55 per cent of the tin used worldwide (Kamilli and others, 2017).

2.1.4. Iron sands update

Iron sand is a sand containing grains of iron oxides (usually magnetite), typically found along coastal areas; the sand is mined for the iron to be used in the steel industry. WOA I presented a case study of iron sands, which occur off New Zealand at water depths of 20 to 42 m. A mining permit was granted to Trans-Tasman Resources Limited (TTR) in May 2014 for up to 50 million tonnes of ore per year for 20 years, which would be mined over an area of 66 km^2. As reported in WOA I, the decision-making committee (DMC) of the New Zealand Environmental Protection Agency (EPA) in June 2014 did not

[225] See https://www.mining-technology.com/features/giant-mining-vessels-how-high-quality-gems-are-exploited-from-the-sea/.
[226] See http://www.timah.com.

grant an environmental permit to mine, based on inadequate environmental data. However, an environmental permit to mine up to 50 million tonnes a year of iron sands for 35 years was granted by the DMC in August 2018 based on a revised application. That decision was subsequently appealed by environmental and fishing groups and the New Zealand High Court ruled in August 2018 that no mining would take place and sent it back to the DMC for further consideration based on the Court's criteria concerning correct legal tests for adaptive management. TTR appealed the High Court's ruling to the Court of Appeals, and has now appealed it to the Supreme Court, where the case currently resides.

Three additional companies have been granted exploration permits for iron sands in New Zealand's maritime zones. Cass Offshore Minerals Limited (Cass) has an iron sands exploration permit off the coast of New Plymouth, the same general region as the mining permit granted to TTR. In May 2018, Ironsands Offshore Mining Limited was granted permission for exploration inside a marine sanctuary off the coast of New Plymouth, the same region as the TTR and Cass permits. Pacific Offshore Mining (POM) has an exploration permit for iron-titanium sands (ilmenite) off the Bay of Plenty, east of the North Island.

2.1.5. Phosphorites: Chatham Rise (New Zealand), Don Diego (Mexico), Namibian Marine Phosphate Sandpiper and other projects (Namibia)

Phosphorite is a sedimentary rock or sediment with enough content of phosphate minerals to be of economic interest. Phosphate is used as a fertilizer in agriculture and in the chemical industry, for example as phosphoric acid used in most soft drinks. Mining has not yet started at any of the three licence areas listed in the 2.1.5. section header (see Figure 1 for locations). Chatham Rock Phosphate (CRP) has held a mining permit since December 2013 and applied for an environmental consent in June 2014, but the decision-making committee appointed by the New Zealand EPA turned down that application in February 2015. CRP anticipates completing the EPA reapplication and hearing by the end of 2021. It plans to mine 820 km^2 for up to 1.5 million tonnes of phosphate annually at water depths of up to 450 m. CRP is currently considering the possibility of extracting rare earth elements as an important potential by-product.

The proposed Mexican Don Diego phosphate project was covered in WOA I, at which time Odyssey Marine Exploration had submitted an environment impact assessment for approval to the Mexican Secretariat of Environment and Natural Resources (SEMARNAT). The application to develop the phosphate project through its subsidiary, Exploraciones Oceánicas, was denied in April 2016. In 2018, the decision was appealed to the Mexican administrative tribunal, which ruled that the decision had failed to consider the extensive environmental mitigation procedures proposed, but SEMARNAT reinstated its previous decision. The project is currently in various stages of negotiation.

Namibian Marine Phosphate Limited (Pty) (NMP) was awarded a mining license (ML170) in July 2011 and, in 2012, NMP provided an environmental impact assessment and environmental management programme. It received an environmental clearance certificate for mining in September 2016; however, two months later the certificate was retracted following protests by various stakeholders. NMP appealed to the High Court of Namibia. In May 2018, the company was successful in its appeal and the High Court of Namibia set aside the retraction[227]. NMP operations will be at water depths of 190–345 m over an area of about 2,200 km^2, 60 km off the coast of Namibia. Other companies also hold permits off Namibia, including CRP.

2.1.6. Seabed mining

[227] https://namiblii.org/na/judgment/high-court-main-division/2018/122.

WOA I anticipated that SMS mining might begin in the Manus Basin, Bismarck Sea, in the Papua New Guinea EEZ in 2017. However, due to an inability to raise the necessary funds, this component of the company has been curtailed (https://dsmf.im).

The Pacific Island States are working to develop and adopt seabed mining legislation for areas within national jurisdiction. The publication of domestic regulatory legislation has been supported by a number of initiatives, including the ongoing Pacific Maritime Boundaries Consortium and the European Union-funded Secretariat of the Pacific Community Deep Sea Minerals Project (2011–2016).

The International Seabed Authority (ISA) is currently administering 30 exploration contracts[228]. Presently, Africa is the only continent without countries sponsoring exploration activities in the Area. Draft regulations on exploitation of marine mineral resources in the Area are currently in discussion within the ISA, and the ISA Council views their adoption should be a matter of urgency.[229]

2.1.6.1. Polymetallic nodules

Polymetallic nodules (PN) form predominantly on the sediment-covered abyssal sea floor of the global ocean at water depths of about 3,500 to 6,500 m (Kuhn and others, 2017) (see Figures 1, 2C, 2D). The economic interest in these deposits is focused on nickel, copper, cobalt and manganese, although molybdenum, titanium, lithium, zirconium, and the rare earth elements and yttrium (REY) also occur in high concentrations (Hein and others, 2013; Kuhn and others, 2017).

Presently, 18 contracts for PN have entered into force, with 16 located in the northeast Pacific Clarion-Clipperton Zone (CCZ) (see Figure 3), one in the northwest Pacific Ocean, and one in the central Indian Ocean basin. The maximum size of the exploration area allocated to a contractor can reach up to 150,000 km^2 but shall not exceed 75,000 km^2 after eight years from the date of the contract[230].

Apart from the CCZ, high prospective areas occur in the Peru and Penrhyn-Samoa Basins. Although most nodule fields are in the Area, important PN deposits can also be found within the EEZ of, inter alia, the Cook Islands, Republic of Kiribati, Niue and American Samoa (Hein and others, 2005; 2015).

2.1.6.2. Seafloor massive sulphides (SMS) or polymetallic sulphides

High-temperature hydrothermal circulation systems occur in all ocean basins along mid-ocean ridge spreading centres, and along volcanic arcs and back-arc spreading centres (see Figure 1). The highest-temperature products are SMS and sulphate deposits in focused-flow systems such as chimneys, and lower-temperature hydrothermal manganese and iron oxide deposits in diffuse-flow systems (see Figure 2E, F). Deposits may form at water depths of 200 to 5,000 m, with deeper water deposits generally along spreading centres and shallower water deposits along volcanic arcs. High concentrations of copper, zinc, gold and silver occur in some SMS deposits at all of these settings. The tonnages of actively forming deposits are generally poorly constrained but are usually small. Tonnages and grades of inactive, off-axis SMS deposits are even more poorly known, but are likely to be of higher tonnage and comparable with some land-based counterparts (German and others, 2016;

[228] See https://www.isa.org.jm/deep seabed-minerals-contractors.
[229] See International Seabed Authority document ISBA/24/C/8/Add.1, part V, paragraph 7.
[230] See International Seabed Authority Document ISBA/19/C/17, Regulation 25.

Jamieson and others, 2017).

Hydrothermal SMS occurrences are common within the EEZ of many Pacific States, like Japan, New Zealand, the Republic of Fiji, the Kingdom of Tonga, the Solomon Islands and the Republic of Vanuatu, as well as the Portuguese Republic and the Kingdom of Norway in the Atlantic, and the Kingdom of Saudi Arabia and the Republic of Sudan in the Red Sea. The latter case corresponds to the metalliferous mud deposit of the Atlantis II Deep, which may be the only SMS deposit similar in scale to the large terrestrial deposits (up to 90 million tonnes) (Hoagland and others, 2010).

In the Area, seven contracts for exploration for SMS have entered into force since 2011, three in the Atlantic Ocean and four in the Indian Ocean. The area covered by each contract for exploration is comprised of not more than 100 blocks, arranged in five or more clusters; each block is approximately 10 km by 10 km and no greater than 100 km^2. The exploration area may not exceed 2,500 km^2 by the end of the tenth year from the date of the contract[231].

2.1.6.3. Cobalt-rich ferromanganese crusts

Cobalt-rich ferromanganese crusts (CFC) form on the flanks and summit of seamounts, ridges, and plateaus where rock is exposed at the sea floor (see Figure 2A, B). Many thousands of such edifices occur in the ocean basins and are especially abundant in the Pacific Ocean (see Figure 1). CFC are found at water depths ranging from about 400 to 7,000 m. In addition to cobalt, nickel and manganese, CFC contain a wide array of rare and critical metals of economic interest and with applications in emerging and next-generation technologies, especially tellurium, niobium, REY, scandium and platinum group metals (PGM), among others (Hein and others, 2013, 2017). Based on grade, tonnage, topography, age of oceanic crust and oceanographic conditions, the best areas within the Area and national jurisdictions for CFC exploration and future mining occur within the central Pacific Prime Crust Zone (PCZ) as defined by Hein and others (2009, 2013), including the EEZ of the Johnston Atoll and the Commonwealth of the Northern Mariana Islands (United States of America), the Republic of the Marshall Islands and the Izu-Bonin Islands (Japan). Seamounts and ridges within the huge PCZ are about half in EEZ and half in the Area. A smaller resource potential occurs in the Pacific EEZ of French Polynesia (France), the Republic of Kiribati, Tuvalu and Niue. Seamounts in the northeast Atlantic Ocean (EEZ of the Portuguese Republic and the Kingdom of Spain) also show metal grades and tonnages that warrant further study.

Exploration for CFC in the Area is currently active under five contracts established with the ISA, four in the western part of the PCZ, and one in the southwest Atlantic Ocean. The area covered by each contract for exploration is comprised of not more than 150 blocks arranged in clusters; each block may be square or rectangular in shape and no greater than 20 km^2. The exploration area may not exceed 1,000 km^2 by the end of the tenth year from the date of the contract[232].

2.2. Technological developments

Technology development for CFC lags far behind those of SMS and PN and will not be included in this section.

2.2.1. Seafloor massive sulphides

[231] See International Seabed Authority document ISBA/16/A/12/Rev.1, Regulation 27.
[232] See international Seabed Authority document ISBA/18/A/11, Regulation 27.

Since WOA I, several seabed test-mining operations have been conducted in situ, the most complete of which was a two-month operation performed by the Japan Oil, Gas and Metals National Corporation (JOGMEC) in the summer of 2017 in its EEZ at a depth of 1,600 m near Okinawa Prefecture (METI, 2017). The operation involved a pilot test of the full system envisaged for the recovery of SMS from the sea floor (see Figure 4D). The three mining production tools designed by Nautilus Minerals to conduct extraction of the Solwara 1 SMS deposit off Papua New Guinea became a reality. The machines, built by Newcastle-based Soil Machine Dynamics Ltd., underwent submerged trials in an enclosed onshore excavation on Motukea Island (Nautilus, 2017). Other SMS mining tools have been developed or are under development, for example the Bauer BC40 SMS trench cutter mining tool (see Figure 4C).

2.2.2. Polymetallic nodules

An *in-situ* test was scheduled in 2019 for PN in the CCZ and inside the contract areas of the Federal Institute for Geosciences and Natural Resources (BGR) and Global Sea Mineral Resources NV (GSR), sponsored by the Federal Republic of Germany and the Kingdom of Belgium, respectively, at a water depth of around 4,500 m. The test focused on the nodules prototype collector (Patania II) developed by the DEME corporation, of which GSR is a division (see Figure 4A). The test was not successful due to damage to the umbilical connector resulting in a power failure (DEME, 2019). In 2017, also in the CCZ, GSR successfully launched the pre-prototype collector Patania I. Other PN mining tools have been developed or are under development, including, for example, the Korea Research Institute of Ships and Ocean Engineering tandem nodule mining tools (see Figure 4B) that are designed to collect PN, which would then crushed before entering a buffering system and then fed up the riser pipe.

2.3. Future directions

The transition towards a low-carbon future committed to by most Governments could invigorate interest in seabed mining and the search for new metal sources. The majority of DSM activities may occur in the Area, which includes most of the abyssal plains, as well as most sections of the mid-ocean ridges and seamounts forming the seabed. This should promote a shift of the paradigm related to the mining industry. Mining of the seabed will be mostly monitored by the international community within the ISA framework that currently includes 168 members. However, many questions still remain open that need to be globally addressed: How will this potential economic activity affect the production of land-based mining, often an important source of income of many developing countries? How and at what level will DSM impact the environment in short-, medium- and long-terms? To answer at least the last question, substantial technological developments are still needed to foster *in-situ* monitoring of the marine environment and acquire representative spatial and time series data.

3. Environmental aspects

3.1. Advances in knowledge and environmental impacts

The deep-water environment covers more than 90 per cent of the ocean area and includes a range of ecosystems and habitats at the sea floor and in the water column (Ramirez-Llodra and others, 2011; Gollner and others, 2017). The different types of mineral resources at the sea floor are located in different geological/oceanographic settings that also host different types of habitats and communities.

Regulations designed to avoid, reduce and mitigate impacts to resource- and non-resource-associated fauna typically would include physical impacts, noise, light and particle plumes. During the last decade, several projects and initiatives identified potential impacts of DSM, such as the extent and impact of sediment or water plumes away from the areas directly mined and their potential toxicity (MIDAS, 2016). Some of the expected impacts on ecosystems (Table 1) include limiting connectivity between populations, interfering with the life cycle of species, behaviour changes, loss of species and habitat, impacts on ecosystem structure and functioning, and impacts on water-column chemistry. Several deep-sea species and ecosystems show vulnerable characteristics such as maturation at a relatively old age, slow growth rates, long life expectancies, and low or unpredictable recruitment.

Recent work highlighted the role of all sea-floor resources as critical habitats for communities. A wide range of fauna habitats are associated with PN, which are the dominant hard substrate on the CCZ abyssal plain (Vanreusel and others, 2016; Simon-Lledó and others, 2019a). Active hydrothermal vent ecosystems are unusual, fragmented habitats colonized by endemic chemosynthetic organisms and mostly rare species (Van Dover and others, 2018). SMS associated with inactive vent fields are not well studied but the existing literature identifies the presence of cold-water corals and sponges, whose dependence on the microbial communities are as yet to be determined (Boschen and others, 2016; Van Dover, 2019). CFC on seamounts host various ecosystems depending on location and water depth, which include cold water corals and sponges and other habitat-forming species (Rowden and others, 2010).

The report from a recent workshop, with the aim of evaluating the nature of midwater mining plumes and their potential effects on midwater ecosystems, states that seabed mining activities may affect midwater organisms in a number of ways, but it is still unclear as to what scale perturbations may occur, and calls for more research of pelagic fauna, especially at the midwater bathyal and abyssal pelagic realms (Drazen and others, 2019).

Although there has been no commercial-scale mining, deep-sea experiments simulating mining activities have been carried out. The first commercial test-mining for PN was carried out in 1970. Since then, there have been a number of small-scale commercial test-mining or scientific disturbance events designed to simulate mining. The results of the simulated mining impacts set a lower bound on the likely intensity of mining disturbance effects and the timescales required for benthic community recovery (Jones and others, 2017 and references therein). Those designed to mimic PN mining provided insights into recovery processes following small-scale disturbance events (up to 26 years ago) on abyssal plains (Gollner and others, 2017; Jones and others, 2017). Results of these studies showed that large sessile fauna have very slow recovery after disturbance (see also Vanreusel and others, 2016) and consistently show major impacts and lack of faunal recovery even over decadal time periods (Jones and others, 2017). While the impacts on the nodule-dwelling fauna were entirely anticipated, as the nodules take millions of years to form, there are also important impacts on the organisms inhabiting the sediments in and near disturbed tracks (Simon-Lledó and others, 2019b).

3.2. Policies and legislation: new regulations and policies, international, regional and national developments

For nearshore deposits, an increase in sand and gravel extraction is foreseen for the next decades, possibly extending to water depths greater than 50 m. Tighter environmental regulation, accompanied by the development of more environmentally friendly extraction technologies, is also expected for marine aggregate exploitation (e.g. Ellis and others, 2017; Kaikkonen and others, 2018).

Environmental management standards and guidelines for DSM are in their infancy (Jones and others, 2019). The ISA has a “Mining Code” to regulate prospecting and exploration activities and will establish regulations for exploitation of minerals in the Area. Development of these regulations will move in parallel with development of standards and guidelines aimed at defining environmental objectives and establishing environmental thresholds. A crucial tool for the definition of environmental objectives is the adoption of regional environmental management plans (REMP) in areas where exploration contracts exist. The first environmental management plan was developed by the ISA in 2011 for polymetallic nodules in the Clarion-Clipperton Zone and adopted in 2012.[233] Several workshops have been held or will soon be convened to develop criteria that will support the establishment of new REMP.[234]

As can be ascertained from the comparative study of the existing national legislation on DSM, as of 5 June 2018, a total of 31 States had provided to the ISA information on or the texts of relevant national legislation related to DSM activities.[235]

3.3. Data and information/knowledge gaps

The definition and accurate quantification of mining impacts on the water column and at the seabed can be approached using specific environmental indicators that determine what represents good environmental conditions and appropriate thresholds for impacts. Currently, there is a significant lack of information on deep-sea ecosystems, deep-sea species basic life history and biological traits, characteristics of future mining technologies and the response of deep-sea organisms to mining impacts. Thus, unforeseen consequences of mining may occur. The knowledge gaps can be grouped into three categories, namely biodiversity, connectivity and function/services (Miller and others, 2018; Thornborough and others, 2019. Information is still lacking on the basic components of each ecological system, the interactions among those components, and relationships of ecosystems to environmental gradients. This baseline ecological information is necessary to allow predictions of how biodiversity, species connectivity and ecosystem functions and services will respond to change.

4. Economic and social impacts

4.1. Economic impacts

The economics of DSM is intimately linked to the state of mining technology as well as the increased demand for metals in cutting-edge technology applications. Of the three seabed mineral deposit types being considered here, polymetallic nodules are the closest to being mined. This is because of a combination of relative ease of retrieval due to the discrete nature of the nodules and anticipated demand growth particularly in cobalt and nickel for new green energy technologies. Consequently, the economic discussion here applies to nodules specifically.

4.1.1. Economics of seabed mining for polymetallic nodules

Commercial mining activities for PN will depend not only on the overall economics of the system, but also on the economics of individual stakeholders. While the potential revenue from the sales of metals

233 See International Seabed Authority, documents ISBA/17/LTC/7 and ISBA/18/C/22.
234 See International Seabed Authority, document ISBA/24/C/3.
235 Available at https://www.isa.org.jm/national-legislation-database.

would be sufficient financially to justify the substantial investments and operating costs associated with DSM, the first call on that revenue in relation to the Area has to be the administrative expenses of the ISA. The remaining funds may be used for meeting other obligations under Part XI of UNCLOS and the Agreement on the implementation of Part XI of UNCLOS, including equitable sharing of benefits in accordance with articles 140 and 160(2)g of UNCLOS and compensation to developing land-based producer countries if impacts from DSM on metal prices affect them. Funding for environmental and regulatory monitoring and remediation should also be provided. Mining operations will occur only if the remaining revenue after payments to the ISA (or their equivalents for DSM in areas under national jurisdiction) can cover operating costs and provide sufficient returns to entice investment. Initial investigations of the economics of DSM suggest that revenues may be capable of reaching such levels, but issues remain, including the level of funds required for meeting obligations under Part XI of UNCLOS, liabilities for environmental damage, and returns required by investors.

4.1.2. Metals revenues

While PN contain many metals, currently only four occur at sufficiently high concentrations to justify the cost of extraction for metals processors. Manganese is by far the largest metal by mass, and so even at relatively low market prices, it is an important part of the revenue stream. While cobalt, copper and nickel concentrations are lower, they command higher prices and thus provide significant sources of revenue.

Future metals prices are difficult to predict and may differ from those forecasts, so this uncertainty can create significant risk for investors. Cobalt and nickel are both expected to play significant roles in future energy storage solutions and, consequently, may experience high demand growth and upward trends in price. For manganese, PN mining will add a large quantity of material onto a market of limited size and may itself put significant downward pressure on prices.

4.1.3. Nodule collection, metals processing investments and operating costs

While the ISA has authority only over activities at the marine mine site, costs beyond their jurisdiction must be considered when evaluating the economic factors that will impact investments. For this reason, studies of the financial systems need to look at investments and costs at sea as well as downstream.

On the cost side, there is the need for large upfront investments and then ongoing operational expenditures. Economies of scale dictate a minimum size of operation that many experts think will involve the extraction and processing of between 1.5 and 3 million dry tonnes of nodules per year. A system generating 3 million dry tonnes per year would require approximately 4 billion United States dollars in upfront investments, including about 300 million US dollars for exploration and feasibility studies, over 1.5 billion US dollars for the nodule collection equipment and a dedicated transport system, and over 2 billion US dollars for a metals processing plant. Annual operational expenses are estimated to be in the order of 1 billion US dollars per year, with roughly one third going towards nodule collection and the remaining two thirds going towards metals processing. Metals revenues for an operation of 3 million dry tonnes per year, with consideration of metallurgical losses and industry forecasts for long-term metals prices, would yield approximately 2.5 billion US dollars in annual revenues.

4.1.4. Distribution of funds across stakeholders

It remains to be seen if the level of revenue remaining after meeting the requirements of Part XI of UNCLOS will be sufficient to motivate all players to participate. It is anticipated that a market for nodules, where they are transferred from collectors to metals processors through a global trading clearance center, will develop if and when they become available. However, until that market emerges, the system economics can be evaluated only by estimating the flow of revenues among all stakeholders. Nodule collectors will pay a royalty to the ISA when they retrieve nodules from the seabed. Metals processors will pay nodule collectors for the resource (nodules). Metals processors will sell the final metal products on the global market to a variety of end consumers. These revenues will have to cover all their operational expenses, plus payment to collectors (and transport providers) to obtain nodules. Any excess will be subject to local corporate taxes. While the ISA will not see these funds, local taxes could have a significant impact on the economics of other stakeholders and, therefore, must be considered when evaluating if the system generates sufficient returns to justify investment.

Collectors will receive payments for the nodules from the metals processors, but will have to cover their operational costs and provide royalty payments to the ISA (or local authority if the operation is within an EEZ) for the rights to exploit the nodules. They may also have to contribute to environmental sustainability funds and provide bonds as guarantees for unanticipated environmental damages. Any profits may be subject to taxes from their sponsor State and may be subject to additional royalty payments to the ISA. The ISA will receive funds in the form of royalty payments for the rights to the nodules. They may also be the guardians of any sustainability funds or environmental liability bonds. Royalty payments must be sufficient to compensate for relinquishing the rights to the nodules plus any other changes to the deep-sea environment.

A variety of royalty systems are under discussion at the ISA, including fixed single or two-stage ad valorem systems, variable ad valorem systems where the rate changes with metal prices or other financial conditions of the market, and combination systems with a fixed ad valorem rate and an additional rate tied to profits. Ad valorem systems are those in which the royalty is tied to the value of the metal retrieved. Each system has different pros and cons, particularly with regard to which stakeholders bear the risks and benefit from the rewards of changes in metals prices and project costs, and the timing of revenues to each stakeholder.

4.1.5. Returns to investors and cash flows to the ISA

The very high upfront investments will require the nodule collectors and metals processors to raise funds on global capital markets. It is estimated that financiers will invest only if their rate of return on investment is around 18 per cent for most reasonable future metals price and cost scenarios. By contrast, investments in traditional land mining often require rates of return above 15 per cent but involve considerably lower levels of technological risk. A variety of royalty systems and rates would leave sufficient revenues for the contractors to achieve these rates of return. It is still unclear if any of these would provide sufficient revenue to the ISA to compensate for the removal of the nodules and changes to the deep-sea environment.

4.2. Social impacts

The potential social impacts from DSM activities are understood to be both complex and cumulative (Koschinsky and others, 2018). While DSM may result in a myriad of social impacts, there is a general view that the direct impact on society will be less than that of terrestrial mining (Roche and Bice, 2013). For instance, terrestrial mining projects often result in community displacements, changes in land use, and the need to construct infrastructure such as roads and railways (World Bank, 2017b). Working conditions (e.g. occupational hazards), as well as the safety and general health of communities (e.g. resulting from on-site disasters as well as exposure to air and water pollution resulting from mining) that live close to mine sites, are also noteworthy impacts of terrestrial mining (International Resource Panel, 2020). These will not be part of DSM. Moreover, mineral deposits on the seabed tend to contain higher metal contents than those on land, and a shift of focus to the seabed as a supplemental source for metals would reduce the need to mine terrestrial sites more extensively (Sharma and Smith, 2019).

One pertinent consideration to ascertain the possible social impacts of DSM is the intended location of related activities. It is becoming increasingly clear that the areas typically associated with seabed mineral deposits are located far from human communities. Thus, issues of relocation or conflicts pertaining to land use do not arise with respect to DSM, as opposed to terrestrial mining (Sharma and Smith, 2019). Further, social impacts related to DSM in the Area will differ from those within national jurisdictions. However, it is acknowledged that these activities may come into conflict with other uses of the marine space, such as fisheries, shipping, deep-sea cables, nursing grounds and migratory routes.

Due to the nature of DSM and the possibility of transboundary harm, the sections of society that could be directly impacted by related activities include the communities in the territory where such activities take place, and those in adjacent coastal States (Dunn and others, 2017). Because the Area and its mineral resources have been declared common heritage of mankind, social impacts need to be considered as a whole (Hunter and others, 2018). Notwithstanding how far any activities in the Area would be from population centres, significant concerns remain as to how the loss of biodiversity and ecosystem services, including the role of the deep sea in climate regulation, could negatively impact society as a whole (Kaikkonen and others, 2018).

When discussing social impacts, an approach that discusses both how society might be able to reap benefits of DSM as well as the potentially negative consequences would provide important information on which to base decisions. This approach might include the distribution of financial benefits through a benefit-sharing mechanism, as well as the introduction of an additional source of metal supply to meet current and future demands. It should be recognized that, while a new source of metal supply might be beneficial, there could be negative consequences, such as for countries whose economy relies heavily on the export of metals obtained from terrestrial mining, and, in accordance with article 151(10) of UNCLOS and paragraph 1, section 7 of the Annex to the Agreement on the Implementation of Part XI of UNCLOS,[236] those consequences need to be studied and addressed.

In addition to the above, the concept of a "social license to operate" deserves particular attention. This concept includes acceptance by society, in addition to the permission required from the regulator, that a commercial activity such as resource extraction may be undertaken (Owen and Kemp, 2013; Parsons and Moffat, 2014). Also, issues of transparency and the inclusion of broad stakeholder participation in the decision-making process are of particular interest (Ardron and others, 2018; Madureira and others, 2016).

Finally, in order to ensure that all external costs to society arising from DSM are internalized, the incorporation of the "polluter pays" principle into the ISA regulatory framework might be considered as an approach (Lodge and others, 2019).

[236] United Nations, *Treaty Series*, vol. 1833, No. 31363.

5. Capacity-building needs

A crucial need exists for capacity-building of deep-sea biodiversity research and conservation as well as offshore mineral deposit identification and assessment, especially for developing States. For cobalt-rich ferromanganese crusts, both exploration techniques and exploration technology are significantly lagging behind those for SMS and PN.

Another key component now needed for offshore mining is an expanded collection of baseline data especially in respect of characterization of ecosystems and their components, as well as natural variations of environmental baselines, including for the shallow-water continental shelf and the deep sea. Finally, there is also a clear need for transparent and inclusive regulatory capacity development to avoid, reduce, and mitigate impacts to ecosystems and for long-term online monitoring of the impacts of mining.

In 2019, the African Group submitted to the ISA (ISBA/25/A/8) a document on ‘Training programmes for developing countries’, which emphasized capacity building and developmental needs. A recent assessment report by the ISA Secretariat entitled ‘Review of the capacity building programmes and initiatives implemented by the International Seabed Authority’ details the work of the ISA with respect to capacity building.[237] This report examines the core capacity-building themes implemented by the ISA thus far, namely the Contractor Training Programme, the Endowment Fund for Marine Scientific Research in the Area, and the Internship Programme. This report, among others, was the subject of an International Workshop on Capacity Development, Resources and Needs Assessment held on 10-12 February 2020 in Kingston, Jamaica. A summary of the workshop is available on the ISA website.[238]

Strategic partnerships amongst the UN and regional institutions focused on the creation of platforms to strengthen international cooperation for capacity-building programs address some particular issues faced by developing countries and help create common ground for improving actions. Within the framework of the ISA, the need is recognized to expand the opportunities for developing States to participate in activities in the Area[239]. While programmes for the training of personnel of the ISA and developing States remain a contractual obligation for contractors under the exploration contracts with the ISA, it is a challenge to monitor the positive impacts and new opportunities that these programmes may have brought to these countries.

[237] ISA Secretariat, 5 February 2020, https://www.isa.org.jm/files/2020-02/assessment.pdf.

[238] ISA website, https://www.isa.org.jm/files/2020-02/outcomessummary_0.pdf

[239] See International Seabed Authority document ISBA/24/A/10

Table 1. Seabed mining pressures, potential impacts on the different habitats, and ecosystem services (Thurber and others, 2014) that might be impacted.

<table>
<tr><th>Pressure</th><th>Potential impact</th><th>Affected ecosystem services</th><th>Habitat</th></tr>
<tr><td>Extraction of sea floor substrate</td><td>Loss of benthic fauna by direct removal
Changes in sediment composition
Habitat loss or degradation
Stress induced on fauna</td><td rowspan="5">Supporting
Nutrient cycling
Circulation
Chemosynthetic production
Secondary production
Biodiversity
Regulating
Carbon sequestration
Biological regulation
Nutrient regeneration
Biological habitat formation
Bioremediation/detoxification
Provisioning
CO_2 storage
Fisheries
Natural products</td><td>Bentho-pelagic
Benthic</td></tr>
<tr><td>Extraction plume</td><td>Loss or damage of benthic species by smothering organisms (from mega to micro)
Behavioural changes in animals
Changes in sediment composition
Changes in seabed morphology</td><td>Bentho-pelagic
Benthic</td></tr>
<tr><td>Dewatering plume</td><td>Clogging of feeding, sensorial or breathing structure
Mechanical damage of tissues
Stress</td><td>Pelagic
Bentho-pelagic
Benthic</td></tr>
<tr><td>Release of substances from sediments (extraction and dewatering plume)</td><td>Toxicity
Nutrient release
Turbidity</td><td>Pelagic
Bentho-pelagic
Benthic</td></tr>
<tr><td>Underwater noise</td><td>Disturbance of animals</td><td>Pelagic
Bentho-pelagic
Benthic</td></tr>
</table>

Underwater light	• Disturbance of animals		Pelagic Bentho-pelagic Benthic

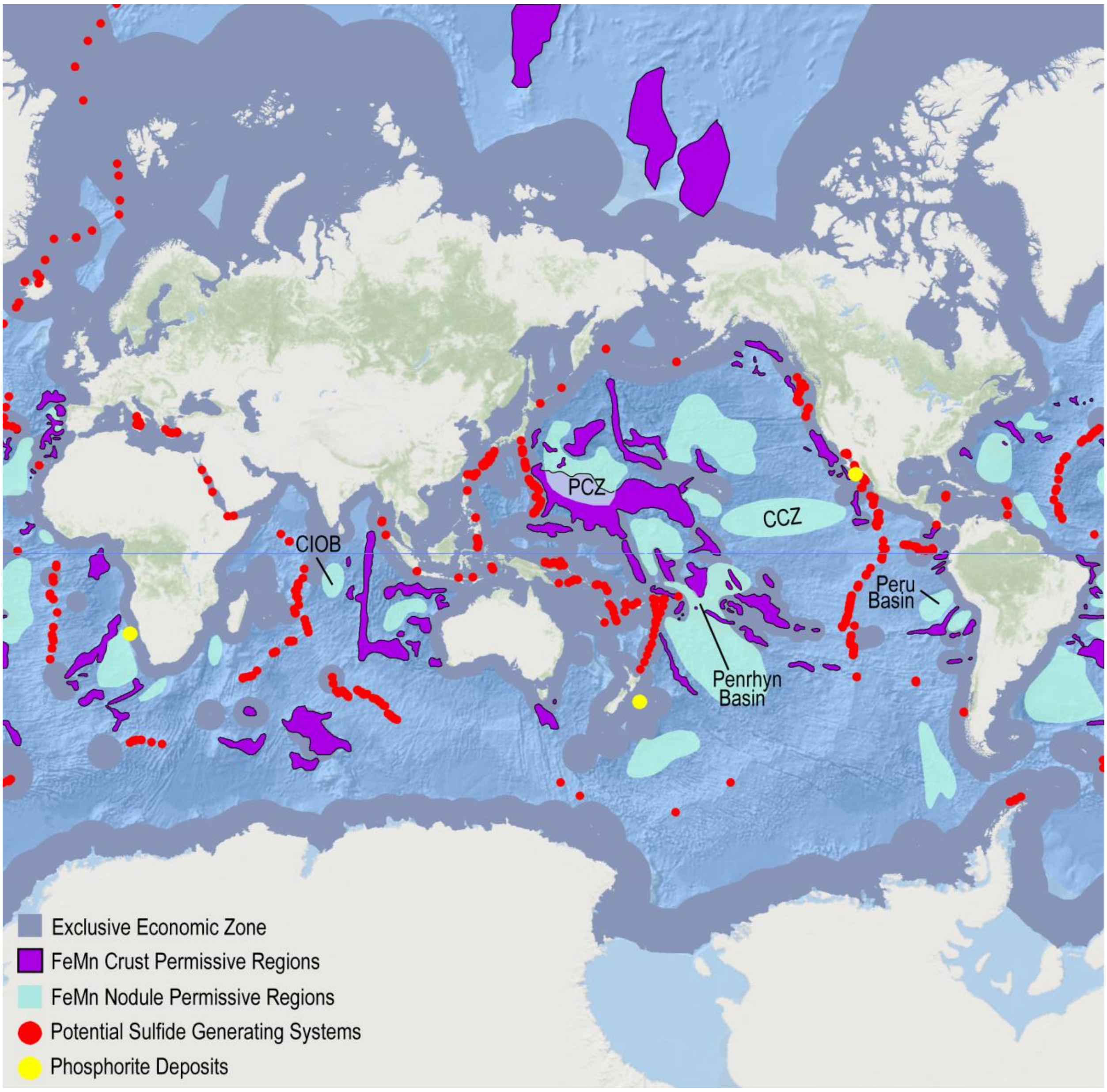


Figure 1. Global permissive areas for deep-water seabed mineral deposits. Red indicates the location of hydrothermal vent sites (after Beaulieu, 2015), which are potential sea floor massive sulphide (SMS)-generating systems; SMS have not been found at all of those sites. In the area of the Prime Crust Zone (PCZ; Hein and others, 2009), the permissive areas for crusts (CFC) and nodules (PN) overlap; nodule fields occur between seamounts and ridges in much of the western PCZ. Location of the three phosphorite deposits discussed in the text are indicated with yellow filled circles. The four well-known polymetallic nodule fields are also indicated: Clarion-Clipperton Zone (CCZ), Peru Basin, Penrhyn Basin and Central Indian Ocean Basin (CIOB); modified from Hein and others (2013); the dark grey area around Antarctica is not an Exclusive Economic Zone, it simply represents the 200 nautical mile extent.

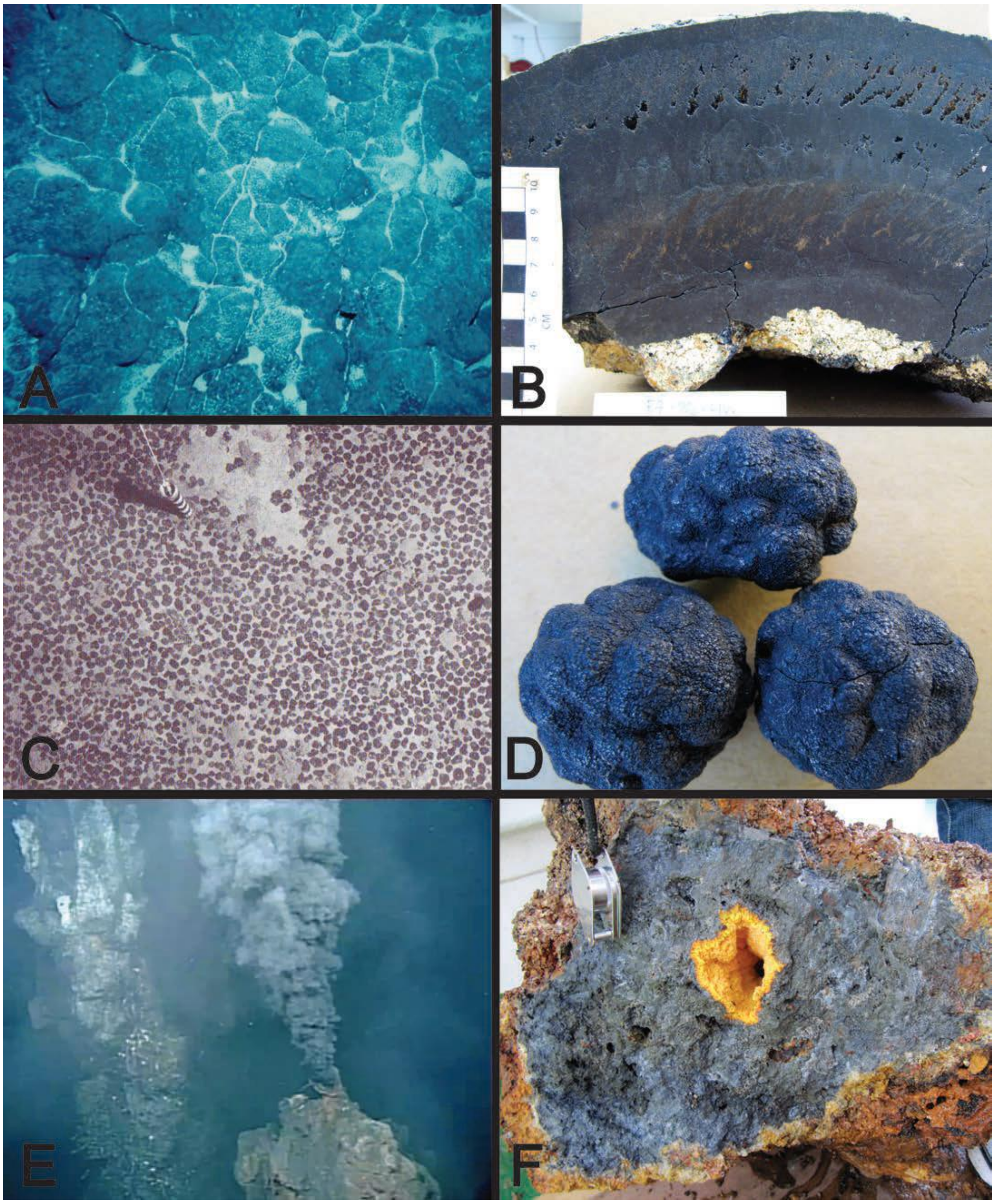
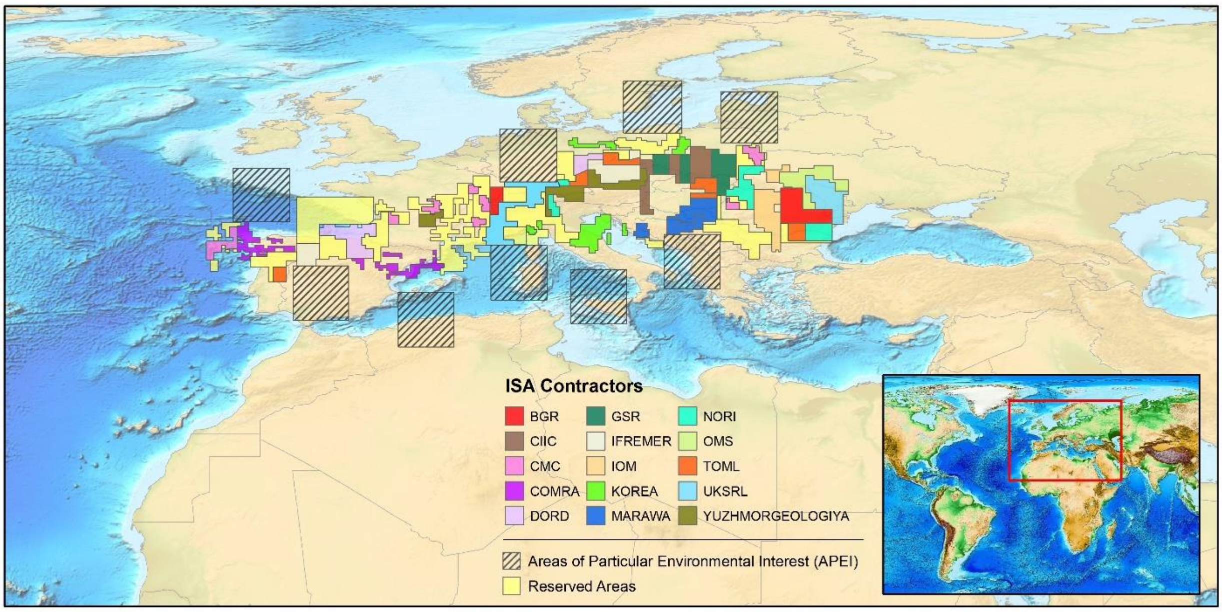


Figure 2. Sea floor and mineral deposit photographs of crusts, nodules, polymetallic sulphides: (A) Sea floor covered with cobalt-rich crust in the Marshall Islands area, West Pacific (cruise USGS F10-89-CP), water depth ~1,650 m, field of view about 3x3 m; (B) 12-cm thick crust (CD29-2, USGS cruise F7-86-HW) from the Johnston Island area, central Pacific, recovered from a water depth of 2,225 m, scale bar represents 10 cm; (C) Seabed covered with polymetallic nodules in the CCZ nodule field, water depth is approximately 5,000 m, field of view is about 3x3 m; (D) Polymetallic nodules from the CCZ, NE Pacific Ocean; each nodule is 3 cm in diameter, approximate water depth is 5,000 m; (E) Seabed with an active black smoker from the NE Pacific Ocean, approximate water depth is 2,200 m, field of view about 4x4 m (NOAA Ring-of-Fire); (F) Cross-section through a large zinc sulphide chimney showing a yellow silica conduit through which the hot fluids flowed; collected at 377 m water depth, Mariana volcanic arc, West Pacific (JAMSTEC, cruise NT10-12).



Datum: WGS84; Projection: Cylindrical Equal Area Projection

Figure 3. ISA CCZ contract map, overlaying Europe to provide scale.

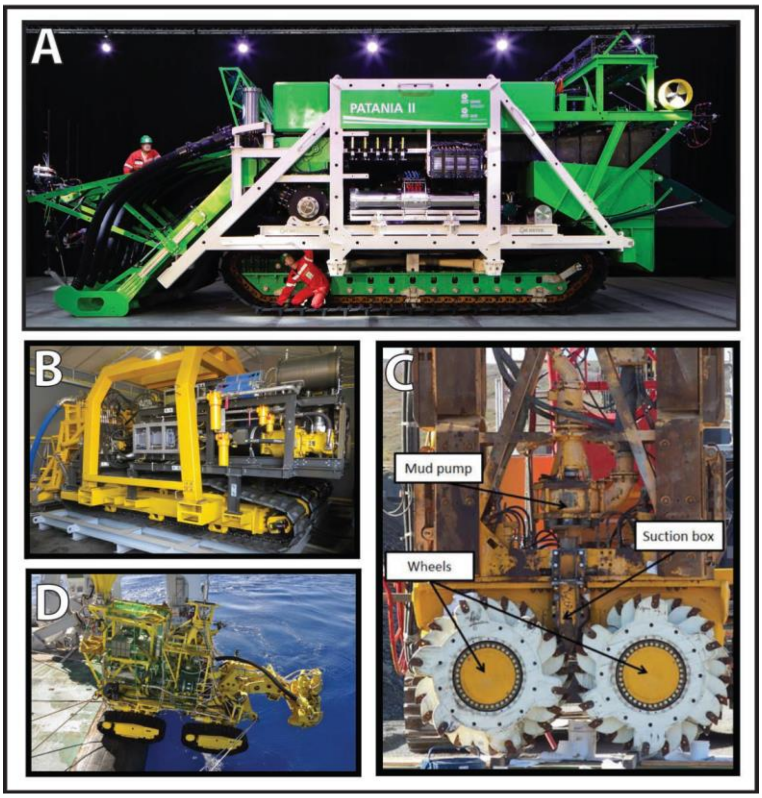


Figure 4. Examples of new prototype deep-water seabed mining tools: (A) Global Seabed Mineral Resources (GSR; Belgium) Patania II mining machine for polymetallic nodules (photo courtesy of GSR); (B) Korea Research Institute of Ships and Ocean Engineering (KRISCO) mining machine for polymetallic nodules (photo by Hein); (C) Bauer Maschinen GmbH, BC40 polymetallic sulphide trench cutter mining tool; (D) JOGMEC (Japan) mining machine for polymetallic sulphides, tested in Okinawa Trough sulphides in the summer of 2017.

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Chapter 20
Changes in Hydrocarbon Exploration and Extraction

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Keynote points

- Since the First World Ocean Assessment (WOA I) (United Nations, 2017b), the offshore oil and gas sector has continued to expand globally, particularly in deep and ultra-deep waters. The use of tension leg platforms, spars and Floating Production, Storage and Offloading systems (FPSOs) are key to such expansion.
- In the next decade, frontier regions such as the eastern Mediterranean, east coast of South America (Brazil and Guyana), and west coast of Africa could be the major growth drivers for offshore oil and gas exploration and production.
- There is an upward trend in decommissioning activity, particularly in mature regions such as the North Sea and Gulf of Mexico.
- Exploration and production practices continue to evolve to minimize potential impacts on the surrounding environment.
- Creation of regulatory capacity to effectively manage offshore resources, especially in frontier regions, requires significant commitment and long-term institutional investment.
- Technological innovation and sophisticated industrial capability built over decades by the offshore oil and gas sector are benefiting the emergence of the marine renewable energy (MRE) industry.
- A major thrust of the offshore hydrocarbon sector since WOA I is technological advancement in analysing offshore exploration and production data to enhance operational and financial efficiencies.

1. Introduction

1.1. Scope

Chapter 21 of WOA I (United Nations, 2017a) provided a baseline state for the offshore hydrocarbon industries in its discussion of exploration and production trends, social and economic aspects, emerging technologies and potential future trends. The discussion also included environmental impacts associated with resource development and production activities and highlighted capacity gaps to assess impacts.

The present Chapter assesses the current state of the global offshore hydrocarbon sector and presents some of the advances made in the field since WOA I. It includes exploration, production and decommissioning trends; an in-depth assessment of economic, social and environmental aspects, including potential impacts; capacity-building, particularly in emerging economies; and the crucial role of the offshore hydrocarbon industry in facilitating the MRE industry globally. Its content relates also to Chapter 6D, Chapter 8, Chapter 9, Chapter 21, Chapter 22, Chapter 23 and Chapter 29 of the present Assessment.

The present Chapter also relates to five United Nations Sustainable Development Goals (SDGs): Goal 8, to promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all; Goal 9, to build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation; Goal 12, to ensure sustainable consumption and production patterns; Goal 13, to take urgent action to combat climate change and its impacts; and Goal 14, to conserve and sustainably use the oceans, seas and marine resources.[240]

1.2 Overview of global offshore hydrocarbon resources and production trends

Global crude oil production has grown steadily and exceeded 100 million barrels a day in 2018, while natural gas production has increased more rapidly to 113.7 billion MMBtu (Million British Thermal Units) in 2016 (IEA, 2019).[241] Onshore oil and gas production continues to dominate, yet offshore oil production, which has been steady at around 27 million barrels per day (b/d) for a decade, is showing an upward trend (Clemente, 2018). Meanwhile, offshore natural gas production has grown steadily in the past decade by 35 billion MMBtu, with gains off Brazil, Australia, the eastern Mediterranean and, most significantly, in the Persian Gulf, with the development of the massive North Field off Qatar (Davis, 2018). Natural gas production is projected to increase mainly from activities in shallow waters; oil production increases will rely largely on drilling in deep and ultra-deepwater areas.

Offshore oil is produced in more than 50 different countries, with Saudi Arabia, the United States of America, Brazil, Mexico and Norway as the most significant producers. More recently, large untapped resources have been discovered off the east coast of South America. According to the Organization of the Petroleum Exporting Countries (OPEC),[242] offshore oil production from Brazil and Guyana will compensate for falling production in other regions, although production in the United States (US) Gulf of Mexico, the oldest offshore oil and gas producing region, may hold steady with discoveries in deep and ultra-deep waters (OPEC, 2019).[243]

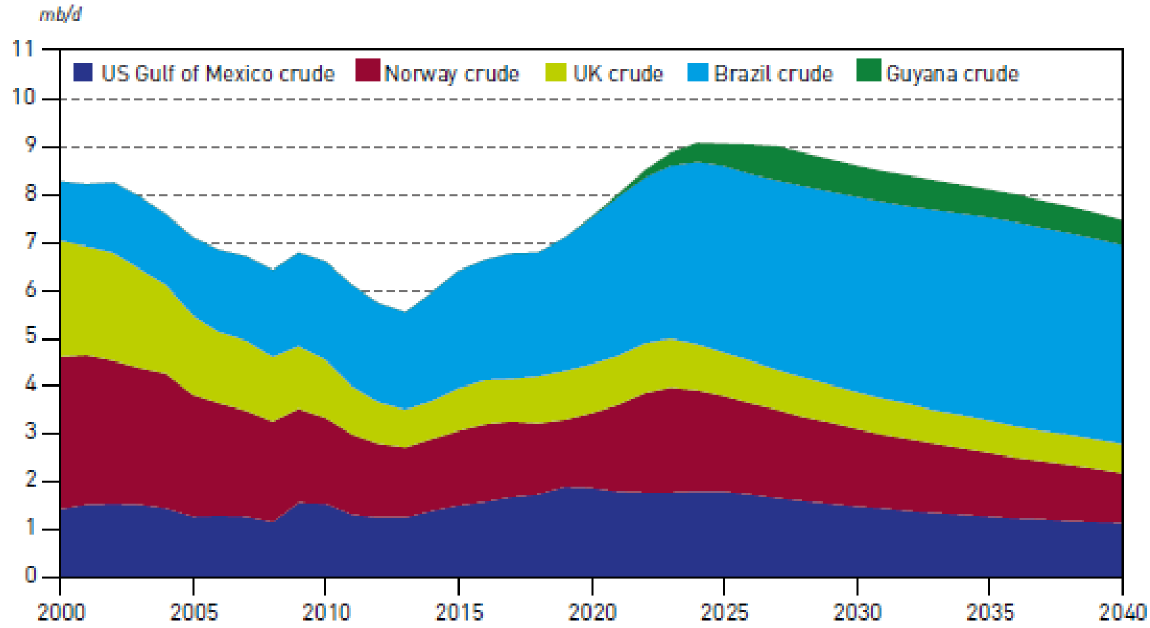

Figure 1. Crude oil output in selected offshore producing areas (Source: OPEC 2019).

1.3. Advances in knowledge and capacity

[240] See United Nations General Assembly resolution 70/1.
[241] Converted to 5.3 mboe/d.
[242] OPEC member countries in 2020 include: Algeria, Angola, Ecuador, Equatorial Guinea, Gabon, Iran, Iraq, Kuwait, Libya, Nigeria, Republic of the Congo, Saudi Arabia, United Arab Emirates and Venezuela.
[243] Shallow waters generally extend to less than 1,000 feet; deep water is between 1,000–5,000 feet; and depths greater than 5,000 feet are considered ultra-deep water.

New exploration and development in offshore areas remains a major source of increasing global oil and gas production. Technological advances in the past decade have encouraged exploration in deep and ultra-deep waters further away from shore and enabled discovery of significant new reserves. The water depth capabilities for offshore exploration increased from 10,000 ft (3,048 m) to over 11,000 ft (3,353 m) between 2010 and 2018, while production capability using floating platforms reached almost 9,500 ft (2,896 m) in 2018, up from 8,000 ft (2,438m) in 2010 (Barton and other, 2019). Such technological advances have in part enabled the expansion of the offshore oil and gas sector to new regions including the eastern Mediterranean and offshore Guyana.

There are also advances in understanding the potential environmental and social impacts of exploration and production activities on the surrounding environment and in the development of new approaches to mitigate impacts. For instance, the United Kingdom of Great Britain and Northern Ireland has created a Marine Noise Registry (MNR) to record human activities in the seas of the United Kingdom that produce loud impulsive noise (10 Hz–10 kHz).[244] This initiative intends to create a baseline level of data and to quantify the pressure on the environment from anthropogenic activities associated with hydrocarbon exploration and development, including seismic surveys, sub-bottom profiling, pile driving, etc. Similarly, SERPENT project (which stands for Scientific and Environmental ROV Partnership using Existing iNdustrial Technology) is an example of international collaboration between the scientific community, environmental regulators, and the oil and gas industry to gather and provide baseline information on ecosystems around offshore oil and gas installations using cutting edge Remote Operated Vehicles (ROV) that can operate in the deep ocean (SERPENT Project, 2020).
More recently, the offshore oil and gas industry has contributed to the MRE sector by providing expertise for the construction, maintenance, and decommissioning of utility-scale offshore wind projects. The design and structural engineering concepts for the floating wind turbines, which can significantly expand the development of wind power in deeper waters associated with higher wind resources, are largely influenced by deepwater oil and gas installations (IRENA, 2016).

2. Offshore hydrocarbon exploration, production and decommissioning

2.1. Offshore hydrocarbon technologies for survey and exploration

Oil and gas survey and exploration techniques locate hydrocarbon resources accumulated under impermeable rock formations. An initial assessment using seismic surveys evaluates the location of hydrocarbon-rich geologic play - a group of oil and gas bearing rocks - that share a common history of hydrocarbon generation, migration, and entrapment (Maloney, 2018; BOEM, 2017). This sets the stage for geological and geophysical surveys to obtain refined data on resource-bearing geological formations. Such surveys also provide an assessment of marine mineral resources, archaeological and benthic resources and any artificial structures buried and abandoned on the ocean floor.

Offshore seismic surveys use specialized vessels equipped with a combination of air guns and other acoustic sources. The equipment also includes hydrophones attached to a set of cables (streamers) towed behind the vessel. The acoustic sources produce a seismic pulse projected toward the ocean floor that reflects off the boundaries between various layers of rock. The reflected pulse is then recorded by the hydrophones and collected for further analysis.

Recent advances in supercomputing and Full Waveform Inversion (FWI) technology are transforming resource estimation. FWI, a new kind of processing technique applied to existing seismic data using supercomputers, creates a model of the subsurface rock layers in rich detail (Advisors, 2019). Similarly, advances in 4-D seismic technology, coupled with superior computing power, now provide new insights into hydrocarbon reservoir characteristics, thus offering greater certainty to prospective

[244] See Joint Nature Conservation Committee, Marine Noise Registry Service. Available at https://mnr.jncc.gov.uk/.

resource developers.

2.2. Technological changes in drilling and production, including emerging technologies

Offshore drilling and production continues to witness significant technological advances. Sophisticated techniques now allow for drilling multiple wells from a single drilling platform, while advances in real-time fibre-optic monitoring of the well bore is optimizing the reservoir performance and mitigating equipment failure risks (Beaubouef, 2019). Similarly, the use of predictive analytics and artificial intelligence tools is enhancing data analysis for detecting equipment breakdown and improving operational efficiency (Husseini, 2018).

The use of floating production, storage, and offloading (FPSO) vessels allows for drilling in areas further offshore and without ready access to a pipeline network to transport oil and gas onshore. It has also opened previously inaccessible hostile environments, particularly in the higher latitudes and in the Arctic, for exploration and development.
FPSO vessels are equipped to store hydrocarbons onboard and periodically transfer their load to tankers for transportation onshore. They can also disconnect from their moorings in case of adverse weather conditions such as cyclones and hurricanes. Once the wells are sufficiently depleted, an FPSO vessel can be redeployed to a new prospective site. The global market for FPSO vessels is currently boosted from large investments in deepwater exploration and development in areas such as offshore Brazil (Rystad Energy, 2019). Meanwhile, FPSO vessel design is evolving to enhance safety, minimize complexity and reduce fabrication and operation costs (Barton, 2018).

Such technological advances have enabled exploration and production in unchartered depths and distance from shore. As of March 2019, the record for an ultra-deepwater exploration well was in depths of 11,155 feet offshore of Uruguay, while the record for an operational production platform stands at 9,500 feet in the Gulf of Mexico (Barton and other, 2019).

Table 1. Drilling platform types by depth

Platform type	**Water depth**
Fixed platforms	Up to ~1,500 ft
Compliant towers	1,000–3,000 ft
Tension leg platforms	7,000–10,000 ft
Spars	10,000–12,000 ft
Floating production and FPSO systems	12,000 ft and above

2.3. Decommissioning techniques and trends

Although decommissioning regulations vary among jurisdictions, regulators increasingly require complete removal of all drilling and production structures from the offshore environment. The 1992 OSPAR Convention[245] provides for protection of the marine environment of the North-East Atlantic. It requires removal of disused offshore installations, unless an exemption is provided to leave the entire

[245] United Nations, *Treaty Series*, vol. 2354, No. 42279. The Convention for the Protection of the Marine Environment of the North-East Atlantic has been signed and ratified by Belgium, Denmark, the European Union, Finland, France, Germany, Iceland, Ireland, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom of Great Britain and Northern Ireland.

installations or parts thereof in place (OSPAR Commission, 1992). Similarly, the 1995 Barcelona Convention[246] provides the framework for decommissioning in the Mediterranean region and mandates removal of all abandoned or disused installations (UNEP, 1976). Other regions have adopted similar regulatory frameworks based on either regional conventions, such as the Regional Organization for the Protection of the Marine Environment (ROPME) Protocol in the Middle East (ROPME, 1989) or, in the absence of a regional convention, the International Maritime Organization guidelines (IMO, 1989) which are based on Article 60 (3) of the United Nations Convention on the Law of the Sea.[247] Regulations pertaining to pipelines vary. While some jurisdictions require complete removal, others deal on a case-by-case basis, depending on the hazards to fishing and navigation (IOGP, 2017). The “Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972," the "London Convention" for short, is the major international treaty to protect the marine environment from all sources of pollution, including dumping of structures and wastes. In 1996, the convention was revised to prohibit all abandonment (for the purpose of deliberate disposal) of man-made structures at sea, including topping of oil and gas platforms at site (IMO, 2020).

The decommissioning process usually involves plugging the abandoned well, preparing the platform for removal by flushing and cleaning any residual hydrocarbons, cutting the pipes and cables between deck modules, and mobilizing equipment such as derrick barrage and cranes to dismantle and move the topside platform onshore for disposal. The process also involves removing the jacket or the foundation structure using heavy lifting equipment, a time-consuming and expensive process. Once on land, the structure is dismantled further for disposal or sold off as scrap.

The offshore decommissioning activity is largely concentrated in the North Sea, US Gulf of Mexico and parts of the Asia-Pacific region. The steady depletion of legacy oil fields in the North Sea has created significant demand for decommissioning, which is expected to cost 32 billion US dollars between 2018 and 2022 (Wood Mackenzie, 2017). In the US Gulf of Mexico, decommissioning is focused on platforms in shallow waters, while drilling and production moves to deep and ultra-deep waters.

Offshore platforms contribute hard structure to the marine environment and, in the process, provide food sources and complex physical habitat for a variety of organisms. Studies indicate higher levels of biological and fish productivity around platforms compared to natural reefs at similar depths (Shinn, 1974; Claisse and others, 2015). Because they recognize the ecological value of these structures, nations including Brunei and Malaysia are looking at converting obsolete platforms into artificial reefs in lieu of complete removal and disposal onshore (also known as “rigs-to-reefs” programmes) (Bull and Love, 2019). The “Rigs to Reefs” program is already operational in the US, where obsolete platforms are reefed on a case-by-case basis in consultation with the coastal states. As of April 2018, 532 platforms previously installed on the US Outer Continental Shelf (OCS) have been reefed in the Gulf of Mexico (BSEE, 2020).

In order to evaluate the decommissioning options, the state of California in the US and other jurisdictions are proposing using Net Environmental Benefit Analysis (NEBA) as a tool to decide on reefing and removal options. NEBA is an analytical approach for comparing alternatives of a proposed action by including non-monetary environmental metrics, such as ecosystem services and values (Efroymson and others, 2004). It is conceivable that other jurisdictions may adopt NEBA and similar approaches to consider holistically the environmental and ecosystem impacts of decommissioning options.

[246] Barcelona Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean.

[247] United Nations, *Treaty Series*, vol. 1833, No. 31363.

3. Economic, social, and environmental aspects of offshore hydrocarbon exploration, production, and decommissioning

3.1. Economic and social impacts

Offshore oil and gas exploration and production is highly capital intensive, with an estimated annual global investment expenditure of 155 billion US dollars in 2018 and projected investment of over 200 billion dollars in 2021 (Sandøy, 2018). Engineering, procurement, construction and installation of drilling and production structures are the major areas of capital expenditure.

The specialized workforce in the offshore oil and gas sector draws significantly from a highly skilled global talent pool. Cities like Houston and Aberdeen have emerged as global hubs, serving not only the regional offshore industry but also providing expertise and services for projects around the world. The industry has also created a strong linkage with local communities, offering much valued business and employment opportunities, often in synergy with traditional activities. For instance, the Louisiana shrimpers, during the lean fishing season, rent out boats for offshore oil and gas activities (Priest, 2016), while some fishermen supplement their income by working on the production platforms. According to the Office for Coastal Management at the US National Oceanic and Atmospheric Administration, offshore oil and gas activities in the US contributed around 80 billion dollars to the economy in 2016 and directly employed approximately 130,000 workers at an average salary of 153,000 dollars per year, which is almost three times the national average wage (NOAA, 2018). Considering direct and indirect employment, over 268,000 jobs are supported by oil and gas activity in the US OCS (US DOI, 2018). Meanwhile in the United Kingdom of Great Britain and Northern Ireland, offshore oil and gas remains a significant source of skilled employment, and supported around 259,900 jobs in 2018, which includes a significant number of indirect and induced jobs (OGUK, 2019). Offshore oil and gas activities in other regions similarly produce high levels of economic output and employ workers at above-average wage levels.

Offshore oil and gas production is maturing in many regions, especially in the North Sea and shallow waters of the Gulf of Mexico. As the production declines and major oil reservoirs deplete beyond recovery, the industry expects to spend around 100 billion dollars globally over the next decade on decommissioning activities (OGUK, 2018). This trend has the potential to create significant employment opportunities, some of which can offset the contraction of exploration- and production-related jobs.

3.2. Environmental impacts

Offshore oil and gas exploration and development practices have evolved significantly in terms of minimizing impacts on the surrounding environment, but operational and accidental discharges and other environmental impacts, still occur. Operational discharges include chemicals that arise from drilling activities, produced water, drilling muds and cuttings, and small amounts of treated domestic and sanitary wastes. Noise, sea-bed disturbance, and impacts on biodiversity are other potential environmental impacts. Additionally, the installation of pipelines and related infrastructure also contributes to certain discharges into the marine environment. Decommissioning of installations can also be accomplished with more or less severe environmental impacts, depending on removal methodologies and subsequent environmental monitoring.

Produced water is a mix of oil and water from underground formations brought to the surface during production. Initially representing a small percentage, over time the percentage of water increases and hydrocarbon decreases (Clark and Veil, 2009). The global average is estimated to be three barrels of produced water for each barrel of oil (Khatib and Verbeek, 2002). Older wells, meanwhile, can display a ratio in excess of 50 barrels of produced water for each barrel of oil. According to a study by IFP Energies Nouvelles, produced water is set to exceed 300 Million barrels/day in 2020 globally, an increase of 20% over 2008 levels. Most of the increase is expected from offshore oil and gas production (IFP Energies Novelles, 2011).

Disposal options include injection into the same formation from where the oil is produced, treating the produced water to meet a certain quality standard and then either discharging it into the environment or using treated water in oil and gas field operations. While most of the treated produced water onshore is injected underground, in the offshore environment, it is discharged in the marine environment. Such discharges are often regulated by local or national water quality regulations, such as the Clean Water Act in the US. The US Department of Energy is currently investing 4.6 million dollars to fund projects that would advance produced water treatment technologies (DOE, 2019). Although the funded projects focus on land-based drilling, many advances will be relevant for offshore oil and gas production.

The emission of criteria pollutants related to platform or non-platform sources can impact air quality in the vicinity of the drilling and production platforms. The platform sources concern emissions from on-board equipment, such as boilers, natural gas engines and pneumatic pumps, while non-platform sources concern emissions from pipe-laying operations, support and survey vessels and helicopters. Additionally, open flaring of unwanted or excess gas from production platforms affects air quality. According to the World Bank, around 145 billion cubic metres (bcm) of gas related to oil production was flared globally in 2018, equivalent to the total annual gas consumption of Central and South America (World Bank, 2019a). Multilateral initiatives such as the Global Gas Flaring Reduction Partnership, led by the World Bank, aim significantly to reduce flaring at production sites. The programme promotes related research, disseminates best practices and works with national oil companies, regional and national governments and international institutions to remove technical barriers to flaring reduction (World Bank, 2019b).

There have been significant improvements in oil spill forecasting, response, and understanding of impacts. Improvements in oil spill forecasting has been achieved through better visualization of the trajectory and fate of oil using expanded modelling suites such as the General NOAA Operational Modelling Environment (GNOME) in the US (NOAA 2019). Similarly, project GRACE (integrated oil spill response actions and environmental effects) in the EU is investigating the hazardous impacts of oil spills and the environmental impacts of oil spill response technologies in cold climate conditions such as the North Atlantic (Jørgensen et al., 2019). There are also advances in the use of satellites and other techniques for oil spill surveillance and monitoring, methods to evaluate the toxic effects of the spilled oil, and understanding impacts on corals, marine mammals, and sea turtles to uncover best ways to protect, rescue, and restore marine wildlife and ecosystems impacted by oil (NOAA 2020).

4. Key knowledge and capacity-building gaps

4.1. Importance of long-term environmental monitoring and mitigation

The short-term marine environmental impacts from oil and gas exploration and development have been studied extensively. However, the understanding of long-term effects is less complete. Long-term monitoring provides valuable insights into ecology, environmental change and natural resource management (Lohner and Dixon, 2013). It also provides a systematic measurement of key environmental, social and economic indicators over time to design and implement effective policies and mitigation measures, while establishing a natural baseline for measuring trends over time. This baseline can then be used to assess changes from ongoing drilling and production activities. Although establishing long-term monitoring programmes in the offshore environment is particularly challenging, the oil and gas industry and regulators are encouraging such programmes to assess changes and design effective mitigation strategies. For example, two observatory systems installed off Angola record long-term changes in the physical, chemical, and biological environment due to oil and gas development (Vardaro and others, 2013). Similarly, the long-term monitoring of the Flower

Garden Banks National Marine Sanctuary in the Gulf of Mexico is one of the longest such programmes to monitor the health of coral reefs in the vicinity of operational oil and gas production facilities (NOAA, 2018). On a global scale, the SERPENT project discussed earlier uses cutting edge technology for long-term monitoring of deep-sea corals habitats and other ecosystems. More such programmes are required to monitor long-term environmental impacts and ensure resource development in an environmentally responsive manner.

4.2. Capacity-building gaps, especially in emerging economies

Offshore oil and gas exploration and production is expanding, sometimes to regions with minimal experience in managing the resources. Resource management in the offshore environment presents unique challenges for oil and gas resource managers to control access and encourage development. At its core, effective management requires the definition of property rights for offshore oil and gas resources within a nation's exclusive economic zone.

National resource management systems generally aim to clarify offshore jurisdiction, resolve multi-use conflict and implement a regulatory framework for development in combination with laws on environmental protection, pollution prevention, health and safety standards, oil spill response, etc. The regulatory frameworks tend to follow one of two approaches (Dagg and others, 2011), namely, prescriptive, whereby operators are told what to do; or performance- or goal-based, whereby goals that operators must achieve are identified but the operators are allowed to choose how they achieve those goals.

These two approaches have their benefits and drawbacks. Prescriptive regulations have the advantage of being relatively simple to implement and track, but they may stifle both innovation and creative solutions due to their emphasis on narrowly defined rules and regulations. Performance-based regulations, on the other hand, can create additional administrative burdens in terms of tracking regulations and verify that goals have been met. Often, these two approaches are blended to create a hybrid regulatory system.

In creating a new offshore oil and gas regulatory framework, a jurisdiction can recalibrate its existing regulatory framework for land-based mineral development, while also appropriating elements from jurisdictions with more established regulatory practices and significant experience managing offshore oil and gas resources. This can be aided by capacity-building facilitated through multilateral institutions, like the World Bank, and through exchanges of information among jurisdictions.

A regulatory framework could be subjected to periodic reviews to assess economic impacts and other unintended consequences. This can be achieved by using the Regulatory Impact Analysis framework, which is used in many jurisdictions for routine assessment and is supported by international entities such as the Organization for Economic Cooperation and Development (OECD, 2019). Additionally, it is important to build good regulatory practices into the administration itself if the public or regulatory agencies are expected to carry out policies effectively and efficiently. Such practices require capacities to judge when, what, and how much to regulate in order to allow responsiveness to changing conditions and to ensure transparency, flexibility, and policy coordination.

Creating capacity to properly and effectively manage offshore energy resources requires significant commitment and long-term institutional investment. The rewards, though, are commensurate, ensuring that resources are developed in a responsible manner, and that economic benefits are distributed fairly.

5. The hydrocarbon industry and the marine renewable energy (MRE) industry

5.1. Role of the offshore hydrocarbon industry in facilitating the MRE

industry

The offshore oil and gas sector has built sophisticated industrial capability through technological innovation and decades of experience operating in some of the most challenging environments around the world. The emerging MRE industry, which includes wave, tidal, ocean current and offshore wind power, is now benefiting from this accrued knowledge. Offshore wind power, the most developed form of MRE, in particular, has seen the use of technology and skills perfected by the oil and gas sector. Wind turbine foundations and towers are engineered to withstand wave, wind, scouring and other forces that were first analysed while designing oil and gas platforms. Similarly, the experience gained from addressing the corrosive impact of salt water and sea spray on oil platforms was applied to marinize and suitably modify terrestrial wind turbines for offshore installation (Breeze, 2016). Biofouling solutions for submerged oil and gas structures have been extensively researched and more recently applied to MRE structures. Similarly, the installation of MRE transmission cables on the ocean floor has seen the use of technologies and expertise first developed for laying submerged pipelines to serve offshore oil and gas platforms.

The large manufacturing infrastructure that serves the offshore oil and gas industry is now supporting the offshore wind industry. The jacket foundations for the first offshore wind project in the US off Block Island, were fabricated and supplied by a company in Louisiana with expertise in building structures for the offshore oil and gas industry in the Gulf of Mexico. Similarly, in the North Sea, extensive expertise in the oil and gas sector was harnessed to design and engineer floating offshore wind turbines for the Hywind Scotland project, where the installation of conventional bottom founded turbines is not viable.

The oil and gas sector experience in maritime logistics is now shaping the MRE industry. In the US, engineers have designed a marine vessel sufficiently versatile both to install wind turbines and decommission oil and gas platforms (McGowan, 2018). Such initiatives enable significant cost saving for MREs. The use of port infrastructure and service vessels are other examples of leveraging already established assets to facilitate the utilization of new marine energy resources.

The MRE industry is considering the use of abandoned offshore oil and gas platforms to install wind turbines, although structural integrity concerns could impede such conversion plans. A potentially more viable option is reconfiguring abandoned platforms to convert MRE-generated electricity into hydrogen or synthetic gas, which could then be used to ride over low wind or wave periods and enhance the market potential of MRE projects. A simulated pilot project to test this concept was conducted by the Energy Delta Institute in the Netherlands in 2015 (Jepma and van Schot, 2016). Repurposing a platform has the additional benefit of delaying the expensive decommissioning costs while providing a new lease of life with positive economic returns. Another proposal envisions supplying electricity from offshore wind turbines to oil and gas platforms for on-board operations, now commonly supplied by gas turbines located on board. A case study employing this approach in the North Sea concluded significant cost savings and a reduction in the emissions of criteria pollutants and greenhouse gases (Korpås and others, 2012). Subsequently, Hywind Tampen, an 88 MW floating offshore wind project, was approved in 2019 to provide electricity to oil and gas platforms in the North Sea (Oil & Gas Journal, 2020). Creating such synergies and leveraging oil and gas sector experience, expertise and infrastructure allows the burgeoning MRE sector to reduce costs and save time and resources.

6. Conclusion

Offshore oil and gas is an important contributor to global hydrocarbon production. Increasing global hydrocarbon demand, coupled with technological advances in offshore exploration and production, has pushed the industry to discover new reserves in ever deeper waters and challenging environments, often in areas with no prior resource development or in semi-closed seas, which are particularly vulnerable to environmental accidents. Global offshore hydrocarbon production therefore, continues to increase, creating economic opportunities for coastal communities and much-needed leasing and royalty revenues for national governments. It is important that new and existing offshore projects are managed in an environmentally responsible manner, while decommissioning of obsolete facilities is undertaken according to national regulations and regional marine environment conventions. A number of major trends have been observed since WOA I, including technological advances in collecting and analysing exploration and production data to enhance operational efficiencies, greater use of flexible platforms such as Floating Production, Storage and Offloading systems to expand production in unexplored areas, and a renewed push by the industry and regulators to minimize environmental impacts by deploying enhanced safety measures and using science to inform resource development.

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Chapter 21
Trends in Inputs of Anthropogenic Noise to the Marine Environment

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Keynote points

- The main anthropogenic noise sources in the ocean include vessels, industrial activity, including seismic exploration and renewable energy development, and sonar.
- Anthropogenic noise levels vary across space and time, primarily driven by levels of human activity and propagation characteristics in the region. Noise does not persist once the sound source has been removed from the environment, although impacts can potentially persist.
- Areas with the highest level of anthropogenic noise are those with heavy industrial use, such as the Gulf of Mexico, the North Sea and the North Atlantic Ocean.
- Areas where anthropogenic noise is expected to increase include the Arctic, as the area opens to shipping, and Africa, as investment in the region increases.
- Understanding of the impacts of anthropogenic noise on marine biodiversity is increasing with associated increased recognition of the need to monitor and possibly reduce noise entering the marine environment.

1. Introduction

Awareness of the importance of sound to marine life and understanding of the potential impact of anthropogenic noise on that life have increased over the last few decades. In the past ten years, there has been increased effort in some regions to develop guidelines and standards for monitoring and regulating anthropogenic noise contribution to the marine environment. While anthropogenic noise was not addressed as a stand-alone chapter in the First World Ocean Assessment (WOA I) (United Nations, 2017), it has been the subject focus of a United Nations Open-ended Informal Consultative Process on Oceans and the Law of the Sea.[248] Increasing awareness of its impacts warrants specific consideration in the present Assessment. Therefore, the current Chapter presents a broad overview, including description of the main sources of anthropogenic noise in the marine environment and the current state of knowledge on the status of anthropogenic noise in the ocean. Additionally, as the main contributors of anthropogenic noise include shipping, energy generation and oil and gas exploration and extraction, those Chapters in WOA I are relevant herein.

The United States Navy was an early source of ocean ambient noise data, with recordings offering insight into ambient sound at frequencies below several hundred hertz (Hz) from the 1950s onward (Ross, 2005). In addition to individual or small group research efforts, over the last decade regional-scale ocean observing systems have started implementing acoustic data collection, first by Neptune Canada, now part of Ocean Networks Canada, and Australia's Integrated Marine Observing System. These observation systems began deploying hydrophones and collecting acoustic recordings in 2008 and 2009, respectively. More recently, the development of metrics and guidelines has also led to advances in impact

[248] https://www.un.org/Depts/los/consultative_process/icp19_report.pdf

assessments and modelling of ambient sound using alternative data sources that serve as proxies for major sources of anthropogenic noise, such as Automatic Information System (AIS) and impulsive noise registry data (e.g. Sertlek and others, 2019; United States National Oceanographic and Atmospheric Administration (2020) CetSound project).

At the same time, challenges remain in measurement of ambient noise and modelling of acoustic propagation, as well as understanding of the impact noise has on animal populations. Measurement challenges include collection of calibrated data and lack of standardization for both measurement and reporting. The American National Standards Institute/Acoustical Society of America and the International Organization for Standardization (ISO) have issued standards for measurement of underwater noise from ships, but the need for arrays of sensors to execute the standard has limited its application. The relatively high cost of deployment and recovery of underwater devices and even costlier installation of cabled systems are an additional impediment to data collection. From the modelling perspective, issues include the lack of fine-scale reliable data on environmental conditions needed for accurate models, and the low spatial and temporal resolution of measured data for validation of models. Finally, on the impact side, understanding of hearing sensitivities of many species, baleen whales, in particular, cumulative impact of multiple noise sources, and evaluation of population-level impact, are starting to be addressed but practical difficulties remain.

2. Description of the environmental status

Sound is an efficient means of communication in the marine environment as sound waves travel very well through water, at speeds approximately five times higher than in the air. Nevertheless, the acoustic power is diminished as sound travels away from the source. Differences in absorption and spreading losses at different frequencies mean that lower sound frequencies travel further than higher frequencies. Additionally, properties of the environment as sound travels through it affect propagation; ocean bottom and water properties affect the sound speed; and bottom topography affects direction of sound travel. In deep waters, special environmental conditions can result in efficient propagation of sound in a deep channel, or convergence of sound at regular distances (Jensen and others 2011). Unique propagation conditions such as the waveguide effect or the Lloyd mirror effect can contribute to the intensification of sound near the surface (Jensen and others, 2011), and bathymetric shielding can create large variability in sound intensity among nearby locations (McDonald and others, 2008).

Sound levels in the ocean, reported in units of decibels, are calculated by referencing the measured sound pressure levels (in units of pascals) to one micropascal (dB re: 1 µPa). Sound pressure levels are typically measured as instantaneous peak or peak-to-peak values or by calculating root-mean-square of sound pressure for longer duration signals. These differences in measurements result in in sound pressure level differences of up to 4.5 dB. Of note, since sound levels in air are calculated relative to 20 micropascals, ocean and air sound levels are not directly comparable. Higher acoustic impedance in water relative to air further contributes to a difference in measurements between these environments. As a result, a correction of 61.5 dB is required to compare airborne sound levels to those made underwater. When reporting noise levels, calculation of power spectral density requires further normalization by the bandwidth of the signal and thus is typically reported in units of dB re: 1 $\mu Pa^2/Hz$. Background ocean ambient sound levels in absence of noise are not uniform across different frequencies, but range from 60 to 70 dB re: 1 $\mu Pa^2/Hz$ at frequencies below 100 hertz and decrease to below 40 dB re: 1 $\mu Pa^2/Hz$ at frequencies higher than 10 kilohertz (Wenz, 1962).

Another component of sound waves, particle motion, is more challenging to measure but is an important to consider when evaluating the impact of sound on fish (Popper and Hawkins, 2019).

Main contributors to the ocean soundscape include geophysical sources, such as wind, waves, ice, volcanos and earthquakes; biological sources, such as marine mammals, fishes and invertebrates; and anthropogenic sources. There are multiple sources of anthropogenic noise in the marine environment. The main ones include vessels (commercial shipping, fishing, recreational and cruise ships, etc.), industrial activity (for example, offshore energy generation, including seismic exploration activity, coastal development and mining operations), and sonar (e.g. fisheries and military and scientific sonars). In some cases, the production of sound is intentional and critical for the activity, such as seismic exploration and sonar, while in others it is incidental, as in shipping and coastal development. Anthropogenic noise levels are variable across space and time, with two primary drivers being levels of human activity present and acoustic propagation characteristics in the region.

Below is an overview of the main anthropogenic contributors to ocean ambient sound (Table 1), their levels, and main frequency range. Following the approach in other reviews of ocean noise, seismic survey activity is considered separately from other industrial activities as it is a major contributor at low frequencies at large scales, with impacts that are substantially different from other industrial noise sources. Also provided is a review of impacts of noise on marine life. Among possible impacts considered here are physiological and behavioural effects, as well as impacts on mortality, when reported in the past. An important extension of these studies on the impact of noise on individuals, however, is understanding the population-level consequences of acoustic disturbance, including cumulative effects (National Academies, 2017).

Marine traffic as a contributor to ocean noise. The dominant sources of sound emanating from marine vessels are cavitation and turbulence generated by propellers, but a substantial component of acoustic energy contribution is also generated by machinery, transmitted and radiated through a ship's hull (Ross, 1976). At a lower level, the flow noise generated as a ship advances through the water adds to the contribution of a vessel to ambient noise. The levels of contribution from different components depend on a series of physical variables, including ship dimensions, tonnage, draft, load and speed, as well as wind and sea state as far as they interfere with ship movement in the water.

Marine traffic involves merchant shipping, cruise liners, military vessels, ferries, fishing boats and coastal boating for recreational purposes. Merchant shipping includes container ships, oil tankers, dry bulk carriers, general cargo ships and passenger liners. Different ship classes have distinct noise signatures that also depend on ship speed and length (Ross, 1976; McKenna and others, 2013). For example, a modern commercial container ship at typical (12 metres per second) operating speed has sound levels of 195 decibels (dB) re 1µPa at 1m with most energy below 100 hertz (Gassmann and others, 2017). For smaller vessels, for example, below 20 metres long, such as passenger and fishing boats, recreational high-speed boats, jet skis, etc., radiated sound levels are lower (128 to 142 dB re 1 µPa at 1m; Erbe, 2013) with a power spectrum including energy above 1 kilohertz (kHz) (Erbe, 2013), resulting in shorter propagation ranges than for commercial shipping.

Merchant shipping noise is often the main anthropogenic contributor to ocean noise at frequencies below 200 hertz (Wenz, 1962; Frisk, 2012; Roul and others, 2019). Globalization of the economy has resulted in a steep increase in merchant shipping throughout the world in the last 30 years. There has been a uniform increase (except for 1985 and 2009) in the global volume of seaborne trade, reaching 10.7 billion tons in 2017 (UNCTAD, 2018; see also Chapter 23 of the present Assessment). A mean annual growth of 3.8 per cent was foreseen in the period 2018–2023, which could be affected by the COVID-19 pandemic. In addition to a steady increase in the volume of trade, vessels are also spending more time at sea, with an increase of 5 per cent in 2017 (UNCTAD, 2018). The total gross tonnage has also increased in line with the volume of trade. Overall increases in merchant shipping are highly correlated with cean sound pressure levels, increasing approximately 3 dB re 1 μPa^2/Hz per decade over the 10 to 50 Hz band throughout several decades of the late twentieth century (McDonald and others, 2006). This increase appears to have plateaued during the twenty-first century (Frisk, 2012, and references therein).

The "distant shipping" component of ambient noise, resulting when signatures from individual vessels are indistinguishable in the data but appear as increased acoustic energy in frequencies below 100 hertz (Wenz, 1962), at any given location and time, strongly depends on the ship distribution at that moment. Shipping is unevenly distributed in latitude, with higher densities in the Northern Hemisphere along heavily used shipping lanes. As a result, high levels of ambient sound (80 to 90+ dB re 1 μPa^2/Hz) at frequencies dominated by shipping (10 to 100 Hz) are typically found in the North Atlantic and the North Pacific Oceans (Ross, 2005; McDonald and others, 2006; Širović and others, 2013; 2016). In the Arctic, where shipping traffic is substantially lower, ambient noise at low frequencies is largely driven by environmental factors, such as sea ice cover and wind conditions (Roth and others, 2012). In coastal waters, near busy harbours and beaches, the noise generated by small and medium-size fishing vessels, recreational boats and small ferries passing by can also be an important contributor to anthropogenic noise (Samuel and others, 2005; Merchant and others, 2012).

Ambient noise levels from distant shipping have not been linked to lethal, tissue damaging or other direct physical injury in marine mammals (although see Chapter 6D of the current assessment for other threats caused by shipping to marine mammals). Shipping and small craft noise has been associated with wide-ranging impacts on the survival, physiology and behaviour of individuals, with potential consequences on the survival of populations and communities across a number of marine taxa. In marine mammals, these include: increased stress levels in North Atlantic right whales (Rolland and others, 2012); changes in the foraging behaviour and vocalisations during the breeding season of humpback whales (Blair and others, 2016; Tsujii and others, 2018); changes in harbour porpoise behaviour (Dyndo and others, 2015); and changes in calling behaviour and masking or reduction in communication space (Parks and others, 2010; Putland and others, 2018). In other taxa, they include increases in stress levels for a number of fish species (e.g. Nichols and others, 2015; Simpson and others, 2016a), potentially resulting in an increased risk of predation in some species (Simpson and others, 2016a), a reduced ability to select suitable habitat for fish and coral larvae (Simpson and others, 2008; 2016b), as well as masking and reduction in communication space (Putland and others, 2018; Weilgart, 2018 and references therein).

Seismic exploration as a contributor to ocean noise. The use of sound to image sub-sea floor geologic structures is the predominant marine geophysical technique employed by the offshore oil and gas industry. Seismic reflection profiling provides information about potential oil and gas deposits several kilometres below the sea floor. To generate the high levels of sound needed to penetrate the solid earth, large arrays of airguns are towed behind survey vessels. Each airgun releases a volume of air under high pressure, creating a high intensity sound pressure wave. Typically, an array of airguns used in the seismic industry will include 25 to 50 individual guns (Dragoset, 2000). The acoustic pressure signal of airgun arrays is focused vertically, producing a signal 12 to 15 dB stronger in the vertical direction for most arrays. The peak source level for these arrays is impossible to calculate at a standard 1 m reference, but for simplified estimate if it is considered as a single source, can reach 260 dB_{peak} re 1 μ Pa at 1 m (Turner and others, 2006). Seismic operations can be limited in duration (weeks to months) but, depending on bathymetry, can affect entire ocean basins as low frequency signals propagate over significant ranges.

Seismic surveys can also be conducted for research purposes. These types of surveys can be conducted even outside of areas that are subject to commercial surveys, such as the Southern Ocean. High resolution geophysical surveys are also conducted in coastal areas for the construction of critical infrastructure such as bridges, ports and, more recently, offshore wind farms. These surveys employ sound sources such as sparkers and uniboom that are less powerful (210 to 230 dB re 1 μPa at 1m) than airguns and operate in a higher frequency band (0.5 to 2.5 kHz; Gontz and others, 2006). While these surveys tend to be localized in both time and space, their impact may be relevant for sensitive inshore species and ecosystems.

Areas with active seismic exploration cover marine areas of all continents except Antarctica. The Gulf of Mexico has among the highest levels of activity in the world with deep-water exploration the dominant source of low frequency ambient noise in this region (Wiggins and others, 2016). High activity has also occurred in the North Atlantic (Nieukirk and others, 2004), the South Atlantic (Miksis-Olds and Nichols, 2016; Haver and others, 2017) and the North Sea (Hildebrand, 2009). Seismic survey activity was increasing in the late 2000s and early 2010s due to increasing prices of crude oil, particularly in areas such as the South Atlantic and the Mediterranean Sea (Maglio and others, 2016). A global average of 40 seismic vessels were active in 2004 (Hildebrand, 2009), which increased to 75 active vessels by 2014 (based on seismic crew records), with the highest levels of activity in the Gulf of Mexico, Europe, Asia Pacific and Africa. However, with a decrease in crude oil prices in 2015 and 2016, active vessels decreased to 58 in mid-2018 (GeoTomo, 2018).

Impacts on marine life associated with sound produced during seismic exploration surveys have been documented across a number of taxa, ranging from zooplankton to marine mammals. McCauley and colleagues (2017) reported zooplankton depletion immediately following seismic operations, concurrent with an increase in dead zooplankton comprising a variety of species. Controlled experiments on scallop larvae showed that they exhibit significant developmental delays and developmental malformations if exposed to seismic airgun pulses (Aguilar de Soto and others, 2013), while adult scallops were observed to have disrupted reflexes (Day and others, 2017). Seismic operations may also be implicated in stranding of giant squids (Guerra and others, 2004). Fish have been observed to exhibit behavioural and physiological changes as a result of seismic operations (Weilgart, 2018 and references therein), with changes in fish catch rates also observed (Løkkeborg, 1991; Løkkeborg and others, 2012). Seismic operations have also been observed negatively to impact baleen whale communication (Di Iorio and Clark, 2009; Cerchio and others, 2014). While a number of impacts of seismic exploration on marine life have been observed, controlled exposure experiments have reported no observable impacts on the development and survival of embryos of southern rock lobster and larvae of Dungeness crab (Pearson and others, 1994; Day and others, 2016) and they had limited effect on the copepod *Calanus finmarchicus* (Fields and others, 2019).

Industrial activity as a contributor to ocean noise. A comprehensive review of underwater noise from industrial activity was completed in 2003 by the National Research Council of the United States of America. Below is a review of the broad findings of that report and a summary of the research in the area of ocean industrial noise published since 2003. For the purposes of the present Chapter, non-seismic oil and gas industry contributions have been separated from the remainder of industrial activity that contributes to marine noise.

(a) Industrial noise from the oil and gas industry*. Aside from seismic surveys, the purpose of which is to search for oil and gas, the oil and gas industry also contributes noise during the drilling and production phase. Oil and gas industrial activities occur worldwide from latitudes 72º North to 45º South. Activities associated with seismic surveys and oil and gas production are present along the coastlines of all the continents of the world except Antarctica (NRC, 2003). The noise levels associated with oil and gas production and associated activities, such as installation of pipelines, generation of energy on platforms, pipeline flow, noise associated with support vessels, etc., are typically much lower than those involved in seismic surveying (Richardson and others, 1995). The impacts of this production noise can be restricted to areas near facilities but persists during the active life of the facility, which can be years (NRC, 2003). Based on data collected along the North Slope of Alaska and the adjoining coast of Canada, drill ships actively engaged in drilling activity have high radiated sound levels with a maximum broadband source pressure level calculated from root-mean-square of pressure across the 10 Hz to 10 kHz band of about 190* dB_{rms} *re 1 µPa at 1 m (Richardson and others, 1995).*

(b) Other industrial and construction contributions to ocean noise*. The range of activities in this category is extremely broad. Pile driving and power-generating wind turbines are often found in deeper waters, while dredging, coastal development and associated construction, shipyards and daily harbour/port functions located near the shore contribute noise in shallow waters. Deep seabed mining is still largely limited in scope because of prohibitive costs (Miller and others, 2018; Thompson and others, 2018) but may expand in the future. The coupling of industrial activity, which can be made up of a combination of terrestrially based, shoreline or nearshore sound sources, into the marine environment is poorly understood. Nevertheless, this broad range of industrial activities produces a range of source levels and acoustic patterns described in detail below.*

Pile driving typically consists of thousands of impacts by large hammers occurring about every second to drive stabilizing structures for above water structures into the seabed. Pile driving noise source levels are substantial, with peak source levels ranging from 226 to 248 dB_{peak} re 1 µPa at 1 m (Bailey and others, 2014; Miller and others, 2017). There are a number of techniques for reducing propagated noise levels from pile driving, including freely rising bubble screens (Würsig and others, 2000), fixed air bubble screens (Rustemeier and others, 2011), and Helmholtz resonator screens (Lee and others, 2012). Deployment of these techniques has the potential to reduce received sound levels away from the activity by up to 20 dB, although average reductions are in the order of 5 dB (Buehler and others, 2015).

Operating offshore wind farms produce noise levels of about 150 dB re 1 µPa at 1 m (Nedwell and Howell, 2004; Hildebrand, 2009). This can represent a 5 to 25 dB increase in overall ambient sound levels at nearby (< ~1km) locations (Norro and others, 2011). Analogous to oil and gas, the noise associated with wind farm construction, largely stemming from pile driving activities, is limited in duration but can affect large areas of the ocean. Once the wind farms are operational, however, noise generated by the operation affects a smaller area but it will last as long as the operation continues.

In recent years, there has been a renewed interest in commercial operations for extracting economically valuable metals from the deep sea, including hydrothermal vent locations worldwide and exploration in the Mid-Atlantic Ridge area around the Azores (see also Chapter 19 of the present Assessment). The levels of sound these activities contribute to the deep sea are unknown.

Anthropogenic noise from dredging consists of sound from ship-borne machinery and mechanical motion such as suction and earth-moving devices, as well as possible use of explosives. Noise levels recorded during dredging range from approximately 163 dB to 190 dB re 1 μPa at 1 m depending on the type of dredging operation (Greene, 1985; Nedwell and others, 2008; Robinson and others, 2011; Reine and others, 2012; McQueen and others, 2020).

This varied industrial activity can have various impacts on marine life. Impulsive noise such as that created by pile driving has been observed to disrupt harbour porpoise habitat use (Carstensen and others, 2006) and has the potential to cause hearing impairment in marine mammals and fish close to the noise source (Madsen and others, 2006; Casper and others, 2013). The noise generated by pile driving has been observed to increase metabolic rate in some fish and mussel species (Spiga and others, 2016; Bruintjes and others, 2017) as well as alter fish swimming and schooling behaviour (Mueller-Blenkle and others, 2010; Herbert-Read and others, 2017), and elicit response in squid (Jones and others, 2020). Vibrations of the seabed resulting from experiments designed to simulate pile driving have also been observed negatively to impact growth and body condition of bottom-dwelling mussels (Roberts and others, 2015). While fish and marine mammals can detect sounds from operating wind farms at distances of a few kilometres, it is not known if these sounds cause any disruptions to their biological functioning, but they were shown to disrupt crab settlement (Pine and others, 2012).

(c) Ocean noise from sonar. Different types of sonars are used for mapping the ocean bottom, as well as for the detection and localization of various objects in the water column (e.g. plankton, fish or submarines). Sonar is used by a variety of stakeholders, including the military, the commercial, charter and recreational fishing community and the scientific research community, and the type of use is different within each of these groups.

Sonar use in the military is primarily focused on anti-submarine warfare and involves two types of sonar: low frequency active (LFA) sonar and mid-frequency active (MFA) sonar. The LFA sonar operates in 100 to 500 Hz band with overall source level of 230 to 240 dB re 1 µPa at 1 m, allowing detection over long ranges (hundreds of kilometres). The MFA sonar operates at frequencies from 2 to 8 kHz, has a source level of 235 dB re 1 µPa at 1 m (Hildebrand, 2009), and operates over ranges of tens of kilometres. The United States Navy has four ships dedicated to LFA sonar use while there are approximately 300 MFA sonars in active service in the world’s navies (Hildebrand, 2009).

In non-military uses, the sonars most frequently encountered on vessels include “fish finders” and other echosounders operating at single or multiple frequencies, called multibeam sonars and side-scan sonars. Sonars not used for military purposes generally operate at lower source levels than military sonars and, in most cases, their beams are directed downward under the vessel track, or across the track in case of multibeam sonar. Typical operating frequency of a fish finder is 15 to 200 kHz. Multibeam mapping sonar typically used by the research community operate at frequencies ranging from 12 kHz for deep-water systems up to 400 kHz for shallow-water systems, with narrow directional beams (~1 degree) and source levels between 232 and 245 dB re 1 μPa at 1 m (Hildebrand, 2009).

The use of LFA sonar has been restricted by some countries due to concerns over its impact on divers and marine mammals (Miller and others, 2000), although it has been reported that LFA sonar does not affect behaviour of herring (Doksæter and others, 2012). The use of MFA sonar has been implicated in the stranding of multiple species of cetaceans (Balcomb and Claridge, 2001). Beaked whales appear to be particularly sensitive to this sound and it has been associated with both physiological damage (Fernández and others, 2005) and behavioural changes in several beaked whale species (Tyack and others, 2011; DeRuiter and others, 2013; Moretti and others, 2014). Overall, however, responses vary by population and there is some indication that beaked whales regularly exposed to MFA sonar may acclimate to the sound (Bernaldo de Quirós and others, 2019). Presence of MFA sonar has been observed to alter the behaviour of baleen whales (Goldbogen and others, 2013) and multiple odontocete species (Sivle and others, 2012). Beaked whales also appear to be sensitive to other forms of sonar, with observations of changes in their behaviour documented in the presence of an echosounder deployed for scientific purposes (Cholewiak and others, 2017).

Table 1. Summary of main sources of anthropogenic noise (reproduced from United Nations document A/73/68, annex).
(* = rms sound pressure level (SPL), ** = peak SPL, *** = peak-to-peak SPL)

Industry sector	**Sound source**	**Sound type**	**Source level (dB re:1µPa @ 1m)**	**Frequency of main energy (kHz)**
Commercial shipping				
Medium-sized ships (50–100 m)	Propeller/cavitation	Continuous	165-180*	< 1
Large vessels (e.g. super-tankers, container ships)	Propeller/cavitation	Continuous	180-219*	<0.2
Resource exploration and exploitation				
Oil and gas	Seismic airgun	Impulsive	220-262***	0.05-0.1
	Drilling	Continuous	124-190*	0.1-1
Renewable energy	Impact pile driving	Impulsive	220-257***	0.1-2
	Operational wind farm	Continuous	144*	<0.5
Navy	Low frequency sonar	Impulsive	240**	0.1-0.5

	Mid-frequency sonar	Impulsive	223-235**	2.8-8.2
	Explosions (e.g. ship shock trials, exercises)	Impulsive	272-287*	0.006-0.02
Fishing	Propeller /cavitation	Continuous	160-198*	< 1-10
	Deterrent/Harassment device	Impulsive	132-200**	5-30
	Sonar (echosounder)	Impulsive	185-210**	20-260
Dredging	Propeller/cavitation, cutting, pumping, grabbing, digging	Mainly continuous	163-188*	0.1-0.5
Marine scientific research (e.g. research vessel)	Propeller/cavitation	Continuous	165-180*	< 1
Recreational activities (e.g. recreational craft/speedboat)	Propeller/cavitation	Continuous	160-175*	1-10
Tourism (e.g. whale and dolphin watching and cruise ships)				
Vessels <50m & >100m	Propeller/cavitation	Continuous	160-190*	<0.2-10
Harbour construction	Impact pile driving (e.g. sheet piling)	Impulsive	200**	0.1-0.5

3. Description of the economic and social consequences and/or the other economic or social changes

During the United Nations Open-ended Informal Consultative Process on Oceans and the Law of the Sea discussions on anthropogenic underwater noise in 2018, the importance of addressing the socioeconomic impacts of anthropogenic underwater noise was stressed. For example, it has been shown that the presence of seismic airgun surveys reduces catch of gadid and sebastid fishes (Hirst and Rodhouse, 2000). This may result in short-term economic loss for those fisheries during seismic survey effort. Impacts of noise on species that are of particular social, economic, and cultural relevance may have socioeconomic effects on coastal communities. particularly if it changes the availability of commercially or recreationally important marine species. A similar decline of social and economic benefits may be expected in association with displacement of marine mammals that are the focus of tourism activities. Additionally, displacement of marine animals may affect traditional and cultural practices of indigenous communities that rely on artisanal fishing and subsistence hunting. This area of interactions between anthropogenic noise and its impact on social and economic factors has not been well studied in the past, but an increased interest in anthropogenic noise in the ocean may lead to more focus on human consequences of the increase in noise.

While anthropogenic underwater noise may be most obviously connected to the success of achieving Sustainable Development Goal 14 of the 2030 Agenda for Sustainable Development, to conserve and sustainably use the oceans, seas and marine resources for sustainable development, it is linked also to a number of other SDGs.[249] Affordable and clean energy (SDG 7) is likely to lead to localized, short-term increases in anthropogenic noise levels in the ocean during the construction of offshore wind farms, but could result in an overall reduction in anthropogenic noise associated with a decrease the need to exploit fossil fuels. Successful implementation of SDGs 11 and 12, on sustainable cities and communities and responsible consumption and production, could ultimately affect overall anthropogenic noise in the ocean if achieving these goals results in changes in global shipping.

4. Key region-specific changes and consequences

4.1. Arctic Ocean

The opening up of shipping channels in the Arctic as a result of climate change-driven decreases in sea ice has started to result in increased ship traffic through the basin (Eguíluz and others 2016). While this is still a rather uncommon path, with further sea ice melt, the Arctic is likely to become a more common shipping and tourism route in the future (Smith and Stephenson, 2013). The consequences of changes in shipping and, in particular, of associated changes in soundscapes to more anthropogenically driven ones on local Arctic communities and marine animals are largely unknown (Ho, 2010). Oil exploration began in the Chukchi Sea in the mid-2000s but further exploration and oil development were abandoned when the region's reserves were found to be insufficient to warrant additional investment (Shell, 2015). Offshore oil and gas development in the Canadian Arctic is currently not allowed, with a review of the ban due in 2021 (Nunatsiaq, 2016).

4.2. North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean and North Sea

The North Atlantic is a busy shipping route year-round (Vettor and Soares, 2015). Seismic exploration noise is seasonally present in the polar areas of the North Atlantic (Klinck and others, 2012; Haver and others, 2017). A rapid expansion of offshore wind farm development in the North and Baltic Seas has resulted in more than 40 operational wind farms as of 2015 and continued development is predicted into the future (4C Offshore, 2020), which will result in substantial increases in noise during the building phase (Miller and others, 2017). The main noise hotspots in the Mediterranean Sea are the areas around major harbours. In addition, the Ionian and Adriatic Seas, as well as coasts along north-western Africa and in the eastern Mediterranean, have seen a recent increase in oil and gas exploratory surveys (Maglio and others, 2016). An increase in seismic activity in the Black Sea is also a possibility (Broad, 2014).

[249] See United Nations General Assembly resolution 70/1.

4.3. Gulf of Mexico, South Atlantic Ocean and Wider Caribbean

The number of vessels conducting seismic surveys decreased in the Gulf of Mexico but expanded off the Atlantic coast of South America (GeoTomo, 2018; USEIA, 2020), potentially increasing noise levels at low frequency over the past decade. Large discoveries of offshore oil by Guyana (Cummings, 2018) may lead to higher levels of seismic exploration and industrial activity related to oil development in the area. Noise associated with vessel traffic is ubiquitous throughout the Caribbean (Heenehan and others 2019).

4.4. Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

The development of Africa, which includes increased number of new ports, is contributing to rapid expansion in shipping in this region (Tournadre, 2014), increasing anthropogenic noise in areas that were previously relatively noise-free. Seismic exploration continues offshore from Australia (Paumard et al. 2019).

4.5. North Pacific Ocean

New offshore wind projects are being developed off Japan, Republic of Korea, Taiwan, and China (Yang and others, 2018; Li and Yuan, 2019). As a part of this process, Japan is also starting to define acoustic monitoring parameters. Likewise, offshore wind projects are proposed but not yet permitted or constructed off the West Coast of the United States of America (Bureau of Ocean Energy Management, 2020). Some areas along the West Coast, as well along the Hawaiian Island chain are designated as Marine Sanctuaries and could be protected from direct development.

4.6. South Pacific Ocean

Seismic exploration continues offshore from Australia and New Zealand (e.g. Cheong and Evans, 2018; Urosevic and others, 2019). The South Pacific remains, otherwise, relatively free from anthropogenic noise sources with little shipping and industrial development.

4.7. Southern Ocean

The Southern Ocean has seen an increase in cruise ship traffic in recent years, both in the Antarctic Peninsula region that has had some cruise ship traffic in the past, and in the previously unexplored Eastern Antarctica and the Ross Sea (Sánchez and Roura, 2016). Overall, however, the region has had few anthropogenic noise sources, with little shipping and industrial development (Dziak and others, 2015).

5. Outlook

Anthropogenic noise in the ocean is largely driven by shipping and oil and gas exploration and, on a more local or regional level, by coastal development. Factors such as, inter alia, population growth, migration to coastal areas, increased industrialization and tourism will result in an increase in activities that contribute to anthropogenic noise, unless accompanied by mitigation efforts. A number of efforts, however, have been initiated to reduce ocean ambient noise. The Scientific Committee of the International Whaling Commission (IWC) has endorsed target goals of reducing ocean ambient sound by 3 dB in the next decade and 10 dB over the next 30 years. The IWC is actively engaged with the International Maritime Organization on discussions regarding strategies to achieve these reductions. To achieve these goals, one step may be to reduce noise from shipping, the major anthropogenic noise contributor at low frequencies in the open ocean (Wenz, 1962; Frisk, 2012; Roul and others, 2019). Shipping noise can be reduced both by modifying propeller blades to make them quieter, and by isolating engines and other noise contributors on the vessel so that their noise does not propagate through the ship into the ocean. These technologies already exist but need wider implementation. Alternative measures being considered that can be implemented without technological advancements include decreasing ship speed or diverting ship traffic away from marine life sensitive areas such as marine sanctuaries, parks or reserves. In the oil and gas industry, new alternatives to exploration surveys using airguns are being investigated, such as marine vibrator technology. Even with new technological advances, adequate protection of the marine environment cannot be reached without a consensus on a global approach that fills the knowledge gaps related to anthropogenic noise impacts. Taking these discussions into account, for example, IMO adopted the Guidelines for Reduction of Underwater Noise from Commercial Shipping to Address Adverse Impacts on Marine Life, in 2014.

The importance of anthropogenic noise has been acknowledged by different United Nations entities. In June 2018, anthropogenic noise was the main topic of the nineteenth meeting of the United Nations Open-ended Informal Consultative Process on Oceans and the Law of the Sea. The presentations and discussions during the meeting covered, inter alia, review of the sources of anthropogenic noise, the effects and socioeconomic impacts of noise, and cooperation and coordination among nations to address anthropogenic noise. Among other things, it was noted that application of a precautionary approach in managing noise impacts has been put forward both regionally and globally and that cross-sector cooperation is needed for identifying and mitigating impacts.[250]

Sound is a form of energy, so its introduction into the marine environment, is regarded by many as a form of contamination because it can cause deleterious effects. The United Nations Environment Programme and the Convention on the Conservation of Migratory Species of Wild Animals[251] explicitly recognize the importance of underwater noise on marine species and encourage further study and mitigation of these issues.[252]

A number of nations have been developing their own management guidelines for managing ocean noise. The European Union (EU) has a mandate for its member States to measure and report anthropogenic noise under Descriptor 11 of the Marine Strategy Framework Directive (MSFD) adopted in June 2008. The aim of the directive is to achieve Good Environmental Status by 2020, with each member State determining how this might be achieved. Driven by the EU MSFD, there has been a proliferation of ocean noise-targeted projects and noise registers, databases with specifications on impulsive noise activity, across the region. Examples of these registers include the Baltic Marine Environment Protection Commission

[250] See A/73/124.
[251] Ibid., vol. 1651, No. 28395.
[252] See UNEP/CMS/Resolution 12.14; available at https://www.cms.int/en/documents/cop-resolutions.

(HELCOM) impulsive noise register[253] and the Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS) noise register for the Mediterranean and Black Seas.[254] Canada is building the Marine Environmental Research Infrastructure for Data Integration and Application Network, a database on underwater acoustics and vessel tracking, including visualization and analytical tools to provide information to managers, the public and researchers.[255] In the United States of America, measures comprehensively to manage the impact of noise on marine species are set out in the Ocean Noise Strategy (Gedamke and others, 2016). This effort also includes mapping tools to assist in evaluating the impacts of anthropogenic noise on cetaceans (NOAA, 2020). These national efforts to document noise sources should lead to an increased ability to map variability in sound levels across the region. At the same time, these initiatives are leading to increased efforts to standardize data collection and measurements. For example, the International Quiet Ocean Experiment, a collaborative international science programme aimed at promoting research, observation and modelling to improve understanding of ocean soundscapes and the effects of sound on marine organisms, has established working groups on data collection and data management standardization.

Sound has also recently been identified as an Essential Ocean Variable by the Global Ocean Observing System (GOOS) Biology and Ecosystems Expert Panel (GOOS, 2020). Ocean sound is recognized as a cross-disciplinary variable as it includes geophysical sources such as wind, bubbles, ice, earthquakes, volcanos, etc. This global recognition and incorporation of observing systems into new initiatives should contribute to an increase in monitoring of anthropogenic noise, a better understanding of its contributions to ambient sound and how soundscapes might change through time, particularly in relation to changing ocean use and climate change.

High levels of noise in the ocean can impact marine life in a variety of ways. A theoretical framework to evaluate population-level consequences of acoustic disturbances is available for marine mammals but should be applicable to other taxa as well (Pirotta and others, 2018). This approach can be used for management purposes, but it also offers a framework to investigate proximate mechanisms of phenomena that induce changes at the individual level and guide future data collection and model development. Considering these consequences occur among commercially and recreationally important species, as well as those that are relied on for subsistence, there is potential for negative social and economic impacts. For example, a reduction in the recruitment of commercially important fishes (Simpson and others, 2008) may result over time in a reduction in catches, and higher mortality may decrease fishery yields. For species that are the focus of tourism activities, those activities, such as whale watching, result in increased noise and can cause impacts (Erbe, 2002; Holt and others, 2009).

6. Key remaining knowledge gaps

Several challenges remain in evaluating the relative increases and possible impacts of anthropogenic noise in the ocean. A fundamental problem is a lack of knowledge regarding baseline ocean ambient noise. Given that no recordings are available from time periods prior to human activities, we have a limited understanding of the marine soundscapes that marine

[253] Available at http://www.ices.dk/marine-data/data-portals/Pages/underwater-noise.aspx.
[254] Available at http://accobams.noiseregister.org/.
[255] See https://meridian.cs.dal.ca/.

life evolved with or to what extent they might have adapted to anthropogenic noise inputs. The best proxy we have are regions outside the influence of human development and activity, which may exist in isolated basins, such as areas of the Southern Ocean or, until recently, were present in parts of the Arctic. But based on our best estimates, many regions of the ocean have at least 20 to 30 dB of increased ambient noise levels at low frequency (10 to 200 Hz) relative to primordial levels.

Another major gap is an understanding of the impact of noise on marine ecosystems. To date, most work has been focused on the impact of a single stressor on a particular species, the result of which may not be directly applicable to populations (Gill and others, 2001). It is unclear, and very difficult to study, how the combination of noise and other stressors (e.g., shifting food webs, changing water temperatures, habitat destruction) affect marine populations. A framework has been developed to assess the population consequences of disturbance, but often many key parameter values are missing to enable evaluation at the population level (King and others, 2015). One large gap in our knowledge, for example, is the hearing response of large baleen whales. In addition, environments can be subject to multiple sources of noise over large scales with the potential to affect multiple species at the same time. This can compound any effects (Shannon and others, 2016). At this stage, many regulations that are based on insufficient data have adopted the precautionary approach. However, expanding on our ability to integrate effects and impacts across different scales and sources will be essential to allow realistic assessment of the impact that anthropogenic noise has on marine animals.

Finally, substantial effort is needed to ensure standardization of monitoring approaches, measurements collected and archival frameworks or systems for acoustic recording approaches and associated collected data. An ANSI/ASA (2009) standard and International Organization for Standardization (ISO) (2016) standard exist for measurement of underwater noise from ships in deep water. However, these standards require multiple sound measurements by arrays of sensors and, in practice, have been rarely applied. Other standards being developed include those on soundscape measures and monitoring, which are currently underway by ISO and will include underwater data. Standards are being developed also through the Acoustical Society of America (ASA) standards procedures regarding towed array systems and data archiving. In the future, standards should be expanded to other parts of the acoustic monitoring effort, such as fixed recordings, calibrations and ambient sound data.

7. Key remaining capacity-building gaps

Thus far, monitoring and modelling of anthropogenic noise efforts have been concentrated in areas of North America and Europe, with some concentrated monitoring effort also taking place off Australia. On the other hand, the Indian Ocean and its adjacent seas are an area where across-board capacity building, including monitoring, impact assessment and development of management frameworks, would help to increase our understanding of the changes taking place in the environment. Since sound travels broadly across ocean basins, and anthropogenic noise sources are found worldwide, there is a need for increased collaboration and cooperation across all States and regions, as well as greater sharing of information and technology. One example of difference in technological availability is AIS for ship tracking. Knowledge of ship positions is essential for accurate mapping of underwater noise. AIS is a localization and identification system developed for ship collision avoidance that, over time, has been adopted and mandated across vessels of a broad range of sizes. Ship monitoring is most comprehensive in the developed world, due to relatively good spatial coverage with AIS receivers. The move to satellite AIS underway will enable broader data coverage, and timely international collaborations to use those data might be an opportunity to bridge some capacity gaps in modelling across States. Enhancement of cooperation and collaboration activities with developing States would support the enhanced sharing of best practices and best available technologies necessary to build national and regional programmes not only to monitor the effects of anthropogenic underwater noise, but also to provide the information needed for well-informed policy decisions.

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Chapter 22
Developments in Marine Renewable Energy Sources

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Keynote points

- The offshore wind (OW) sector is expanding globally to regions with no utility (grid) scale installations at present. The use of floating platforms is a step change for the industry to open up large areas with deeper waters.
- In 2019, 28.3 gigawatts (GW) of installed capacity from OW has been deployed globally, with 22 GW off of Europe, primarily in the North Sea, 5.9 GW off of China, and 0.4 GW in other markets.
- In the next decade, Asia and the United States of America could be major growth drivers for OW power development and installation.
- Wave and tidal/ocean current energy projects have not yet achieved full commercialization at utility scale.
- Progress in energy storage could make a significant contribution in the development of OW power and other marine renewable energy (MRE) technologies.
- Proper siting of MRE projects could minimize conflicts with other ocean uses and potential impacts on the marine environment.

1. Introduction

This Chapter discusses advances made in recent years in knowledge and capacity for the various types of MRE at the global level. For this purpose, MRE as a category includes OW energy, tidal/ocean current energy, wave energy, ocean thermal energy, osmotic power, marine biomass energy, offshore solar and geothermal energy. The Chapter has linkages with Chapters 6F, 8C, 7M, 9, 20, 21, 29, 30 and 31 of the present Assessment.

1.1. Climate change and the clean energy challenge

The fossil fuel energy use accounts for much of global anthropogenic greenhouse gas (GHG) emissions. As of 2019, the global energy consumption increased by 0.6 per cent[257], and the total emissions of energy-related carbon dioxide fell by 3.2 per cent (IEA, 2020). On the other hand, the global average atmospheric carbon dioxide was 409.8 parts per million, the highest level in the past 800,000 years (Dlugokencky and Tans, 2020), while the global average temperature was around 1.1±0.1 °C above pre-industrial levels (WMO, 2020).

Under the present status of GHG emissions, it is very likely that the agreed temperature thresholds of 1.5 °C or 2 °C above pre-industrial levels will be exceeded. As clearly

[256] We would like to acknowledge the substantial contribution of Dr. N. Koukouzas with respect to offshore geothermal energy.
[257] https://yearbook.enerdata.net/total-energy/world-consumption-statistics.html [Accessed 25 July 2020].

highlighted in the IPCC Special Report (2018) "… global net human-caused emissions of carbon dioxide (CO_2) would need to fall by about 45 percent from 2010 levels by 2030, reaching 'net zero' around 2050. This means that any remaining emissions would need to be balanced by removing CO_2 from the air". Therefore, reducing GHG emissions is an important step towards climate change mitigation. In this direction, many states are taking measures to increase the development of renewable energy sources such as MRE to meet national clean energy and climate change goals. MRE is also linked to the United Nations' Sustainable Development Goal (SDG) 7, which recognizes affordable renewable energy as a key driver for development.[258]

2. State of MRE at the global level

2.1. Advances in knowledge and capacity between 2010 and 2020

The ocean has the potential to be a major source of renewable energy. In addition to climate change mitigation, MRE can contribute to socioeconomic development, energy security, and energy access in remote coastal regions (Edenhofer and others, 2011). In 2019, global installed OW capacity increased by 4.7 GW, a 19.8 per cent increase on 2018, now totalling 28.3 GW. The global capacity of other MRE reached 531 megawatts (MW), 90 per cent of which came from two tidal barrages in France and the Republic of Korea (IRENA, 2020a).

The MRE sector is evolving and developing at different speeds: bottom-fixed OW technology is mature and technically advanced, floating OW technology is on the cusp of being commercial, tidal energy converters have reached the pre-commercial stage, while other MRE technologies are currently at the development stage.[259] The emerging markets in OW include India, Japan, the Republic of Korea, and the United States of America.[260] There has been a significant increase in wind turbine rated capacities, with up to 12-MW turbines expected to be on the market in 2021.[261]

2.2. Regional advances

Offshore wind energy. Global technical potential for OW is estimated by IEA (in collaboration with Imperial College London) at more than 120,000 GW (IEA, 2019). Europe dominates with cumulative capacity of 21.98 GW in 2019. The main countries developing OW are the United Kingdom of Great Britain and Northern Ireland (1.7 GW installed in 2019 and 9.9 GW in total), Germany (1.1 GW installed in 2019 and 7.5 GW in total), and China (1.3 GW in 2019 and 5.9 GW in total) (IRENA, 2020a).

There have been significant developments in the sector. The largest OW farm in the world, the Hornsea One Project in the United Kingdom, was completed in 2020 with an installed capacity of 1.2 GW. In 2019, the U.S. wind turbine manufacturer GE's prototype Haliade-X 12 MW became the largest wind turbine ever built. With the continuous increase of both OW turbine and OW farm size, concerns about potential environmental impacts, impacts on

[258] See United Nations General Assembly resolution 70/1.
[259] Available at https://ec.europa.eu/jrc/en/news/new-technologies-ocean-energy-sector [Accessed 18 July 2020].
[260] Available at https://gwec.net/the-growth-of-the-global-offshore-wind-market-will-be-driven-by-asia/ [Accessed 21 July 2020].
[261] Available at https://www.ge.com/news/press-releases/ge-renewable-energy-unveils-first-haliade-x-12-mw-worlds-most-powerful-offshore-wind [Accessed 15 July 2020].

fisheries, and issues related to human use of areas near or within wind farms are becoming more important.

OW is demonstrating the viability, both technically and economically, of utility-scale project in different marine environments. The globally weighted Levelised Cost of Energy (LCoE)[262] for utility-scale projects has fallen 28.6 per cent since 2010, thus driving installation around the world (IRENA, 2020b). Moreover, the sector anticipates that LCoE values of the order of 50 €/MWh are achievable by 2030.[263] The main drivers for cost reduction include the use of larger, more efficient turbines in bigger OW farm developments, the reduced capital cost to finance projects, and the certainty of a long pipeline of projects, which has allowed the supply chain to invest and innovate. Fixed platforms are viable for water depths up to 60 m, although the industry also plans to operate in deeper waters using floating platforms in the next decade. Many coastal countries worldwide see floating wind becoming a major contributor towards meeting renewable energy production targets. The world's first utility-scale floating OW farm began production in 2017 (offshore Peterhead, Scotland) using the Norwegian Equinor's Hywind concept (Musial and others, 2019); see Figure 1. This marks an important milestone for the OW industry to develop projects in deeper water and further away from the coast.

FIGURE 1. THE WORLD'S FIRST COMMERCIAL WIND FARM COMPRISED OF FLOATING WIND TURBINES (PHOTOGRAPHER: ØYVIND GRAVÅS / WOLDCAM, IMAGE KINDLY PROVIDED BY EQUINOR)

The success of OW power in reducing installation and production costs, combined with the existing expertise from onshore wind energy, has made OW the leader in the MRE sector.

Tidal/ocean current energy. Global tidal energy capacity (combined theoretical tidal range and stream resource) is estimated at 3 terawatt (TW) (Lewis and others, 2011; Scottish Enterprise,

[262] LCoE is the present value of the average minimum price of produced electrical energy in order to offset the total cost of its production (construction, operation and maintenance, and fuel costs). LCoE is levelized over the lifetime of a generating plant.
[263] https://analysis.newenergyupdate.com/wind-energy-update/offshore-wind-opex-set-fall-40-2030-suppliers-dig-deep [Accessed 13 July 2020].

2018), while the worldwide potential of ocean currents is estimated at 450 GW.[264] Tidal stream energy requires flow speeds greater than 2.0 m/s in order to be feasible (Encarnacion and others, 2019). The funnelling effects of bays, estuaries, and inlets can provide a viable tidal/current energy resource. Locations such as the Bay of Fundy in Canada, Cook Strait in New Zealand, and the Pentland Firth in Scotland are known for significant resources and have been targeted for development. Tidal energy was initially harnessed by impoundment through the construction of barrages. This was the basis for early commercial ventures, such as the 240 MW La Rance tidal energy station in France and the 254 MW Sihwa Lake Tidal Power Station in the Republic of Korea.

Although various tidal projects have been proposed, particularly on the west coast of the United Kingdom, progress with regard to construction has been slow, mainly because tidal barrages can have impacts on ecosystems and water quality (Kadiri and others, 2012). Very high capital costs are another deterrent. Therefore, the tidal energy industry has focused primarily on extracting energy from fast-flowing tidal streams using horizontal axis tidal turbines, which have progressed from single prototype deployments to small-scale arrays (Encarnacion and others, 2019). The environmental monitoring programme implemented for the deployment of the first large-scale commercial tidal stream generator (SeaGen) became the roadmap for future tidal projects (Savidge and others, 2014). The first grid-connected tidal array with three 100-kW turbines has been operating successfully since 2016 in the Shetland Islands,[265] while the MeyGen project in Scotland is the largest tidal energy array currently deployed, with 6 MW.[266] However, since 2016, the industry has largely stalled, particularly in the United Kingdom. In addition, the high-profile collapse of OpenHydro technology created significant negative publicity for the industry.[267] As of 2020, tidal energy has yet to make a significant leap to installing utility-scale projects.

Wave energy. The theoretical potential global wave power resource is estimated at 2.11 TW, and sites with values around 30 kW/m (or below) are usually considered commercially viable for wave energy extraction, depending on the technology (Sandberg and others, 2016). The locations with the largest wave power resource are between 40⁰ and 60⁰ latitudes (Gunn and Stock-Williams, 2012). For instance, wave energy sites off the coast of Ireland present annual average power density levels above 80 kW/m.

As of 2019, the sector is still not close to commercialization, but progress has been made in assessing the difficulties involved in extracting wave power at a reasonable cost. Significant challenges are the hostile environment in which wave energy converters (WEC) produce power and designing technologies that can reliably operate for the life of a commercial project. There is a large number of WEC concepts and devices under development, but their variety has resulted in lack of convergence and overall focus within the sector. However, since 2015, multiple full-scale WECs have been deployed by developers such as Wello Oy[268] and SeaBased[269]; OceanEnergy's WEC will be deployed in Hawaii.[270]

Salinity and thermal gradient energy. Salinity and thermal gradient energy depend on the

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[264] Available at https://www.oceanenergycouncil.com/ocean-energy/ocean-current-energy/ [Accessed 15 July 2020].
[265] Available at https://microgridknowledge.com/baseload-tidal-power-station/ [Accessed 15 July 2020].
[266] Available at https://simecatlantis.com/projects/meygen/ [Accessed 15 July 2020].
[267] Available at https://marineenergy.biz/2018/07/27/openhydro-another-casualty-of-innovation-valley-of-death-emec-says/ [Accessed 15 July 2020].
[268] Available at https://wello.eu/ [Accessed 15 July 2020].
[269] Available at https://seabased.com/projects [Accessed 15 July 2020].
[270] Available at https://aeehawaii.org/blog///wave_article [Accessed 15 July 2020].

differences in salinity and temperature of seawater masses, respectively. Salinity gradient energy is obtained when fresh water and saltwater are mixed. The estimate of theoretical resources available globally range between 647 GW and 1,183 GW (IRENA, 2014; Alvarez-Silva and others, 2016). Pressure-retarded osmosis (PRO) and reverse electrodialysis (RED) are the promising technologies to date (Schaetzle and Buisman, 2015). PRO technology was first utilized in 2009 in Norway (Chae and Kim, 2018) and RED technology in 2014 in a pilot plant in southern Italy (Tedesco and others, 2017).

Energy can also be harnessed from the temperature differences between different seawater masses at various depths (Rau and Baird, 2018). Estimates of theoretical ocean thermal energy conversion (OTEC) potential range between 1–3 TW and up to 7 TW when desalination is also included (Scottish Enterprise, 2018). The minimum required temperature differential between the seawater masses should be on the order of 20 °C, which is met in areas extending between 30º north and 30º south (Breeze, 2019). The most active countries in the OTEC sector are China, France, Japan, Malaysia, the Netherlands, Oman, the Philippines, the Republic of Korea, and the United States of America (Edenhofer and others, 2011; Lewis and others, 2011). Several projects are under development or operational including a 100-kW onshore OTEC installation in Kailua-Kona (Hawaii) that was connected to the grid in 2015 (Patel, 2015), an onshore OTEC prototype installed in 2012 in Réunion (France)[271], and a 250-kW plant operational on Kumejima island (Japan) since 2013.[272] The nutrient-rich deep water can also be used to enhance mariculture and farming onshore, creating significant additional revenues. OTEC, as well as wave and ocean current energies, constitute an important potential for the African continent.

Marine biomass energy. This type of source involves the use of marine algae and other viable sources for the production of biofuels. The use of marine biomass could circumvent many constraints associated with terrestrial biomass energy production, including competition for agricultural land with food crops and the use of energy-intensive fertilizers and pesticides in farming. Interest in biomass energy is also driven by the high productivity of marine ecosystems compared to terrestrial ecosystems (Sheehan and others, 1998; Perlack and others, 2005) and the versatility of marine biomass, which can adapt to a wide range of salinity and light intensity conditions.

The marine biofuel production cycle has two components: the first involves cultivation of marine biomass on a sufficiently large scale and continuously to feed the biofuel production cycle, and the second involves the conversion of marine biomass into biofuels. Giant kelp is considered one of the most prolific organisms on Earth, with growth rates up to 60 cm per day.[273] Efforts are currently underway off the Pacific coast of the United States to develop an open ocean cultivation system for giant kelp, which can then be converted to biocrude (Buck, 2019). Even though energy from biomass remains promising, scaling biofuel production on an industrial level is yet to be achieved. Moreover, regarding the calculation of the carbon intensity of marine biofuels (taking into account, among others, the absorption of carbon dioxide through photosynthesis in the cultivation system and the corresponding emissions during biofuel combustion) further research is needed.

Emerging MRE sources. This category includes offshore solar energy and ocean floor geothermal energy. Offshore solar energy is still at an infant stage of development, but with significant commercial potential (Wang and others, 2019). On the other hand, ocean floor

[271] Available at https://www.oceanenergy-europe.eu/ocean-energy/otec/ [Accessed 17 July 2020].
[272] Available at http://otecokinawa.com/en/Project/index.html [Accessed 17 July 2020].
[273] Available at https://oceana.org/marine-life/corals-and-other-invertebrates/giant-kelp [Accessed 17 July 2020].

geothermal energy is at a conceptual phase in contrast to inland geothermal power generation technology (Shnell, 2009; Shnell and others, 2015; Pedamallu and others, 2018).

Offshore solar energy is based on floating solar systems that are designed to withstand the harsh environmental conditions at sea.[274] The offshore environment can take full advantage of solar irradiation during the day, so it seems an ideal alternative for the solar industry. Although installation of offshore solar systems is more expensive than the land-based ones, offshore systems are usually more efficient, since the panel is in direct contact with the seawater, thermal losses are reduced, and the panel temperature is lower (Trapani and Redón Santafé, 2015; Sahu and others, 2016; Ranjbaran and others, 2019; Spencer and others, 2019). The first floating solar power farm for the marine environment was installed in 2014 in the Republic of Maldives.[275] Japan, the Netherlands, Singapore, and the United Arab Emirates are interested in developing offshore solar farms. Floating solar power farms in inland water bodies are operating or are under development/consideration in many other countries, including Australia, Brazil, China, India, Japan, and the Republic of Korea (World Bank Group and others, 2019).

The use of geothermal energy is currently limited to areas on land that host geothermal resources (Tester and others, 2006; Saibi and others, 2013). However, access to vast amounts of geothermal resources can be found in the ocean floor in a supercritical state (fluids of very high temperature and pressure), e.g., in mid-ocean volcanic ridges (Hiriart and Hernandez, 2010). Benefits of offshore geothermal energy include the use of seawater as unlimited geothermal fluid, while the cold temperature of seawater can serve as a limitless condenser for the heat exchanger system (Banerjee and others, 2018). Offshore geothermal power plants require no land space or extension of the energy field and, when compared with land-based plants, have potential for further development, although it is not profitable under the current financial framework (Karason and others, 2013).

Current initiatives like the Marsili project in Italy and the hydrothermal vents project in the Gulf of California utilize steam from underwater volcano and hydrothermal vents, respectively, to produce power. Additional locations for potential offshore geothermal exploration are located in Iceland and Indonesia (Karason and others, 2013; Prabowo and others, 2017). In the Netherlands, the Exploration Working Programme for Ultra-Deep Geothermal Heat is exploring the viability of offshore geothermal projects to assess further investments (Heijnen and others, 2019).

3. Potential environmental impacts from MRE development

MRE-based electricity generation can contribute towards reducing GHG emissions, water pollution, particulate matter, and waste products and help in climate change mitigation. On the other hand, as any human intervention in the marine environment causes inevitable impacts on the surrounding biotic and abiotic systems, it is vital to mitigate or avoid potential negative impacts and increase potential positive impacts; environmental impact assessment is an integral part for the evaluation of these possible impacts (Mendoza and others, 2019). The magnitude and temporal extent of the environmental impacts depends on the project size and scale, the location and the implemented MRE technology; for example, simulation studies have shown that small arrays of WECs have minimal effects on the physical environment. A

[274] Available at https://kosatka.media/en/category/vozobnovlyaemaya-energia/news/v-severnom-more-poyavyatsya-pervye-offshornye-solnechnye-parki [Accessed 17 July 2020].
[275] https://swimsol.com/solar-projects-offshore-solarsea-and-rooftop/

practical way to systematize the environmental impacts of a MRE installation is to introduce the context of environmental stressors (i.e., features of MRE device or system that may put pressure on the marine environment, such as collision, underwater noise) and receptors (i.e., ecosystem element, such as marine mammals, seabirds) and assess their in-between interactions. The receptors that will be discussed are benthic and pelagic habitats, fish and fisheries, marine birds and bats, marine mammals, and oceanographic system/coastal morphology.

OW projects have been operating since 1991, so there is accumulated experience regarding their environmental effects. For instance, in the Belgian part of the North Sea, an extensive environmental monitoring programme started in 2008 with the operation of the first OW turbines, and annual reports (up to 2019) are published describing the environmental impacts found.[276] However, the impacts of other MRE devices have not been studied in detail due to the scarcity of operating WECs and tidal/ocean current turbines, resulting in the paucity of baseline and post-installation data (Copping and Hemery, 2020). For reviews regarding the environmental impacts of MRE installations, see Bray and others, 2016; Willsteed and others, 2017; ICES, 2019; Copping and Hemery, 2020.

3.1. Benthic and pelagic habitats

Underwater infrastructure of MRE installations (foundations and anchors, mooring systems, cables, etc.) may affect benthic (reefs, coralligenous formations, seagrass meadows, etc.) and pelagic habitats by causing changes in their behaviour and presence. These changes refer to damaging effects (e.g., during cable installation, scouring around device and mooring foundations) and creation of habitats (through artificial reef and reserve effects, biofouling) (Copping and Hemery, 2020). The addition of a hard substrate makes the installed infrastructure important for the creation of new habitats (by replacing previous habitats or for restoration of damaged ones) that may also attract new species to a site; this issue should be considered in the frame of the particular management objectives. Additional indirect effects are described in Copping and Hemery (2020).

Although further research is certainly required, properly designed artificial reefs can provide positive impacts to the marine environment. Wind turbine foundations can be utilized as artificial reefs, enhance connectivity among marine protected areas, and allow sustainable aquaculture (Bishop and others, 2017; Boero and others, 2017; Roa-Ureta and others, 2019; Glarou and others, 2020). Moreover, there are significant anticipated environmental benefits of partially dismantling an OW farm during decommissioning; the remaining substructures can enhance biodiversity, provide reef habitats, and protect from bottom trawling (Topham and others, 2019).

Regarding the interactions of floating solar energy and ocean floor geothermal energy with the aquatic habitats, much more research is needed. Floating solar panels are subject to biofouling, and there may be environmental effects on species dependent on solar radiation (including corals, seagrass, and kelp forests) and changes in biodiversity (Sahu and others, 2016; Pimentel Da Silva and Branco, 2018). The potential environmental impacts of ocean floor geothermal energy are attributed to changes in the fluid concentrations that may cause large-scale impacts such as habitat loss and degradation (Pedamallu and others, 2018).

[276] Available at https://www.naturalsciences.be/en/news/item/19116 [Accessed 17 July 2020].

3.2. Fish and fisheries

The presence of underwater infrastructure of MRE installations may pose risk collision to fish. Collision risk is variable and depends, inter alia, on fish abundance, water velocity, and turbine rotational frequency. However, actual collisions of fish and underwater turbines are still unknown and, if they happen, they are difficult to observe. Consequently, the collision outcomes (injuries, death, etc.) are also unknown, and further research on sublethal and non-contact effects is necessary (Copping and Hemery, 2020). There is also lack of relevant information regarding fish behavioural issues with respect to the presence of MRE underwater structures. Entanglement issues are probable for large marine animals (Taormina and others 2018).

Underwater transmission cables connecting MRE projects to land-based electrical substation induce electromagnetic fields (EMF). The organisms that may be affected by EMF are those that have specific electroreceptors for orientation, mating, navigation, and hunting purposes, such as elasmobranchs, marine mammals, and invertebrates. Potential factors that determine the vulnerability of marine organisms to EMFs are: i) the volume/size of electrical current being carried by the cable; ii) the cable design; and iii) the distance of marine organisms from the power cable (Snyder and others, 2019). Evidently, more research is needed to understand whether EMFs are harmful to the few species that can detect them. In Copping and Hemery, 2020, it is noted that "preliminary evidence indicate that the risk of … EMF from small numbers of MRE devices could be retired."

Finally, further research is needed regarding the potential environmental interactions of MRE with fisheries, keeping in mind that some major OW markets, such as Denmark and the United Kingdom, allow commercial fishing within OW farms. In the context of marine biomass energy, potential impacts on fisheries and hazards to protected species should be considered for any large-scale production of macroalgae (Langton and others, 2019).

3.3. Marine birds and bats

Birds are considered to be at risk from MRE development. The physical presence of OW farms may pose threats to seabirds at individual and population levels, while the magnitude of impact relies on numerous factors, including bird species, characteristics and conditions of the site, and seasonal variations. The most important effects refer to bird collisions (which cause mortality and sublethal effects), barrier effects with respect to movement (i.e., mainly displacement from foraging sites), avoidance, attraction, and habitat loss. Dierschke and others (2016) note that the extent to which seabirds are displaced from, or attracted to, OW farms is uncertain. Specifically, the analytic study of 20 OW farms in European Seas revealed that the behavioural responses of seabirds exhibited diverse features (from strong avoidance to strong attraction). On the other hand, many species showed little behavioural response, while some species used the OW farm structures for dry roosting. The increase in food availability due to the artificial reef effect seems to be an important influence for several species. There is also evidence that large-bodied birds avoid OW turbines (Fox and Petersen, 2019). Nevertheless, actual long-term monitoring campaigns are needed to fill the gaps in the understanding of birds', including seabirds', behaviour around turbines and provide robust estimates of the numbers of bird collisions at wind turbines. The proper siting of OW farms and shutting down of turbines on demand may decrease bird fatalities during OW farm operation (Marques and others, 2014; Best and Halpin, 2019).

Regarding the direct interactions of diving seabirds with tidal turbines, there is lack of evidence to show that interactions will occur or that tidal turbines will harm individual seabirds or populations due to the limited number of related studies. The state of the art of the effects of MRE development on seabirds is presented in Copping and Hemery (2020), while recommendations are provided in Isaksson and others (2020).

Finally, potential impacts of OW farms on bats are poorly understood. Observations have shown that bats can be found offshore and, as in the case of onshore wind farms, similar impacts may be expected (Arnett and others, 2016).

3.4. Marine mammals

Although the collision of marine mammals with moving parts of MRE devices (e.g., blades of a tidal turbine) has not been observed, it remains an active area of research, along with the corresponding consequences, which are still unknown. Entanglement of marine mammals in mooring lines, cables, and anchors is another emerging topic of investigation. Injury and mortality of marine mammals due to entanglement risk is considered low for single devices, while the combination of modeling results and field observations will enhance the assessment of this risk. Knowledge gaps and uncertainties include the scaling of collision risk from a single turbine to arrays, the translation of individual collision risk to population-level risk, etc. (Copping and Hemery, 2020).

Underwater noise emitted from operational MRE devices is unlikely to cause acoustic injury to marine animals, and there is a low possibility that it causes behavioural responses. On the other hand, underwater noise generated during the construction phase of an MRE installation can have significant impacts. Underwater noise generated during pile-driving operations (for piled bottom-fixed OW farms) can mask the echolocation sounds used by some marine mammals for navigation, hunting and communication, while potentially impacting fish and mammal hearing. These problems can be addressed through restrictions on pile-driving operations, for example, during migration of marine mammals or by noise mitigation measures (Koschinski and Lüdemann, 2013). In this respect, floating wind technology and bottom-fixed OW farm foundations that negate the need for piling- such as gravity-based foundations and suction buckets- compare favourably against piled bottom-fixed OW farm foundations. Additional sources of underwater noise include increased vessel traffic during construction and decommissioning activities, rotation of the turbine itself, displacement of fluid by turbine blades, and operations such as underwater explosives, rock-dumping, and dredging.

3.5. Oceanographic system and coastal morphology

MRE development in large-scale arrays have the potential to alter the physical processes driven by waves, currents, and tides. Based on results from numerical model simulations, changes are encountered in water circulation, wave height, current speed, salinity, sediment transport, and water quality within and around the area of MRE installations. Up to 2020, the impacts of MRE devices have been quantified by few field and laboratory studies. The alteration of the hydrographic characteristics and the physical presence of large-scale MRE installations, especially when sited nearshore, may also cause impacts on the neighboring coastal areas, e.g., increased flooding risk (Cazenave and others, 2016; Soukissian and others, 2017).

Overall, minimizing environmental impacts while ensuring energy generation at a competitive cost is necessary for successful deployment of MRE projects. In this context, more real data and coordinated studies are necessary to have the full picture of the environmental impacts for various types of MRE devices.

4. Socioeconomic benefits and impacts from MRE deployment

4.1. Socioeconomic benefits

MRE has the potential to drive regional and local economic development by providing access to reliable energy in coastal areas and in non-interconnected islands and island states (Kuang and others, 2016). The presence of MRE in the energy mix can reduce vulnerability to volatile energy prices and availability.

Creation of new jobs. MRE development can provide economic opportunities and jobs in coastal areas (Hoegh-Guldberg and others, 2019). Ocean Energy Systems[277] has set a global target of 300 GW for MRE, excluding OW, by 2050, which could save up to 5.2 billion tons of carbon dioxide by that year and create 680,000 direct jobs (Huckerby and others, 2016).

In 2018, onshore and OW energy sectors employed 1.16 million people (REN21, 2019). In 2019, the OW sector received 29.9 billion United States dollars in investments globally, of which China received the highest percentage (14 billion dollars) (Frankfurt School and UNEP Centre/BNEF, 2020). OW farms require more labour inputs than onshore wind farms, which can result in revitalization of coastal communities from an economic perspective (IRENA, 2019).

Synergies with other marine sectors. Aquaculture and MRE could be synergetic sectors. Aquaculture sites are mainly located in areas of low energetic conditions; thus, an MRE installation could provide an ideal environment in its lee for aquaculture development. Moreover, multifunctional co-location of these two sectors (by sharing, for example, the same infrastructure) can be facilitated through marine spatial planning (MSP, see Chapter 29) and technical advances in the design of more robust fish cages, technological developments in automation, advances in mooring systems, and benefit sharing (where MRE arrays provide shelter to fish farms).

Moreover, abandoned oil and gas platforms may be converted into production and storage units that convert electricity from OW farms into hydrogen and synthetic gas (Jepma and van Schot, 2016; see also Chapter 20). Synergies may also arise between the MRE sector and other marine industries, such as transport and operations, supply and manufacture, new materials and mining (Huckerby and others, 2016) and shoreline protection and marine conservation issues (LiVecchi and others, 2019).

4.2. Potential adverse socioeconomic impacts

MRE, as a new energy source, has to confront considerable challenges to achieve significant scale and deployment. Apart from the higher energy cost of MRE installations compared with

[277] Ocean Energy Systems is an intergovernmental collaboration between countries, founded in 2001, which operates under a framework established by the International Energy Agency (IEA). It promotes development of ocean energy around the world. https://www.ocean-energy-systems.org/ [Accessed 15 July 2020].

land-based installations, social acceptance needs to be addressed. MRE installations may meet strong opposition from other maritime sectors and local coastal communities that are reluctant to share marine space (Dalton and others, 2015; Lange and others, 2018). Important issues resulting from the interactions of fisheries and OW farms are related to loss of fishing grounds and displacement, gear damage, inadequate compensation schemes, and the need for a more dynamic engagement of fishers into planning processes (Gray and others, 2016). MRE installations may also be a cause for concern for the coastal tourism sector due to potential visual disturbance. Studies conducted in the French Mediterranean coasts, North Wales (United Kingdom), and New Zealand revealed opposition of coastal communities to OW farms and wave energy installations, especially for places with high scenic beauty (Devine-Wright and Howes, 2010; Westerberg and others, 2013; Brownlee and others, 2015). Potential conflicts regarding safe navigation and operation of marine vessels may also arise when MRE installations are close to existing maritime transport routes.

Overall, potential environmental and socioeconomic risks underline the importance of extensive stakeholder engagement, robust environmental impact assessment, and risk analysis before planning and siting MRE projects.

5. Key remaining knowledge and capacity-building gaps

MRE cost reduction. The most important issue that the MRE industry has to deal with is cost reduction. Bottom-fixed OW may approach cost parity with conventional electricity generation sources in some markets; however, no other MRE technology is close to being commercially viable without further research & development (R&D), targeted innovation, and significant financial incentives. Reduction of MRE costs is necessary to attract investors and advance development of the sector. Cost reduction can be based on the following pillars (SI Ocean, 2013; Smart and Noonan, 2018):

- **Scale and volume**: Larger scale MRE devices and array installations decrease the manufacturing and installation costs, and scale production of MRE devices reduces the overall individual component cost.
- **Experience/generation of knowledge:** Knowledge generation is important regarding MRE capacity building and cost reduction. New knowledge coming from experience and learning by doing will foster the integration of MRE into relevant state policies. Sharing of data and information, exchange of experiences, R&D, and lessons learned are important drivers to cost reduction.
- **Innovation**: Targeted innovation (in the R&D phase of an MRE concept or in the context of actual industrial MRE projects) will reduce costs and increase the yield and reliability of MRE devices.

Energy storage. Accurate short-term forecasting and energy storage are related to intermittent electricity generation and stochastic fluctuation, respectively. Current technologies for energy storage consist of electrochemical systems (e.g., batteries and fuel cells/hydrogen energy storage), electrical storage (e.g., supercapacitor energy storage, magnetic systems), mechanical systems (e.g., flywheel, water pumps), and thermal systems (Ould Amrouche and others, 2016; Olabi, 2017). Pumped hydroelectric energy storage is the most mature and largest scale technology (see also Wang and others, 2019).

Environmental monitoring and mitigation measures. Environmental monitoring of marine organisms and metocean characteristics is essential to identify and quantify the variability in the marine environment from the design to the decommissioning of an MRE installation, while

mapping of the ocean floor may significantly contribute to the proper siting of MRE installations (Mulcan and others, 2015).

Establishing environmental baselines (e.g. seabed mapping and characterization, sediment composition, shallow/deep geology) and monitoring of biotic elements is necessary to confirm that the relevant activities will not have an adverse impact on biodiversity . In this context, there is need to define standards for the analysis of environmental monitoring data for MRE development sites and to identify the area over which biological effects may occur to inform baseline data collection. Detecting potential [278] It is also necessary to set thresholds, determine changes (in abundance, diversity, distribution, and behaviour), and readjust management actions (Foley and others, 2015). The MRE technologies used and the stressors in the marine environment should be considered when designing the monitoring procedures. Predictive models can be a supplementary tool, ideally when combined with *in situ* observations.

Metocean data (including oceanographic and meteorological parameters) may be obtained from *in situ* measurements, outputs from numerical models, and remote sensing instruments. Long-term data are required for the preliminary estimation of the available MRE resource and the metocean climate characteristics in the area of the MRE installation. Short- (up to 3 days) and medium-term (3–7 days) forecasting of metocean conditions is also important for operational planning activities. During the operation phase, reliable short-term forecasts of the expected power production are required for large-scale power integration.

Strategic considerations for developing MRE, including funding. There can be a number of objectives when developing national energy strategies. In this context, some critical factors should be considered, such as reducing MRE cost and enhancing integration of large-scale MRE into electric power systems; leveraging a diversity of MRE sources and determining their geographic distribution; reducing barriers to deployment, including siting conflicts and permitting; and attracting significant investment in the sector.

Furthermore, the sixth World Conservation Congress of the International Union for Conservation of Nature asked nation states and competent authorities to implement a strategy for development of MRE that takes into account environmental issues and subject this strategy to rigorous strategic environmental assessment (IUCN, 2016). This commitment is completely in line with SDG 7.[258]

The full development of MRE can enhance the diversity of low-carbon energy options and provide viable alternatives to fossil fuel. Traditional commercial funding sources are often insufficient to achieve this goal, so innovative strategies are required. Private-public partnerships are considered critical for the launch of MRE. For example, the European Commission initiated the Ocean Energy Forum, bringing together industry, finance, academia, and public authorities to identify solutions and make investment more attractive. In the United States of America, the Business Network for Offshore Wind has promoted the OW industry.[279]

The importance of public sector's support is not confined to the funding of the early stages of development of new technologies. The creation of a favourable private investment

[278] Available, for example, at https://www.govinfo.gov/content/pkg/FR-2019-04-30/pdf/2019-08666.pdf [Accessed 15 July 2020].
[279] Available at https://www.offshorewindus.org/about-us/ [Accessed 15 July 2020].

environment through financial and fiscal incentives, renewable portfolio standards, offsets or feed-in tariffs has proved equally, if not more, important. Investment in new technologies is generally limited to nation states with the financial means to accept the risks associated with technologies that are not commercially viable. However, developing countries could invest in MRE that are more mature.

6. Anticipated future trends

Although considerable progress has been made towards exploiting MRE, the industry is still in the early stages of development, except for the OW sector. Wave and tidal energy are not yet commercially viable, so the immediate target is to encourage more offshore deployments of single prototypes or small-scale arrays. Such deployments, if successful, will build confidence in the sector and encourage investments required to develop large-scale farms. Technological advances are also required to improve power takeoff performance and reliability along with control systems to maximize power absorption. The survivability, reliability, and cost reduction potential of wave and tidal technologies offset the significant investment risk.

In Europe, the Strategic Energy Technology Plan has set ambitious targets for an LCoE reduction for OW, wave, and tidal energy (EC Directorate-General for Energy and others, 2018). The goal for OW energy is to reduce LCoE to a no-subsidies point for fixed OW and, for floating OW, less than 120 €/MWh by 2025. The corresponding targets for wave and tidal energy are 200 €/MWh and 150 €/MWh, respectively. Worldwide support of national governments would allow the industry to develop the critical mass that, in turn, would generate large cost reductions. The corresponding LCoE projection for salinity gradient is 80 €/MWh and 150–200 €/MWh for OTEC (Ocean Energy Europe, 2016).

A recent trend in relation to more open sea deployments of wave and tidal/ocean current devices is to focus on niche markets. For off-grid areas, remote coastal and island communities (e.g., Small Island Developing States [SIDS]) and local MRE options may offer a solution to their energy needs for desalination, aquaculture, etc. (LiVecchi and others 2019; Rusu and Onea, 2019).[280] In these applications, wave and tidal energy have the potential to be competitive with diesel generators. In most cases, wave and tidal energy devices would be smaller in size, so a high capital outlay would not be required. Working towards utility scale, by incrementally scaling up devices and array size, may provide the pathway to commercialization for wave and tidal energy.

The OW sector is expected to expand globally, covering areas where no OW farms are currently operational. In the next decade, it is foreseen that Asia and the United States of America will make significant progress, and nascent markets will accelerate OW growth. The use of floating platforms is a step change for the industry. Floating wind is on the cusp of commercial deployment, and there are new technologies with potential for offshore deployment at earlier stages of development. For example, rather than continually increasing wind turbine size, multi-turbine platforms may offer an alternative future development route for OW. High altitude wind concepts, such as autonomous kites or unpiloted aircraft, and hybrid platforms that can combine different MRE technology types on a single platform are also moving along the development process.

[280] https://www.energy.gov/eere/water/downloads/powering-blue-economy-report [Accessed 15 July 2020].

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Chapter 25
Invasive Species

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Keynote points

- Globally, about 2,000 marine non-indigenous species (NIS) have been introduced to new locations via human-mediated movements. A few of these have economic value, but most have had negative ecological, socioeconomic or human health impacts. With increased trade and climate change, biological invasions will likely increase.
- NIS can pose significant biosecurity and biodiversity hazards. Large-scale NIS surveys with broad taxonomic coverage are lacking, as are studies documenting the range of potential impacts in recipient environments.
- Major invasion vectors (i.e. ballast water, biofouling, aquaculture, trade in live organisms, canals, debris/plastics) lack characterization and understanding at global and many regional levels and, with the exception of ballast water/sediment management, regulation is lacking. The multi-vector nature of both NIS introduction and spread requires comprehensive and integrated legal instruments with robust enforcement to mitigate the movement of species and holistic monitoring programs that can detect them.
- Better tools are urgently needed to assess the potential risks of NIS under changing environmental conditions, to identify the native species and ecosystems most at risk, and determine the best way to respond (i.e., Early Detection Rapid Response). This is especially true for species with no previously documented invasion history.

1. Introduction

Invasion by non-indigenous species (NIS) is a major driver of biodiversity change that can reduce biodiversity, alter community structure and function, diminish fisheries and aquaculture production and impact human health and well-being, and is exacerbated by climate change (including extreme events) and other human-induced disturbances (Bax and others, 2003; MEA, 2005; Ojaveer and others, 2018). NIS are those species, including microbes, that have overcome a natural dispersal barrier to become established in a new biogeographical area outside their native range due to human-mediated activities, either intentionally or unintentionally (Carlton, 1999). These species can then spread either naturally or via additional human-mediated activities in the newly invaded area via a wide range of invasion vectors (i.e. the physical means by which individuals are moved: biofouling, aquaculture, trade in live organisms, canals) (Carlton and Ruiz, 2005; Richardson and others, 2011). Invasion pathways represent a combination of processes and opportunities that allow individuals to be moved from a source location to a recipient (non-native) one and include elements of the invasion vector (and has been used interchangeably with invasion vector) (Carlton and Ruiz, 2005; Richardson and others, 2011). Species that undergo distributional changes due to ecosystem regime shifts or in response to climate change in their native range are not considered NIS and neither are cryptogenic species - species whose native range is unknown (Carlton, 1996). A subset of all NIS pose significant biological, economic or human health impacts and these are often identified as "invasive alien species" (Williamson, 1996; UNEP, 2002). Given that it is often impossible to predict which NIS will become invasive in which area and under which circumstance, we take the precautionary approach in this Chapter and include all NIS from marine and estuarine systems.

NIS are drivers of change in invaded ecosystems and are influenced by the ecosystems they are invading and the activities and events that allow them to be moved from their native range. Also, there is increased recognition that NIS are a critical component of multiple stressors, especially in coastal marine habitats and that developments in the global economy and improved transportation are contributing to the spread of NIS (MEA, 2005). NIS have been shown to benefit from already stressed or degraded habitats due to other human impacts on marine ecosystems such as overfishing, eutrophication, ocean acidification and habitat alteration (Crooks and others, 2011). Thus, changes in native biodiversity (including CITES species), productivity (including fisheries), harmful algal blooms, and ecosystem structure and function (Chapters 6, 7, 10 and 15) can all directly affect marine invasion success, including where NIS are pathogens. Also, expected increases in artificial habitats (Chapter 14) that allow fouling species to establish in otherwise unsuitable environments may facilitate NIS introductions and spread, while NIS also benefit from being redistributed by human-mediated activities such as marine transportation/shipping, aquaculture and fishing-mediated movements/stocking, habitat restoration, canals and diversions, marine debris/litter (especially plastics which do not degrade rapidly and thus can persist as a transport vector), and research activities (Chapters 16 and 23)(Ruiz and others, 1997; Carlton and others, 2017; Galil and others, 2018; Therriault and others, 2018).

NIS have the potential to directly or indirectly affect the biota and ecosystems that support healthy and productive human communities. Although in some cases, NIS have been exploited following either unintentional introduction or escape to the wild from intentional introduction events (e.g. the Pacific oyster *Crassostrea gigas*, the Red Sea prawn *Penaeus pulchricaudatus*, the Asian tiger shrimp *P. monodon*, the blue swimming crab *Portunus segnis* and the Manila clam *Ruditapes philippinarum*), the longer-term impacts tend to be negative, with reduced native diversity. Impacts also extend to coastal communities directly or indirectly by reducing the overall productivity and resilience of marine systems that traditionally support sustainable fisheries or aquaculture (Molnar and others, 2008; Schröder and de Leaniz, 2011).

To improve our understanding of invasions at the global scale, there is a need for validated, detailed georeferenced inventories of NIS accessible in searchable databases that can be used to better understand the distribution of NIS and the potential mechanisms of their redistribution. Currently, there are many locations around the world where there is limited, incomplete or even no understanding of NIS, including when they first arrived (or were found), or what the likely introduction vector(s) were. Although there have been advancements in biodiversity assessments (Costello and others, 2010; Narayanaswamy and others, 2013), especially with advances in molecular techniques (Darling and others, 2017), there remain critical gaps with respect to NIS. Specifically, not only does the taxonomy need to be fully resolved for each species, especially where NIS and sibling native species overlap, but an understanding of the native range of these species is also required. Similarly, there is a need for improved geospatial and temporal understanding of invasion vectors and pathways. Although some regional studies exist for ballast water, in general there is limited information on NIS transported via many invasion vectors. Also, there is an incomplete understanding of important invasion pathways such as their characteristics, routes, frequency, and intensity. Collectively, such information is essential to inform NIS policy and management.

2. Documented baseline and changes in NIS

Since there was no formal assessment of status and trends of NIS in the First World Ocean Assessment (WOA I) (United Nations, 2017), it is not possible to evaluate changes relative to that baseline period. However, there are multiple lines of evidence confirming that NIS continue to be redistributed globally with new introductions reported from new locations as management and control is generally lacking. Globally, the International Convention for the Control and Management of Ships' Ballast Water and Sediments, 2004,[281] came into force in September 2017 (IMO, 2019) but the degree to which it has been implemented globally or its effectiveness at reducing marine invasions regionally is not clear, however the current experience-building phase may provide important information for future assessments. Similarly, some States have implemented the International Council for the Exploration of the Sea (ICES) Code of Practice on the Introductions and Transfer of Marine Organisms (ICES, 2005) to reduce the threat of NIS when intentionally introduced to new areas for culture, but invasions have still occurred. Recognizing the growing importance of hull fouling as a vector, ICES has recommended four actions to evaluate and mitigate biofouling introductions (ICES, 2019) but there remain many invasion vectors that are not currently globally regulated (see below).

Globally, available information on NIS is quite variable spatially, temporally, and taxonomically. There are many locations where NIS are not routinely surveyed or monitored. There are also strong biases in the breadth and depth of taxonomic coverage and expertise. There is better information on larger, more conspicuous species (i.e. fishes, large crustaceans) but significantly less information on smaller, less conspicuous ones (i.e. worms and other small invertebrates).

It is important to note that consequences of marine invasions can take considerable time to manifest and are notoriously difficult to quantify. There are often time lags between when a NIS is introduced to a new location and when the species is detected or impacts noted. Further, important baseline data are often not available pre-invasion. Thus, it is difficult to attribute observed ecosystem changes to NIS specifically, especially when so many other external stressors are affecting marine ecosystems. However, by establishing global or regional baseline inventories as suggested by Tsiamis and others (2019) for European Union countries, it will be possible to better understand both the changes in NIS over space and time and their impacts on ecosystems and human well-being recognizing critical validation of these inventories will be required to ensure they are fit for purpose. Thus, we provide the first global, region-specific analysis of baseline status and trends for multiple taxonomic groups (see section 4 below).

3. Consequences for human communities, economies and well-being

NIS have the potential to interact directly or indirectly with many Sustainable Development Goals (SDGs)[282] beyond SDG 14 (Life Below Water) where they are contributing to the degradation of coastal habitats and the ecosystem goods and services they provide (see ICSU and others, 2017). The achievement of SDG 1 (No Poverty) may be reduced by the continued

[281] International Maritime Organization, document BWM/CONF/36, annex.
[282] See United Nations General Assembly resolution 70/1.

spread of NIS that negatively impact fisheries and aquaculture directly or indirectly by altering ecosystem structure and function. This could be especially true for Small Island Developing States (SIDS) and Least Developed Countries (LDCs) where NIS regulations, policy, and monitoring/early detection and rapid response plans are lacking. Similarly, NIS could also compromise the achievement of SDG 2 (Zero Hunger) by compromising seafood safety and security via the same mechanisms. In many cases, NIS can be considered a biological contaminant, especially those that have the potential for human health impacts. Thus, the continued global spread of NIS, especially human pathogens such as vibrio cholera, is also implicated in the achievement of SDG 3 (Good Health and Well-being). Some NIS have the potential to dramatically alter marine coastal environments and communities and as such they could negatively influence the achievement of SDG 6 (Clean Water and Sanitation). There is growing evidence that many biofouling marine NIS are able to exploit anthropogenic structures, including docks, oil platforms, wind farms, and so forth. As growing energy demands result in the development of coastal and offshore infrastructure, NIS could be implicated in the achievement of SDG 7 (Affordable and Clean Energy). Sustainable growth in fisheries and aquaculture could be compromised in areas where NIS continue to spread unmanaged. Thus, NIS also have the potential to compromise the achievement of SDG 8 (Decent Work and Economic Growth) and SDG 9 (Industry, Innovation and Infrastructure).

Good ocean governance (SDG 16: Peace, Justice and Strong Institutions) could play an important role in improving our understanding of marine NIS and their impacts globally. This could include the development of a reporting framework or database that would allow the ever-changing distributions of NIS to be documented such that informed management or policy development in areas beyond national jurisdictions could occur. Further, there are many marine ecosystems where even basic information on NIS is lacking (see sections 2 and 4 below). Thus, global partnerships and capacity building may be possible under SDG 17 (Partnerships for the Goals). Also, if progress is slow on achieving the SDGs, then the spread and impacts of NIS could be exacerbated. For example, without progress on SDG 13 (Climate Action), the few marine ecosystems that currently have a limited number of NIS such as the Arctic and Southern Ocean (see section 4 below) will likely see invasions proceed at a much faster rate as these environments become more suitable to a wide variety of taxa and abiotic and biotic barriers to invasion are degraded or removed.

NIS are also implicated in other global policy documents, especially those pertaining to biodiversity given the negative relationship between the two. For example, the Convention on Biological Diversity (CBD)[283] recognizes the threat of NIS and article 8(h) of the Convention states that, each contracting party shall, as far as possible and as appropriate, “prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species”. Also, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has recognized the negative impacts of NIS around the world and has started a process for the assessment of these species.

Some NIS have the potential to impair human health and well-being. For example, introduced *Vibrio* bacteria and harmful algal species (dinoflagellates, diatoms and cyanobacteria) that create toxins can negatively impact marine biota and human consumers, and are expected to worsen as they benefit from climate change (Ruiz and others, 2000; Paerl and Huisman, 2009). In the highly invaded Mediterranean Sea, nine venomous/poisonous NIS from the Indian Ocean or the Indo-west Pacific Ocean pose human health risks (Galil, 2018). Further, the Pacific lionfish (*Pterois volitans*) produces a toxin that is venomous to humans although it

[283] United Nations, *Treaty Series*, vol. 1760, No. 30619.

rarely results in death. However, only fragmentary information is available concerning the spatial and temporal trends of these human health impacts as under-diagnosis and under-reporting hampers quantitative assessment of global incidence of medically treated health impacts, and ignorance of the extent, severity and trends of these emerging public health risks may prejudice risk analyses.

Some NIS have provided economic benefits, whether introduced intentionally or not, but this often represents a trade-off with ecological consequences. For example, the Pacific oyster has been introduced to coastal environments around the world, including in North America, South America, Africa, Australia and Europe, resulting in economic opportunities with global production in excess of 4 million tonnes (Shatkin, 1997; FAO, 2019). However, in many locations this species has spread beyond culture locations and in some areas has negatively impacted both native biodiversity and ecosystem functioning as well as human well-being (Molnar and others, 2008; Herbert and others, 2016). Atlantic salmon (*Salmo salar*) also has been used to create economic opportunities in countries around the world but large-scale escape events can result in negative ecological and socioeconomic impacts (Schröder and de Leaniz, 2011). In the Barents Sea, red king crab (*Paralithodes camtschaticus*) was introduced intentionally for fisheries but has rapidly spread to adjacent waters and increased in abundance, thus creating conflicts among different user groups and negatively impacting biodiversity and ecosystem functioning, especially in coastal fjords (Falk-Peterson and others, 2011). There are longer term implications for establishing fisheries on NIS, especially amid a push to ensure fisheries are sustainable. Further, some NIS such as the salt marsh grass *Spartina alterniflora*, that was intentionally introduced to China is an ecosystem engineer has significantly changed the ecosystems it has invaded (Wan and others, 2009). Schlaepfer and others (2011) also suggest some NIS may provide ecological or conservation benefits but predicting these is often complex and context dependant.

4. Key region-specific baselines, changes and consequences

4.1. Arctic Ocean

Although basin-wide assessments of NIS in the Arctic Ocean are lacking, there appears to be relatively few invaders presently (Molnar and others, 2008; Chan and others, 2013). However, with rapid environmental changes, including increased temperatures and reduced sea ice, these waters could be suitable for a number of potential invaders in the future (Ware and others, 2016; Goldsmit and others, 2018). Further, these environmental changes could lead to changes in human-mediated invasion vectors in the Arctic Ocean, especially marine transport that could result in increased propagule pressure in the future (Miller and Ruiz, 2014).

4.2. North Atlantic Ocean, Baltic Sea, Black Sea, Mediterranean and North Sea

The Mediterranean Sea has a long history of invasions - 22 NIS had been recorded before 1900 (Galil, 2012). By the early 2000s, country level NIS inventories were initiated and, as of 2011, there is a total of 787 NIS listed in European Union marine waters (Macaronesia included), with the highest number (242 NIS) reported in the western Mediterranean Sea (Tsiamis and others, 2019; see Gómez, 2019, regarding 52 microalgal species) but omission of data from the eastern and southern Mediterranean Sea induced a major bias since the number of NIS is substantially greater in the eastern than in the western Mediterranean Sea (over 400 NIS recorded along the coast of Israel alone). There are 727 metazoan NIS in the entire Mediterranean Sea, and the number is rapidly increasing (Galil and others, 2018) (Figure 1) while, as of 2018, 173 NIS and cryptogenic species have been reported in the Black Sea. Despite the growing awareness of the role of the Suez Canal in Mediterranean Sea invasions, the “New Suez Canal” project was initiated in 2014 to substantially increase the depth and width of the canal, but measures to mitigate probable NIS propagule increases have yet to be considered (Galil and others, 2017). Thus, the main invasion vectors for the Mediterranean Sea include: the introduction of Red Sea biota via the Suez Canal; shipping (commercial and recreational); mariculture; and the aquarium trade. Although the latter vectors contribute fewer NIS, some have had disproportionate impacts, including the green alga (*Caulerpa taxifolia*) introduced with aquarium spill-over (Meinesz and Hesse, 1991) and the brown alga (*Fucus spiralis*) introduced in the packaging of fishing bait (Sancholle, 1988).

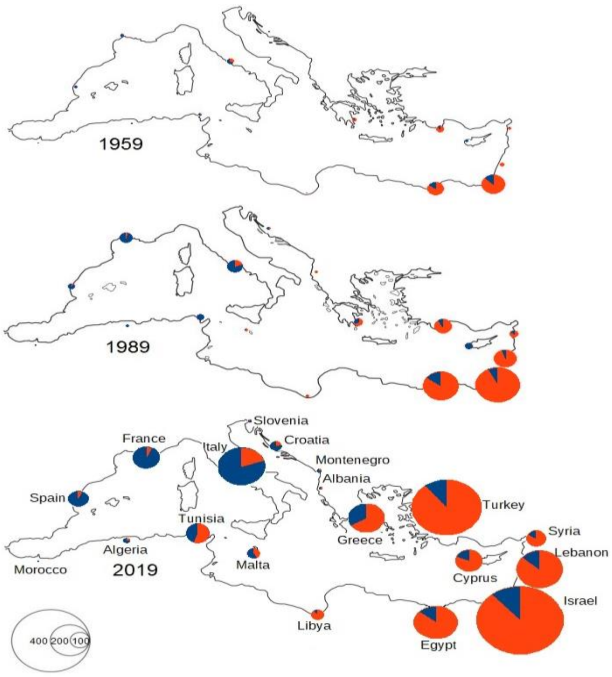

Figure 1: Changes in non-indigenous species reports over time for the Mediterranean Sea. Red indicates species introduced via the Suez Canal and blue represents species introduced by other vectors (A. Marchini and B. Galil).

Since the beginning of the twenty-first century, the apparent annual introduction rate to the Baltic Sea has been almost two times higher: 3.2 and 1.4 species per year, respectively, between 1950 and 1999 (ICES 2018). Both ballast water and hull fouling are the main vectors for primary introductions, followed by natural spread of NIS introduced via rivers and the North Sea. Most of the NIS in the Baltic Sea originate from North America, the Ponto-Caspian region and East Asia but, more recently, introductions of subtropical NIS have been increasing such that 174 NIS and cryptogenic species have been recorded from the Baltic Sea (AquaNIS, 2019; Ojaveer and others, 2017; ICES, 2018). However, there remains considerable uncertainty about the direction and magnitude of impacts for even the most widespread NIS on the structure and dynamics of Baltic Sea ecosystems (Ojaveer and Kotta, 2015).

Although lists overlap, reported NIS from the eastern Atlantic include: at least 80 from the North Sea (Reise and others, 2002); 90 from waters around United Kingdom of Great Britain and Northern Ireland (Minchin and others, 2013); 104 from French Atlantic waters (Goulletquer and others, 2002); and more than 100 from the English Channel (Dauvin and others, 2019). There are at least 189 NIS reported for the western Atlantic (Ruiz and others, 2015) but this number is likely higher. For policy and management, validated regional integrations are required.

4.3. South Atlantic Ocean and Wider Caribbean

Records of NIS in this region are incomplete both spatially and temporally. The earliest historical compilations are from South Africa, where 12 NIS were reported in the early 1990s, including two global invaders, the European green crab (*Carcinus maenas*) and the blue (Gallo) mussel (*Mytilus galloprovincialis*) (Griffiths and others, 1992). Mead and others (2011) reassessed NIS occurrences in the region and identified 86 NIS, and singled out ballast water and ship fouling as the main vectors. Apart from South Africa, most of the South-East Atlantic coast remains unexplored regarding NIS, although a recent study from Angola reported 29 NIS (Barros Pestana and others, 2017). For the South-West Atlantic, the earliest compilations were for Argentina and Uruguay, and identified 31 NIS, including one intentionally introduced species (*Crassostrea gigas*) (Orensanz and others, 2002). A recent reassessment for this region identified more than 120 NIS from diverse taxonomic groups (from viruses to plants and fishes), including 33 new detections since 2002 (Schwindt and others, 2020) and, as in the case of South Africa, ships were the main vector for species introductions. The most recent surveys from Brazil have identified 73 NIS (Lopes, 2009; Teixeira and Creed, 2020), along an extensive coastline with a long history of shipping, which suggests that this number could be underestimating true NIS richness. A data gap exists for the North Atlantic coast of South America (from French Guiana to Guyana) where there has been little attention to NIS (Schwindt and Bortolus, 2017) and no extensive compilations are available for the Wider Caribbean region, although smaller-scale information is available for Venezuela (Pérez and others, 2007- 22 NIS) and Colombia (Gracia and others, 2011- 16 NIS). The lionfish (*Pterois volitans*) is one of the most problematic and studied NIS in the Caribbean region. Similarly, two invasive sun corals, *Tubastraea coccinea* and *T. tagusensis*, have spread rapidly in the tropical Western Atlantic and Gulf of Mexico, outcompeting, overgrowing and replacing native corals (Creed and others, 2017).

4.4. Indian Ocean, Arabian Sea, Bay of Bengal, Red Sea, Gulf of Aden and Persian Gulf

Regional records of NIS are incomplete both spatially and temporally. Despite its size and diversity, Indian Ocean studies on marine NIS are scarce, mostly qualitative and geographically scattered, resulting in significant knowledge gaps for this large and diverse area (Indian Ocean Commission, 2016). For example, the Philippine-derived red algae *Eucheuma denticulatum* and *Kappaphycus alvarezii* were introduced for mariculture along the east African coastline (Kenya, Tanzania, Mozambique) which resulted in deleterious impacts (Bergman and others, 2001; Halling and others, 2013). *K. alvarezii* was also introduced along the western Indian coast and has spread into the Gulf of Mannar Biosphere Reserve in India, where it has impacted native corals (Chandrasekaran and others, 2008). As elsewhere, intentional introductions have been attributed to mariculture activities to address food security and the aquarium trade for economic benefits, while unintentional introductions are mostly due to maritime shipping activities or transport on floating objects (Indian Ocean Commission, 2016; Anil and others 2003).

4.5. North Pacific Ocean

This Ocean is large and biogeographically diverse but, as with the other regions, NIS reporting is incomplete. However, like the Mediterranean Sea, as of 2012 there have been at least 747 NIS reported from 23 ecoregions studied (including Hawaii and Northern Central Indo-Pacific), with more than 70 per cent of these belonging to four phyla - Arthropoda (224); Chordata (Tunicata + Fish) (114); Mollusca (110); and Annelida (89) (Lee II and Reusser, 2012; Kestrup and others, 2015). Of these NIS, 32 per cent were native elsewhere in the North Pacific Ocean, 48 per cent were native to regions outside the North Pacific Ocean, and 20 per cent were cryptogenic (Lee II and Reusser, 2012; Kestrup and others, 2015). The Northeast Pacific (368 NIS) and Hawaii (347 NIS) had similar numbers of invaders, while lower numbers were observed for the Northwest Pacific (208) and the Northern Central Indo-Pacific (75), possibly owing to different levels of sampling effort. Further, it is important to note that there are at least 27 additional ecoregions in the North Pacific Ocean, predominately in Southeast Asia (Spalding and others, 2007) where there is no systematic survey effort, so the number of NIS is expected to be higher for the entire Ocean. There have been some more in-depth studies at smaller spatial scales and/or focused on specific taxonomic groups. For example, there are at least six planktonic and 10 algal NIS in the Bohai Sea and port locations in China (Qiao, 2019) compared with recorded baseline observations (Liu, 2008; Wang and Li, 2006), while San Francisco Bay has more than 234 NIS (Cohen and Carlton, 1998).

As for other regions, ballast water discharges, hull fouling, intentional stocking, aquaculture escapees, aquaculture-associated species, and aquarium/plant trade were all important vectors for the North Pacific. Intentional stocking and aquaculture escapees were more prominent in the Northwest Pacific compared to the Northeast Pacific or Hawaii, likely reflective of large-scale aquaculture efforts in Asia. Another difference between the Northeast and Northwest Pacific was the importance of aquaculture-associated species in the Northeast Pacific (about 42 per cent of NIS), likely reflective of the large number of NIS introduced via importation of Atlantic oyster (*Crassostrea virginica*) from the Atlantic coast of North America and Pacific oyster from Asia which resulted in many hitchhikers becoming established outside their native range. Increased regulation in recent decades has been effective in reducing the number of inadvertent NIS movements related to aquaculture. In 2011 the Great East Japan Earthquake and resulting tsunami provided a unique vector for NIS to be transported from Japan to North America and Hawaii across the North Pacific (Carlton and others, 2017; Therriault and others, 2018).

4.6. South Pacific Ocean

There have been no synthetic assessments of the status of marine bioinvasions across this geographically, culturally and ecologically diverse area. Most existing information comes from literature and field studies undertaken since the late 1990s in Australia, New Zealand and Chile. A literature review combined with NIS surveys in 41 Australian shipping ports between 1995 and 2004 identified 132 NIS from throughout Australia (Sliwa and others, 2009), with 100 NIS detected in Port Phillip Bay alone (Hewitt and others, 2004). There were more NIS in southern temperate Australia than in tropical northern Australia (Hewitt, 2002) but these patterns are confounded by poorer taxonomic resolution in the tropical environments and by the larger urban centres and longer history of shipping in southern Australia (Hewitt and Campbell, 2010). Forty-three similar baseline surveys were conducted in New Zealand between 2001 and 2007 (Seaward and others, 2015) and, when combined with published records, museum holdings and submissions to the Marine Invasives Taxonomic Service

(Cranfield and others, 1998; Kospartov and others, 2010), as of March 2018, 377 NIS have been recorded from New Zealand marine waters (214 are considered to have established in recipient systems, while the remaining 163 species have been recorded only from vessels or transient structures or were failed introductions). Forty-six new NIS were recorded between 2010 and 2018, only 15 of which appear to have established (Seaward and Inglis, 2018).

At least 53 marine NIS have been reported from Chile (1 seagrass, 15 algae, 26 invertebrates and 11 fishes) (Castilla and Neill, 2009; Turon and others, 2016). However, this is likely an underestimate as there appear to have been few studies of biofouling assemblages in ports and harbours where introduced species tend to be more abundant. For example, 53 NIS marine invertebrates were recently reported from the Galápagos Islands, Ecuador (Carlton and others, 2019) of which 30 species (57 per cent) were first recorded in fouling plate and shoreline surveys undertaken around shipping docks and infrastructure while Cárdenas-Calle and others (2019) identified 6 NIS from mainland Ecuador.

There is limited information about the distribution and impact of NIS in the Pacific Island Countries and Territories (PICTs) as relatively few systematic studies have been done in the region. Surveys undertaken in American Samoa in 2002 identified 17 NIS, most of which were restricted to Pago Pago Harbour and were species known to occur across a broad geographic range (Coles and others, 2003). Forty NIS have been identified from Guam (Paulay and others, 2002) and a preliminary survey of fouling assemblages in Malakal Harbour, Palau, identified 11 NIS (Campbell and others, 2016), in each case comprising mostly ascidians, bryozoans, hydroids and bivalve molluscs. Six NIS - 5 invertebrates and an alga - have been recorded from the remote Palmyra Atoll (Knapp and others, 2011). Nuisance blooms of fucoid algae, possibly spread by shipping have been reported in Tahiti (Stiger and Payri, 1999) and Tuvalu (De Ramon N'Yeurt and Iese, 2013).

Over 80 per cent of known NIS in Australia and New Zealand have been associated with incidental transport in ballast water or biofouling (Hewitt and Campbell, 2010; Kospartov and others, 2010) while deliberate introductions of aquaculture species accounted for less than 2 per cent of records. Introductions of aquaculture species have been more important in Chile and Peru (Castilla and Neill, 2009) and the PICTs. At least 38 NIS have already been transported deliberately throughout the PICTs over the past 50 years in attempts to establish fisheries or small-scale aquaculture ventures (Eldredge, 1994). In the 1970s–80s, green mussels (*Perna viridis*) sourced from the Philippines were successively introduced to New Caledonia, Fiji, Tonga, Society Islands, Western Samoa and the Cook Islands (Baker and others, 2007).

4.7. Southern Ocean

The Antarctic Circumpolar Current acts as a strong barrier to natural dispersal that has likely contributed to the uniqueness of Southern Ocean communities. Further, the Southern Ocean has limited shallow-water continental shelves and a poorly described fauna (Brandt and others, 2007). Thus, it appears the most likely vectors for NIS to these waters would either be direct human-mediated transport such as shipping, or indirectly via longer-distance rafting on artificial marine debris (Lewis and others, 2003; Barnes and others, 2006; Hughes and Ashton, 2017). In addition, any NIS that may reach these environments would face challenging environmental conditions but, with increased rates of climate change, these waters may be more prone to invasions in the future. Currently, only the North Atlantic spider crab (*Hyas araneus*) appears to have been introduced by human activities to the Southern

Ocean (Tavares and de Melo, 2004) but it is likely this will change in the future. Suggested future invaders include the blue mussel (*Mytilus*) (Lee and Chown, 2007), the predatory sea star (*Asterias amurensis*) (Byrne and others, 2016) and the kelp (*Undaria pinnatifida*) (James and others, 2015). Due to the relatively low biodiversity, simple ecosystem structure and unique assemblages dominated by soft-bodied organisms, this system may be especially vulnerable to NIS introductions, especially predatory species that could result in significant impacts.

5. Outlook

NIS introductions continue as species are redistributed by human activities but there were many regions where NIS information is either very poorly documented or lacking completely such that temporal analyses were not possible. Further, climate change will add to other drivers of ocean change - including water pollution, severe storm events and overfishing - to potentially enhance NIS abundances, ranges and impacts by altering recipient ecosystems where native species will be increasingly stressed and changing human-mediated connectivity by shifting vectors and pathways. About 40 per cent of the world's population live in coastal communities, increasing pressure on coastal marine ecosystems through multiple activities, including (but not limited to) shipping, boating, marine farming, land-based pollution and marine litter, coastal installations and development, energy production and multiple extraction activities (oil/gas, sediments, fisheries/aquaculture), which contribute to the introduction and spread of NIS. For regions like the Arctic, it has been predicted that changing environmental conditions will increase the likelihood of new invaders from a variety of taxa (e.g., Goldsmit and others, 2018) and may also change shipping patterns, which could increase the supply of propagules (Miller and Ruiz, 2014) where traffic is expected to increase along the Northern Sea Route and become possible along the Northwest Passage.

Despite the risks posed by NIS, they are substantially underrepresented in existing databases and registries such that many of the challenges inherent in dealing with NIS stem from a limited/incomplete knowledge base. The magnitude and breadth of this gap is difficult to assess, and it varies amongst taxa, habitats and regions, and owes much to the inaccessibility of marine ecosystems (including higher costs of research, lack of expertise and lack of interest in NIS that do not benefit or interfere with human needs). Generally, impacts are not well documented unless the NIS is profitable or highly destructive. Thus, for the vast majority of marine NIS, impacts remain unknown and have not been quantitatively or experimentally studied over sufficiently long temporal and spatial scales, and their cumulative and synergetic connections with other drivers of change affecting the marine environment are unknown (Ojaveer and others, 2015).

Vector management is the most effective strategy for preventing translocation of species, thereby reducing introduction and spread of marine NIS. Lack of effective control on propagule transfer by the major vectors, as mentioned above, reduces management to frequently futile eradication/removal and control efforts. NIS known or suspected to cause harm, and identified while spatially confined, should be removed, thus mitigating long-term, ongoing management costs. Once NIS have spread widely, eradication/removal is virtually impossible, and attempts for long-term reduction of the population to an economically or ecologically acceptable level are rarely successful (Forrest and Hopkins, 2013). Legislation, regulations and policies to date have been reactive and fragmentary, often following disastrous and costly NIS outbreaks. The United Nations Convention on the Law of the Sea[284] was the first global legally binding instrument dealing with the intentional or unintentional introduction of marine species. While guidelines for preventing the introduction of unwanted aquatic organisms and pathogens from ships' ballast water and sediment discharges were established in 1991, and the International Convention for the Control and Management of Ships' Ballast Water and Sediments[281] entered into force in 2017, the management of ships' biofouling is not yet required despite guidance to do so from the IMO in 2011 (IMO, 2019; Resolution MEPC.207(62)). Also the CBD-revised Strategic Plan for Biodiversity 2011–2020[285] called for invasive alien species and pathways to be identified and prioritized, for priority species to be controlled or eradicated, and for measures to be taken to manage pathways by 2010 - a target that was missed. The European Union (EU) Marine Strategy Framework Directive aims to ensure, among other things, that NIS are at levels that do not adversely alter ecosystems by 2020 is also likely unattainable. EU Regulation No.1143/2014, on the prevention and management of the introduction and spread of invasive alien species, which focused only on widespread established species and those of "Union Concern", also is unlikely to succeed in marine ecosystems where only one marine species has been listed so far. Despite some national-level regulations, including those in Australia, Canada, New Zealand and the United States of America, major global and regional introduction vectors such as biofouling, culture and trade in live organisms, and maritime canals, all lack legally binding and strictly monitored NIS frameworks and tools.

6. Other

Although NIS have long been recognized as a major threat to native biodiversity (Bax and others, 2003), they have been largely overlooked in conservation/protected area planning, regulations and management (Giakoumi and others, 2016; Mačić and others, 2018). This omission, given global commitments to establishing and extending conservation areas (i.e. Aichi Target 11,[285] CBD article 8 and SDG 14) may undermine conservation efforts, including the effectiveness of Marine Protected Areas (MPAs), in regions overrun by NIS (Galil, 2017; Iacarella and others, 2019). In the Caribbean Sea and Gulf of Mexico, large populations of the Indo-Pacific lionfish have been documented in MPAs where abundant lionfish populations have impaired native biodiversity (Ruttenberg and others, 2012; Aguilar-Perera and others, 2017). Similarly, in the Mediterranean Sea, many Erythraean species have become the most conspicuous denizens in MPAs, having displaced and replaced native species, thereby reversing marine conservation efforts and hampering stock recovery of key economically and ecologically important species (Jimenez and others, 2016; Galil, 2018; Stern and Rothman, 2019).

Thus far, few NIS have been reported from areas beyond national jurisdiction where a United Nations resolution on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction would apply. It is possible that this is due to limited survey efforts to detect NIS in these ecosystems but it is also likely that most NIS that have been reported globally are primarily from coastal waters (from all continents). In addition, oceanic abyssal communities have been poorly described so it is possible that, even if potential NIS are detected, they would not be recognized as such and may actually be classified, at least initially, as a native species. This would mimic the experience in South America with smooth cordgrass (*Spartina alterniflora*) where "ecological mirages" masked the true situation

[284] Ibid., vol. 1833, No. 31363.
[285] United Nations Environment Programme, document UNEP/CBD/COP/10/27, annex, decision X/2, annex.

(Bortolus and others, 2015).

Globally, marine NIS pose significant biosecurity and biodiversity hazards, but identifying and mitigating these hazards lag behind comparable efforts in terrestrial systems where there has been a longer history dealing with agricultural and forest pests. Efforts must be increased to document NIS, their vectors/pathways and their impacts at larger spatial scales, given that existing marine NIS data were often sparse and incomplete, possibly reflective of logistical and capacity constraints. Policies aimed at preventing introductions and the development of Early Detection/Rapid Response plans can reduce the potential impacts of NIS. Devoted funding, political will and capacity building related to invasion science are required to effectively understand and ultimately manage marine NIS and their vectors globally. Only then can we ensure sustainable marine ecosystems.

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Hall.

Chapter 26
Developments in Exploration and Use of Marine Genetic Resources

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Keynote points

- Marine genetic resources (MGRs) continue to be the focus of an expanding range of commercial and non-commercial applications.
- Rapidly sinking sequencing and gene synthesis costs and swift advances in the metabolic engineering and synthetic biology fields within the biotechnology sector have rendered scientists less reliant on physical samples, and increasingly dependent on the exponentially expanding public databases of genetic sequence data.
- Sponges and algae continue to attract substantial interest for the bioactive properties associated with their natural compounds.
- Within the context of the Sustainable Development Goals,[286] capacity-building issues persist, with entities in a handful of countries conducting the majority of research and development associated with MGRs.
- There are international processes and agreements with relevance to MGRs, most notably the Nagoya Protocol under the Convention on Biological Diversity (CBD), and the Intergovernmental conference on the elaboration of a legally binding instrument under the United Nations Convention on the Law of the Sea on the conservation and sustainable use of marine biodiversity in areas beyond national jurisdiction at the United Nations.

1. Introduction

The ocean is home to a vast diversity of life constituting a rich source of marine genetic resources (MGRs), that is, genetic material of marine origin containing functional units of heredity and of actual or potential value, characterized by high biological and chemical diversity (Appeltans and others, 2012; United Nations, 2017). Over 34,000 marine natural products (MNPs) have been described, with recent discovery rates reaching more than 1,000 compounds each year (Lindequist, 2016; Carroll and others, 2019). New marine natural products produced by organisms from the deep sea have been described from the Bryozoa, Chordata, Cnidaria, Echinodermata, Mollusca and Porifera, in addition to microbes, with 188 reports since 2008 (Skropeta and Wei, 2014). Approximately 75% of these MNPs have remarkable bioactivity, with 50 per cent exhibiting moderate to high cytotoxicity towards a range of human cancer cell lines. Although the bioactivity of many MNPs suggests the potential for drug discovery, only thirteen marine-derived drugs have gained market approval (Liang and others, 2019; Mayer and others, 2010[287]), although at the time of writing, 28 candidates are currently in clinical trials (Alves and others, 2018). Marine antifoulant research is currently focused on identifying viable non-toxic substances, and a recent review has estimated that more than 198 antifouling compounds have been obtained from marine invertebrates, specifically sponges, gorgonian and soft corals (Qi and Ma, 2017), in addition

[286] See United Nations General Assembly resolution 70/1.
[287] See https://www.midwestern.edu/departments/marinepharmacology/clinical-pipeline.xml Accessed 16/7/20

to the products derived from macro- and microalgae highlighted in the First World Ocean Assessment (WOA I) (United Nations, 2017). Innovative research has also identified ingredients from discarded fish that are suitable for high-end cosmetics as well as a number of other products (Young, 2014). As of 2018, a total of 76 publicly available MNP cosmeceutical ingredients have been marketed, reflecting a new growth sector (Calado and others, 2018).

Simultaneously, consumer demand for nutraceuticals has increased rapidly, as anticipated in WOA I. The global nutraceutical market is expected to reach 580 billion United States dollars by 2025, more than tripling the 180 billion dollars projected for 2017 in WOA I, and growth in the market has been linked to increased innovation and consumer awareness (Grand View Research, 2017). Marine nutraceutical products such as fish oil and collagen represent a large portion of the global market, and demand for these products is expected to grow in the Asia-Pacific region, particularly in China and India (Suleria and others, 2015).

While the global blue economy continues to develop with respect to MGRs, most commercial activity is concentrated in a comparatively small number of countries, suggesting potential for technology transfer and capacity building (Thompson and others, 2017; Blasiak and others, 2018). Several international processes addressing genetic resources, including MGRs, are currently underway.

2. Trends between 2010 and 2020

Technological innovations have been key for the recent advances in the exploration and exploitation of marine genetic resources. The discovery of new marine molecules, and their corresponding sources, has been increasing rapidly, particularly since the 1970s (Figure 1). By November 2019, a total of 34,197 marine natural products had been documented (Carroll and others, 2019). This growth is most likely associated with modern sampling and analytical techniques that have allowed the collection of novel MGRs from deeper environments and covering a wider range of chemical diversity. Approximately 11 per cent of MGRs associated with patent applications are found in deep-sea and hydrothermal vent communities, reflecting increased research in remote and extreme ocean environments (Blasiak and others, 2018). However, the number of MGRs collected at depths of more than 50 metres remains insignificant when compared to the whole MNP library (Skropeta and Wei, 2014). The discovery of enzymes from marine organisms is also accelerating due to the development of innovative screening methodologies (Ferrer and others, 2019). Enzymes from microorganisms adapted to extreme conditions are of particular interest for their application in industrial processes, as they are often active under challenging operational conditions (Birolli and others, 2019).

2.1. Commercial application highlights

2.1.1. Pharmaceutical applications

Thirteen drugs of marine origin have received market approval from the United States Food and Drug Administration (FDA) or European Medicines Agency (EMA), six of those were approved after 2010. The majority of marine drugs have been developed for anti-cancer chemotherapy (Calado and others, 2018; Liang and others, 2019; Mayer and others, 2010[288]).

[288] See https://www.midwestern.edu/departments/marinepharmacology/clinical-pipeline.xml Accessed 16/7/20

Since the approval of cytarabine as an anti-cancer agent in 1969, sponges have been regarded as one of the most promising source of anti-cancer drugs (Hu and others, 2015; see Section 2.3 below). Other marine invertebrates such as tunicate and cone snail species are also very important sources of MNPs, as are fish. Trabectedin (ET-743) gained FDA approval in 2015 to treat soft tissue sarcoma and ovarian cancer, while Plitidepsin was approved by Australia's Therapeutic Goods Administration in 2018 to combat multiple myeloma, leukemia and lymphoma (based on Mayer and others, 2010[289]). Most recently, Lurbinectedin was approved in 2020 for the treatment of metastatic small cell lung cancer (based on Mayer and others, 2010[290]). In all three cases, the relevant compounds were derived from tunicates. Macroalgae are also a source of pharmaceutical products. For example, OligoG, an oligoalginate with a defined structure produced from brown algae, is currently in a phase II clinical trial for the treatment of cystic fibrosis patients (Rye and others, 2018), and the red algae biopolymer Carragelose is used for treating respiratory diseases due to its broad anti-viral properties (Hackl, 2017).

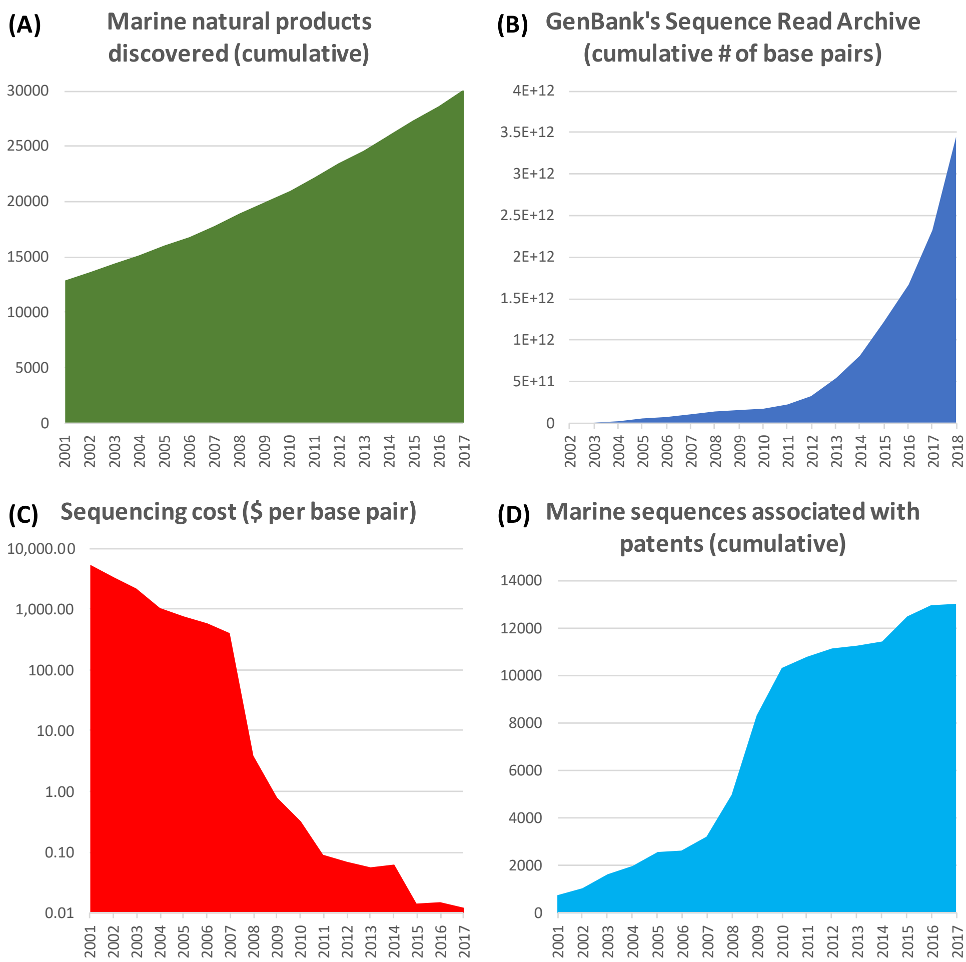

Figure 1. Recent trends related to marine genetic resources. (A) Number of new marine natural products (Carroll and others, 2019); (B) Number of sequences deposited in GenBank (Data from the US National Institute of Health (Wetterstrand, 2018; NCBI, 2018); (C) Cost of sequencing (in USD per base pair); (D) Number of marine sequences associated with patent filings (Data from Blasiak and others, 2018).

289 Ibid.
290 Ibid.

2.1.2. Cosmeceutical applications

Within the context of commercializing MNPs, the cosmeceutical pipeline is among the fastest growing markets, and the cosmeceutical pipeline is shorter than the pharmaceutical and nutraceutical pipelines, resulting in a more rapid growth (Rampelotto and Trincone, 2018). An entire new class of beauty care, combining cosmetics and pharmaceutical properties into novel products with biologically active ingredients, is emerging and will be a hallmark of the next decades. The majority are derived from macroalgae and microalgae, but an increasing number are being generated through marine biotechnology processes based on microorganisms like bacteria and fungi (Calado and others, 2018). However, there are environmental concerns associated with certain cosmetic ingredients (Juliano and Magrini, 2017).

2.1.3. Food and feed applications

The consumption of omega-3 long-chain polyunsaturated fatty acids (LC-PUFAs) is linked with multiple positive health outcomes (Ruxton and others, 2007). However, production of aquaculture species rich in omega-3 LC-PUFAs remains reliant on fish-based feeds. The development of algal oils and alternative transgenic crops of omega-3 LC-PUFAs have consequently attracted substantial interest. Initial efforts have focused on oilseed crops while relying on enzymes from marine species (i.e. marine algae) (Ruiz-Lopez and others, 2014; Zhao and Qiu, 2018). Agro-industry corporations have filed for patents associated with these innovations and large-scale production is envisaged by 2020 (Sprague and others, 2017). Further, the use of macroalgae as feed additives is showing potential for biological methane mitigation in the cattle industry (Roque and others, 2019), in addition to their direct use as human food (Costello and others, 2019). Microalgae are also emerging as important biofuels (Fedder, 2013).

2.2. Growth of public databases of genetic sequence data

Public data archives are integral to modern biological research (Ellenberg and others, 2018; Rigden and Fernandez, 2019). This is in large part due to rapid technological developments over the past two decades that have substantially democratized the availability of nucleic acid sequencing technology. The cost per base of sequencing has fallen more than four orders of magnitude over the past decade alone (Wetterstrand, 2018), and this has been paralleled by exponential growth in the size of publicly available repositories (Figure 1). Overall, the number of bases in GenBank has doubled approximately every 18 months since 1982 (NCBI, 2018).

Although the size of public databases has grown substantially, there is good reason to believe that the current state of knowledge still substantially underrepresents the extant genetic diversity in the ocean. The best evidence for this interpretation comes from omics-based studies. The most recent and comprehensive survey of marine eukaryotic genetic diversity identified ~53 million genes (Carradec and others, 2018), with about half of the detected genes showing no similarity to existing proteins (de Vargas and others, 2015). Estimates for oceanic plankton also suggest the presence of about 150,000 eukaryotic species, which is far greater than the ~11,200 formally described species (de Vargas and others, 2015). Large-scale initiatives such as Tara Oceans (Sunagawa and others, 2015) and Ocean Sampling Day (Kopf and others, 2015) are generating vast quantities of information that are increasing our understanding of the microbial diversity in the ocean at a global scale (Coutinho and others, 2018). The resulting available public data sets represent an important source of information for sequence-based research efforts (Kamble and others, 2019) and enables new research directions such as the use of environmental DNA (eDNA) in molecular ecology and in diversity assessments (Seymour, 2019).

2.3. Highlighted research

Two comprehensive volumes focused on marine biotechnology were published in 2018: the first systematically describes recent developments in the marine biotechnology sector and seeks to define the current and future economic potential (Rampelotto and Trincone, 2018); the second goes beyond research and development aspects to also delve into intellectual property law and the protections offered through patent claims (Guilloux, 2018). Previous studies focused on patents associated with marine genetic resources (Arrieta and others, 2010; Arnaud-Haond and others, 2011) were updated with an analysis that identified patent filings associated with 12,998 genetic sequences from 862 marine species (Blasiak and others, 2018). Actors located or headquartered in 10 countries were responsible for patent filings covering 98 per cent of these sequences, while 165 countries were unrepresented (Blasiak and others, 2018).

SponGES, a four-year project funded since 2016 through the European Union Horizon 2020 research and innovation programme,[291] aims to couple exploration with bioprospecting for industrial applications, namely drug discovery and tissue engineering. Sponges and their associated microorganisms are the richest and most prolific source of marine natural products, comprising more than 30 per cent of those described to date (nearly 5,000 compounds) (Mehbub and others, 2014). From 2001 to 2010, more than 2,400 sponge-derived natural products were discovered from 671 species of sponges (Mehbub and others, 2014). SponGES research has already identified unexpected microbial diversity and resulting biotechnological potential, including unconventional C30 sterols and new barrettides with potential for anti-fouling activity (Lauritano and Ianora, 2018).

3. Economic and social consequences and/or changes

Interest in the exploration and use of marine genetic resources is increasing, at the same time as rapid advances are being made in the global biotechnology industry and initiatives to explore the potential of the blue economy (Wynberg and Laird, 2018). Divergent views exist regarding the economic potential linked to MGRs, particularly those from areas beyond national jurisdiction (Leary, 2018; Blasiak and others, 2020). However, the robust pipeline of marine-derived drugs in clinical trials suggests substantial interest, given that bringing a new drug to market can cost as much as 2.8 billion United States dollars (Wouters and others, 2020) and take 10 to 15 years (Blasiak and others, 2019).

The regulatory framework for accessing MGRs and engaging in subsequent utilization varies depending on whether those resources are from areas within national jurisdiction or beyond. While the former fall under the scope of the Convention on Biological Diversity (CBD)[292] and the Nagoya Protocol thereto,[293] MGRs of areas beyond national jurisdiction are one of the elements of a package of issues currently under negotiation in relation to the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction. In

[291] Available at http://www.deepseasponges.org.
[292] United Nations, *Treaty Series*, vol. 1760, No. 30619.
[293] United Nations Environment Programme, document UNEP/CBD/COP/10/27, annex, decision X/1.

December 2017, by resolution 72/249, the United Nations General Assembly decided to convene an intergovernmental conference to elaborate the text of an international legally binding instrument under the United Nations Convention on the Law of the Sea[294] on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction. Accordingly, three meetings of the conference were held in 2018–2019, with a fourth to take place in 2020. The conference is mandated to address, among other elements, MGRs, including questions on the sharing of benefits. The Nagoya Protocol details obligations related to the access of MGRs, benefit-sharing and compliance aimed at creating fair and equitable sharing of benefits arising out of the utilization of genetic resources.

Both in the context of the conference and in the context of the CBD and the Nagoya Protocol thereto, discussions are taking place on whether to address and regulate the use of digital sequence data and/or information, with different views expressed on this issue and on terminology. In 2019, the CBD commissioned studies covering the concept and scope of digital sequence information (CBD, 2020), traceability and databases, and domestic measures, which are now published following an open review period.

Finally, the World Intellectual Property Organization took steps in 2017 to extend the mandate of its Intergovernmental Committee on Intellectual Property and Genetic Resources, Traditional Knowledge and Folklore. The Committee has been called upon to address issues "relating to intellectual property which will ensure the balanced and effective protection of genetic resources".[295]

All of these regulatory frameworks are only applicable to the signatory countries, and therefore only govern marine genetic resources collected in/by states that are parties.

4. Key region-specific knowledge developments and consequences

In WOA I, the focus was on providing a general review of marine genetic resources rather than providing regional assessments or overviews. This is in part because regional summaries are with information on trends are difficult to obtain. Below is a brief summary of regional issues for the Pacific, Southern Ocean and Arctic, highlighting trends over the last decade. The Mediterranean and Atlantic Ocean have relatively lower development of MNPs (Skropeta and Wei, 2014), but the Mediterranean, with its high biodiversity is a potential source of new pharmaceuticals and nutraceuticals (Briand, 2010).

Skropeta and Wei (2014) conducted an update of their 2008 regional analyses of marine natural products reporting, and found that while a high proportion (24 per cent) of MNP continue to come from Australia, there has been a marked increase in reports of metabolites from deep-sea sediment sampling from the South China Sea (18 per cent) and the Pacific Ocean (17 per cent, including maritime zones off the coast of Guam and Palau). This has been attributed to increased accessibility to remote deep-sea environments (Skropeta and Wei, 2014). Indeed, the regional pattern of MNP discovery was linked to access to manned submersibles and trawling operations rather than regional biodiversity. This was also reflected in the depth distribution of the discoveries where, by 2008, only 8 per cent of MNP were from organisms found at depths of over 1,000 metres but, by 2013, this had increased to 37 per cent (Skropeta and Wei, 2014).

[294] United Nations, *Treaty Series*, vol. 1833, No. 31363.
[295] See World Intellectual Property Organization, document WO/GA/49/21.

The Antarctic region is subject to the Antarctic Treaty and related agreements known as the Antarctic Treaty System (ATS) (Oldham and Kindness, 2020). Bioprospecting has been discussed under the ATS but the issue is very complicated due to governance issues related to research activity, ethics and benefit-sharing. With increased scientific research taking place in Antarctica, research there has increased along with the growing number of patents derived from Antarctic organisms in the United States of America and in Europe (Oldham and others, 2014; Oldham and Kindness, 2020).

A collaborative international research model was established (Leary, 2008), although research on the biotechnology potential of Arctic genetic resources is largely occurring within the exclusive economic zones of the Arctic States.

5. Capacity-building gaps

Many States are faced with challenges in engaging directly in marine genetic resources research. These include limited knowledge of the biodiversity, capacity (both in terms of facilities and technological expertise), financial resources for research and development, experience with access and benefit-sharing mechanisms, and the need to increase collaborations across academic, government and private sectors (Thompson and others, 2017). Capacity-building initiatives in these countries, such as Brazil’s National Research Network in Marine Biotechnology (Thompson and others, 2018), are key to alleviating some of these limitations.

Wynberg (2016) has highlighted rapidly increasing research activity in the Western Indian Ocean, particularly along the Eastern and Southern African coastline, the latter being associated with higher biodiversity and endemism. This research is largely being undertaken by developed countries from other regions with few countries of the Western Indian Ocean engaged as collaborators (with the exception of South Africa and Kenya). Comparatively few countries operate their own research vessels, and only a handful have the capacity to undertake collections in areas beyond national jurisdiction or from deep-sea environments (Figure 2). Although public databases of genetic sequence data are available globally, many countries lack the cyberinfrastructure to access such data sets, or to establish and manage comparable national databases (Thompson and others, 2017).

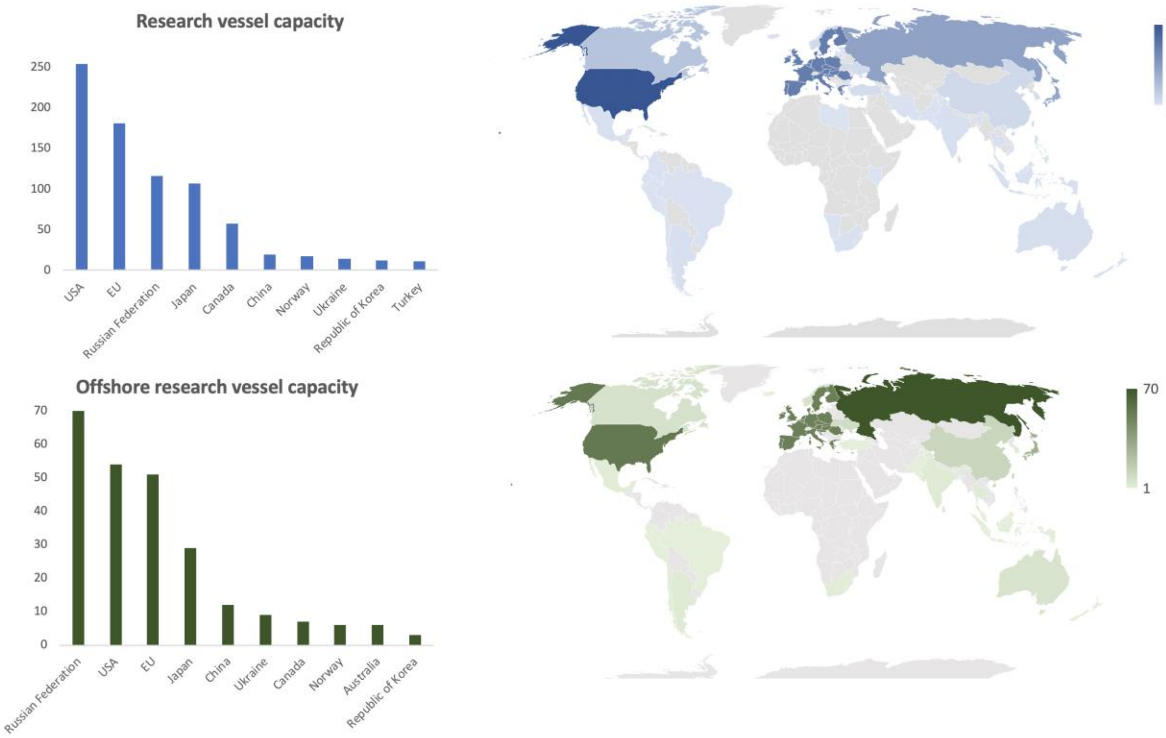

Figure 2. Country of origin for marine research vessels (as of June 2019): (A) Number and distribution of research vessels by flag state; (B) Number and distribution of research vessels with offshore capacity (60+ metres in size) (from the International Research Vessel Database).

6. Methodological challenges and future trends

6.1. New developments in omics approaches

Over the last decades, innovations in technologies for the analysis of biomolecules have facilitated more comprehensive studies of marine organisms and their communities (Coutinho and others, 2018). Sequences technologies with ultra-high throughput allow high coverage in the analysis of microbial communities, single-molecule sequencing technologies produce long sequence lengths from DNA and RNA, and portable real-time sequencing instruments can be used in the field (Ip and others, 2015). The current focus of the sequencing technology field is generating platforms for specific applications, and improving sequence length and output while decreasing sequencing error rates (Wuyts and Segata, 2019). Improvements in sequence length and accuracy are key for generating less fragmented data sets. Assembling deduced amino acid sequences, instead of DNA data, can also generate large catalogues of complete protein sequences from complex metagenomic datasets (Steinegger and others, 2019). Unlike ecological studies, complete proteins and gene clusters are needed for biotechnological applications.

While high-throughput sequence platforms have drastically eased sequence data acquisition, assigning functions to predicted genes, proteins and pathways remains problematic (Woyke and others, 2019). Often it is not possible to assign a putative function or only general functional predictions are possible, in particular, for enzymes. The experimental characterization of selected sequences with biotechnological potential is time-consuming and expensive. A combination of gene synthesis, cell-free protein expression systems and sensitive high-throughput screening methods are being developed for the discovery of novel biocatalysts and enzyme variants with improved characteristics (Rolf and others, 2019). Advances in the detection systems for a different bioprospecting approach, functional metagenomics, are also having a positive impact on biodiscovery (van der Helm and others, 2018).

In spite of recent advances in sequencing technologies, it remains difficult to obtain high-quality near-complete genomes from uncultured microorganisms. Sequencing the genome of single microbial cells and the reconstruction of genomes from complex metagenome data sets have generated genomic information from thousands of uncultured marine microorganisms (Parks and others, 2017; Coutinho and others, 2018; Tully and others, 2018) - a public resource available for bioprospecting efforts. Technological advances are needed, however, for improving the completeness and reducing the contamination of genomes generated using these culture-independent approaches (Woyke and others, 2019). Another technique that is facilitating the analysis of genomes from uncultured microorganisms is metagenomic chromosome conformation capture (meta3C), which reveals physical contacts in different regions of the DNA present within a cell. When applied to microbial communities, this technique not only facilitates the assembly of genomes but also allows analysis of the tridimensional organization of these genomes (Marbouty and others, 2014). Improvements in cultivation techniques for marine microorganisms are also needed, in particular, in the context of the utilization of microbial marine genetic resources for industrial purposes.

The exponential growth of data generated by the different omics approaches represents a challenge, and new bioinformatic tools and platforms continue to be developed for the analysis and integration of omics data for a better understanding of biological systems (Dihazi and others, 2018; Rohart and others, 2017). One example is the open-source platform KBase (United States Department of Energy Systems Biology Knowledgebase).[296] This software and data platform enables collaborative analyses of multi-omics information, including (meta)genome assembly, annotation, transcriptomics and metabolic modelling (Arkin and others, 2018). The integration of metabolomics data, that is, the analysis of small biomolecules from organisms or microbial communities, can validate identified pathways, as well as link microbial community structure, dynamics, interactions and function (Baidoo and others, 2019). Another example of a multi-omics integration tool, focused on data exploration and data mining, is mixOmics (Rohart and others, 2017).[297]

6.2. Marine genetic resources and synthetic biology

Due to the exceptional biodiversity of marine organisms, marine genetic resources are a promising source of genes and gene clusters for the artificial redesign of organisms for industrial applications (Bloch and Tardieu-Guigues, 2014; Reen and others, 2015). Synthetic biology, in combination with enzyme and/or metabolic engineering, can greatly ease the development of high-performance strains for the production of chemicals, biomaterials and services. For instance, a synthetic biology approach can be used as an alternative to chemical synthesis for the production of marine natural products, when the extraction from the original source is not sustainable (Kiran and others, 2018).. Public health and ethical considerations are also important issues in synthetic biology, and the public perception on the safety of genetically modified organisms will also play a role in the translation of this technology into the industrial sector (Kiran and others, 2018).

[296] Available at http://kbase.us.
[297] Available at http://mixomics.org.

7. Marine genetic resources and the Sustainable Development Goals

Regardless of the scale of economic benefits associated with commercializing marine genetic resources, capacity-building gaps remain (Section 5), with substantial implications for achieving the United Nations Sustainable Development Goals.[286] Table 1 summarizes the relevance of MGRs to the Sustainable Development Goal targets that are most applicable.[298]

Table 1: Marine genetic resources and the Sustainable Development Goals

Selection of relevant Sustainable Development Goal Targets	**Relevance of marine genetic resources**
14.2 *By 2020, sustainably manage and protect marine and coastal ecosystems to avoid significant adverse impacts, including by strengthening their resilience, and take action for their restoration in order to achieve healthy and productive oceans* **14.5** *By 2020, conserve at least 10 per cent of coastal and marine areas, consistent with national and international law and based on the best available scientific information*	Ensure that protected areas take genetic diversity of populations into account, among other things, to promote resilience. Use MGRs as tools to understand biotic and abiotic interactions to help manage ecosystem services. Promote and focus exploitation on sustainably harvested and/or developed MNP.
14.a *Increase scientific knowledge, develop research capacity and transfer marine technology, taking into account the Intergovernmental Oceanographic Commission Criteria and Guidelines on the Transfer of Marine Technology, in order to improve ocean health and to enhance the contribution of marine biodiversity to the development of developing countries, in particular small island developing States and least developed countries* **9.5** *Enhance scientific research, upgrade the technological capabilities of industrial sectors in all countries, in particular developing countries, including, by 2030, encouraging innovation and substantially increasing the number of research and development workers per 1 million people and public and private research and*	Promote inclusive innovation and other mechanisms to ensure broader capacity for States to engage in the exploration and use of MGRs.

[298] See United Nations General Assembly resolution 71/313, annex.

development spending **9.b** *Support domestic technology development, research and innovation in developing countries, including by ensuring a conducive policy environment for, inter alia, industrial diversification and value addition to commodities* **17.6:** Enhance North-South, South-South and triangular regional and international cooperation on and access to science, technology and innovation and enhance knowledge sharing on mutually agreed terms, including through improved coordination among existing mechanisms, in particular at the United Nations level, and through a global technology facilitation mechanism.	
3.b *Support the research and development of vaccines and medicines for the communicable and noncommunicable diseases that primarily affect developing countries, provide access to affordable essential medicines and vaccines, in accordance with the Doha Declaration on the TRIPS Agreement and Public Health, which affirms the right of developing countries to use to the full the provisions in the Agreement on Trade-Related Aspects of Intellectual Property Rights regarding flexibilities to protect public health, and, in particular, provide access to medicines for all.*	Rich pipeline of marine-derived medicines in clinical trials, and potential of marine organisms as source of new antibiotics.

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Chapter 27
Marine Hydrates – a Potentially Emerging Issue

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Keynote points

- Marine hydrates (mainly methane hydrates) exist mainly on continental slopes where there are large quantities [in the ocean where] of methane gas [available], pressure is high enough, and temperature is low enough
- Concern has been expressed about the climatic risks from the sudden release of large amounts of methane from marine hydrates. However, this hypothesis is not widely supported at present and is not mentioned in the recent special report of the Intergovernmental Panel on Climate Change on the ocean and cryosphere in a changing climate.
- Areas of gas seepage in the deep sea associated with gas hydrates host a very rich biodiversity supported by chemosynthetic bacteria.
- Initial successes have recently been noted by China and Japan in producing methane from marine methane hydrates.

1. Introduction

The First World Ocean Assessment (WOA I) (United Nations, 2017c) did not contain detailed material on marine hydrates. The overall summary noted that they were among the deep-water deposits that had generated continuing interest, but were not mined at that time.

Chapter 21 of WOA I (United Nations, 2017a) reported that marine hydrates were a potential area for future offshore energy development and provided an estimate of the amount of marine hydrates and their carbon equivalent worldwide. While hydrates are potentially an immense store of hydrocarbons, Chapter 21 noted that methane production from hydrates had not been documented beyond small-scale field experiments and that its relevance to global gas supply was likely overshadowed by the increased development of onshore natural gas.

Chapter 35 of WOA I (United Nations, 2017b) noted that, because of the close relationship of gas seeps on continental margins to areas of resource exploration interest (oil and gas, methane hydrates), assessment of the nature of the rich associated biodiversity and its role in ecosystem function would be important before potential alterations and/or extractions occurred. This biodiversity is discussed in Chapter 7R of the present Assessment on hydrothermal vents and cold seeps.

The present Chapter aims to provide a fuller assessment of the origin and estimated abundance of marine hydrates, their potential as a source of energy and the risks to the earth's climate, slope stability and human society associated with them.

2. What are marine hydrates?

A marine hydrate is a crystalline solid composed of natural gas molecules retained within an ice-like cage of water molecules. The most common form of marine hydrate is methane hydrate, which has the chemical formula $(CH_4)_4(H_2O)_{23}$, or 1 mole of methane for every 5.75 moles of water, corresponding to 13.4 per cent methane by mass. (Maslin and others, 2010; Chou and others, 2000). Marine hydrates are often referred to as marine or methane clathrates from the Latin *clathri* meaning lattice, since the water molecules form a lattice within which the gas molecules are held. See the schematic drawing of a gas hydrate in Figure 1.

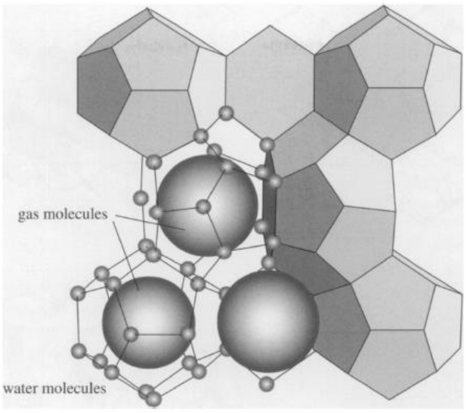


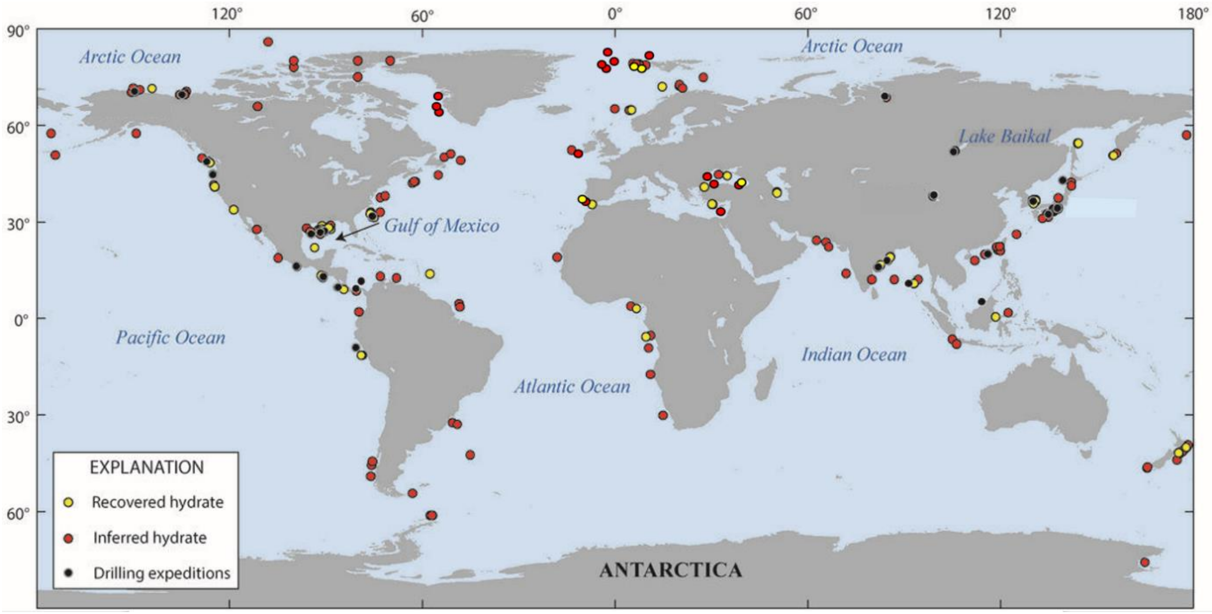
Figure 1. Typical structure of a gas hydrate with water molecules linked together to form a cage that traps gas molecules such as methane within. Source: Maslin and others, 2010.

Methane hydrates were first recognized in the late nineteenth century (Wróblewski, 1882; Villard, 1894). In the 1930s, they were identified in nature when their formation clogged natural gas pipelines in cold weather. In the 1950s, theoretical models for gas hydrates were developed and, in the 1960s, Russian scientists, such as Vasiliev and colleagues (Vasiliev and others, 1970) argued for the existence of substantial marine deposits around the world. This conclusion was confirmed in the early 1970s by the retrieval of samples of methane hydrates from the seabed in the Black Sea (Yefremova and Zhizhchenko, 1974). Since then, there have been similar retrievals all around the world (Figure 2), and countries such as Canada, China, Germany, India, Japan and the United States of America have established major hydrate research programmes (Sloan and Koh, 2007; Maslin and others, 2010; Song and others, 2014).

2.1. Location and scale of marine hydrates

Gas hydrates occur in areas of significant gas generation in which temperatures are sufficiently low and the pressure is sufficiently high to form and maintain them. The vast majority of gas hydrates occur as marine hydrates, while just over one per cent are located in permafrost soils (Ruppel, 2015). Most marine hydrates are formed by the accumulation of methane produced from the degradation of organic matter in buried sediments. Gas hydrate deposits (often several hundred metres thick) are embedded in sediments (Milkov and Sassen, 2002; Ruppel and Kessler, 2017). Marine hydrates are primarily driven by gas flowing through faults and channels in the sedimentary column and can be found exposed at the sea floor.

Marine hydrate distribution is driven by the combination of a gas source, water depth (usually more than 500m, but depends on gas composition) and temperature (geothermal gradient) to stabilize hydrates and the permeability of sediments. The most common way of inferring the presence of gas hydrates is by seismic investigation: the boundary between the gas hydrates and the underlying sediments containing free gas reflects forms with a negative impedance contrast, which mimics the sea floor (Bottom-Simulating Reflector) and can be interpreted to show the base of the gas hydrate stability zone. Sea floor samples can also be taken directly with cores or other sampling devices, but special steps need to be taken to maintain their stability as they are brought to the surface (Maslin and others, 2010). Seismic data indicate that methane hydrates are found in the sediments of the continental slope, with those in the Arctic Ocean at lesser depths, because of the lower temperature of the water column (Dillon and Max, 2012). In the middle of ocean basins, where biogenic generation of gas is low due to lack of organic material, and in marginal seas where sea floor pressure is lower, hydrates do not form. Hydrates also form in and below the terrestrial permafrost soils of Alaska and Siberia (Maslin and others, 2010). Figure 2 shows a recent map of known and inferred locations of methane hydrates.



Any boundaries or names shown, and the designations used, on this map do not imply official endorsement or acceptance by the United Nations.

Figure 2. Map showing locations where gas hydrate has been recovered, where gas hydrate is inferred to be present on the basis of seismic data, and where gas hydrate drilling expeditions have been completed in permafrost or deep marine environments, also leading to the recovery of gas hydrate. Source: Ruppel, 2018; amended to reflect Ryu and others, 2013, and Minshull and others, 2020.[299]

The presence of marine hydrates is constrained by the conditions in which they can persist. First, there needs to be a source of gas, generally methane of biogenic origin, derived from the decaying of organic material trapped in seabed sediments, that leads to the presence of methane in quantities greater than what is soluble in surrounding waters. Secondly, there has to be an appropriate combination of high pressure and low temperature at the sea floor. In Arctic waters, where the temperature is very low, the necessary pressure can, depending on the gas composition, be found at depths as shallow as 400 metres. In warmer waters, the depth required can be as great as 1,000 metres. Thirdly, there is a lower limit to the occurrence of marine hydrates: even at high pressures, the increase of temperature with depth below the sea floor (geothermal gradient) will set a limit to the stability of marine hydrates at around a depth of 1,600 metres (Kvenvolden and Lorenson, 2001; Maslin and others, 2010). The presence of methane hydrates can also act as a seal for free gas, thus retaining substantial amounts of methane in the sediments below them (Hornbach and others, 2004).

In 1988 and 1990, two independent estimates indicated a total global hydrate quantity of 21 ×

[299] The writing team is grateful to Mr Chibuzo Ahaneku Valeria for assistance in updating the map.

10^{15} cubic metres (MacDonald 1990; Kvenolden 1999), which became a consensus view. However, in 2011, based on an exhaustive review of other assessments and considering the lessons of many drilling programmes, an estimate was made of 3×10^{15} cubic metres of methane gas in place (calculated at standard temperature and pressure; Boswell and Collett, 2011). This is similar to the lower end of the range (1 - 5 to 15 - 20 $\times 10^{15}$ cubic metres) calculated by Milkov (2004), and more than 30 times smaller than the 1×10^{17} cubic metres estimated by Klauda and Sandler (2005). Some experts still support a larger estimate (Kvenvolden, 2012). The Milkov range equates to a range of 500-1,000 to 7,500-10,000 gigatons of carbon (Maslin and others, 2010). By way of comparison, the United States Geological Survey estimated in 2000 that the total reserves of all other fossil fuels contained 5,000 gigatons of carbon (USGSWEAT, 2000). Subsequent work has supported the call for further research into the global total of marine hydrates on the basis of a wide-ranging discussion at the Royal Society of London in 2010 (Day and Maslin, 2010).

3. Potential risks from marine methane hydrates

3.1. Risks in relation to the atmosphere

Methane is a powerful greenhouse gas with a heat-trapping potential over a century of 25 times that of carbon dioxide, as estimated by the Intergovernmental Panel on Climate Change (IPCC, 2013). Some more recent calculations suggest that this factor should be higher, by possibly as much as 25 per cent (Etminan and others, 2016). For the decade 2008–2017, global methane emissions were estimated at 0.572 gigatons of methane per year (Saunois and others, 2019). The temperature and pressure dependence of gas hydrate stability (mainly temperature; Figure 3) has led to a perception that global warming could cause catastrophic methane releases from gas hydrate reservoirs (the so-called “clathrate gun” hypothesis) (Henriet and Mienert, 1998; Haq, 1999). A similar mechanism has also been proposed as a way of explaining periods of rapid warming during the Quaternary Period (Kennett and others, 2000; Maslin and others, 2004). However, this hypothesis is not widely supported and empirical evidence is inconclusive (Sowers, 2006; O’Hara, 2008).

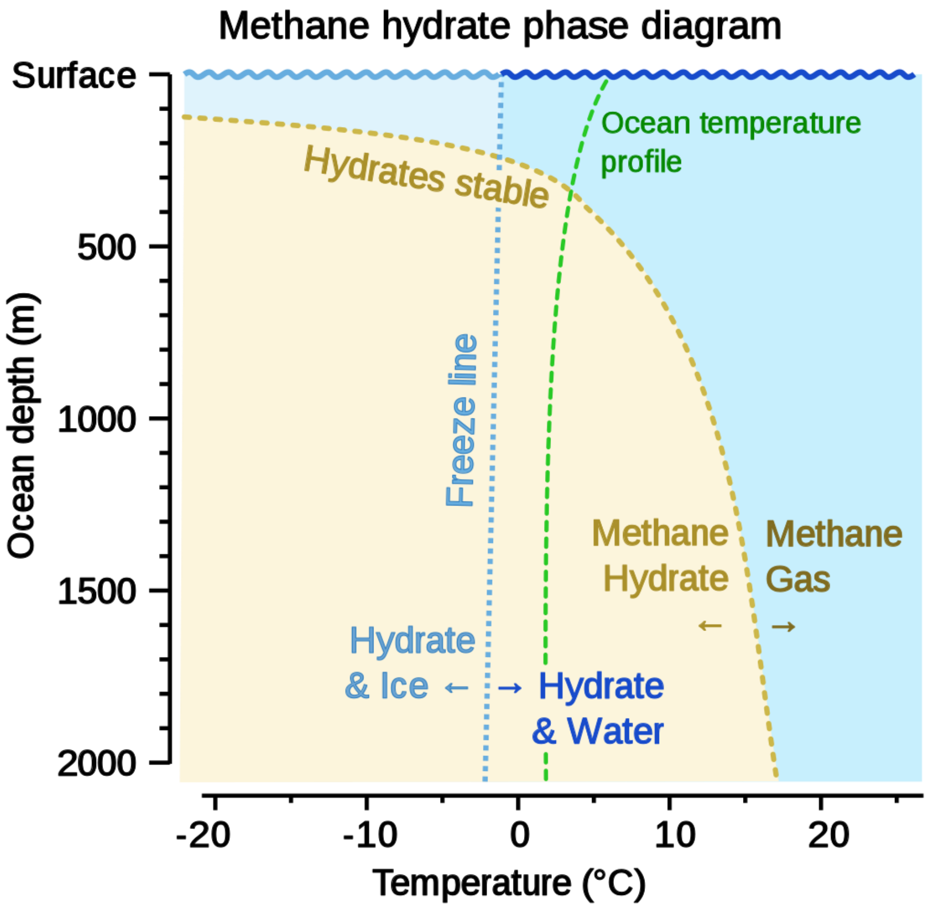


Figure 3: Methane hydrate stability diagram. (Source: https://commons.wikimedia.org/wiki/File:Undersea_methane_hydrate_phase_diagram.svg).

A recent thorough review of the interaction of climate change and methane hydrates concluded that there is no current evidence from observations that hydrate-derived methane is reaching the atmosphere or that the amounts that could potentially reach the atmosphere are significant enough to affect the overall methane budget. It went on to note that, in considering potential effects on methane flux to the atmosphere from the dissociation of marine methane hydrates, it is essential to consider the processes (sinks) that would intercept the methane before it reaches the atmosphere: in passing through sediment, methane may be broken down by anaerobic oxidation by microbes. In general, the conclusion is that methane from dissociated hydrates would not reach the atmosphere - it may dissolve in water in the sediment or in the water column, and it may be broken down further by microbial oxidation in the water column. However, more observational data and improved numerical models are needed to better characterize the climate-hydrate synergy in the future (Ruppel and Kessler, 2017).

Thus, the role of methane hydrates in contemporary and future climate change is unclear. Rather than with catastrophic, abrupt impacts, the release of methane from marine hydrates in response to rising ocean temperatures may have occurred gradually in the past and may occur over time scales of millenniums or longer (Archer, 2007; Archer and others, 2009).

However, the Arctic is warming at a faster rate than the rest of the globe (Larsen and others, 2014) and there is evidence of significant methane release into the Arctic Ocean, which may come from near-shore, submarine permafrost on the East Siberian Arctic Shelf (Shakhova and others, 2014). However, seasonal changes in the mixing of the water column appear to prevent methane from reaching the atmosphere during the summer (Yurganov and others, 2019).

The recent special report of the Intergovernmental Panel on Climate Change on the ocean and cryosphere in a changing climate (IPCC, 2019) does not mention marine hydrates, except to note (in its chapter 5), with low confidence, that rising bottom temperatures or shifting of warm currents on continental margins could increase dissociation of buried gas hydrates on margins, potentially intensifying anaerobic methane oxidation (which produces hydrogen sulphide) and expanding cover of methane-seep communities.

3.2. Risks in relation to seabed stability

When enclosed in sediments, and when the saturation is high enough, gas hydrates can act like cement, compacting and stabilizing the sea floor. However, if formed in deposits that are still unconsolidated, gas hydrate prevents the normal increase of compaction as the weight of the sediment increases. If destabilized by lower pressure and/or particularly by increased sea floor temperature, the gas hydrate can then dissociate. If this occurs, submarine slope failures may occur (Maslin and others, 2010). One particularly notable case where gas hydrates are thought to have been implicated is the Storegga slide off the middle of the west coast of Norway, dated to about 8,200 years ago. According to calculations, it had a volume of 3,000 km^3 and produced a tsunami that impacted Norway, the Faroe Islands (Denmark), and Scotland and northern England, United Kingdom of Great Britain and Northern Ireland, with a run-up of up to 20m. While an earthquake was probably the proximate cause, dissociation of marine hydrates appears to have contributed significantly to this occurrence (Bondevik and others, 2005; Bryn and others, 2005; Micallef and others, 2009). In general, the consensus at present seems to be that, while dissociation of marine hydrates can contribute to the scale, and thus to the impact, of major slope failures, there is usually a separate trigger in the form of an earthquake or extreme weather event (Tappin, 2010).

4. Marine hydrates as a source of energy

Methane, as natural gas, is a well-known source of energy. Several countries have undertaken large research programmes to investigate the possibilities of using marine hydrates as a source of natural gas. Because of their lack of terrestrial resources of natural gas, China and Japan have been among the States putting most effort into this exploration.

Japan established a research consortium, MH 21, in 2002 to explore and develop energy from marine hydrates in its seas. The consortium brought together the Japan Oil, Gas and Metals National Corporation, the National Institute of Advanced Industrial Science and Technology, and the Engineering Advancement Association of Japan. The work was planned in three phases. Phase one ran from 2002 to 2008, and included cooperation with a number of other States, including Canada, Germany, India and the United States of America. The main outcomes were improved knowledge of Japan's marine-hydrate resources and two successful onshore methane-hydrate production tests, yielding about 13,000 cubic metres of methane. Phase two, from 2008 to 2015, ran a successful offshore production test, developed an environmental impact assessment and completed an economic valuation and field verification. Phase three, whose major focus is establishing a technical platform for commercialization, is still in progress. The significance of the programme has increased since the Tōhoku earthquake in 2011 which has led to a policy of reducing planned dependence on nuclear energy (Oyama and Masutani, 2017).). A collaborative effort between the Department of Energy National Energy Technology Laboratory, Japan Oil, Gas and Metals National Corp., the U.S. Geological Survey and Petrotechnical Resources-Alaska, in cooperation with Prudhoe Bay unitholders successfully drilled a natural gas hydrate test well which showed two gas hydrate reservoirs suitable or future testing. The Prudhoe well struck reservoirs at about 2,300 feet and 2,770 feet below the surface. According to the USGS gas hydrate was found to be filling 65 percent to more than 80 percent of the spaces, or porosity, between the grains of sand and silt in the upper reservoir that comprise the rock formation. Japan is also collaborating with US to carry out production testing within the Prudhoe bay unit in fiscal 2021-22. The experience gained in this collaboration will help Japan in her endeavour towards pilot testing in fiscal 2027-2028.

Energy related exploration for methane hydrates has been extensive in the Gulf of Mexico. The Gulf of Mexico (GoM) gas hydrate joint industry project (JIP-I, 2005) was undertaken to develop technology and collect data to assist in the characterization of naturally occurring gas hydrate in the deep water of GoM. The primary goal of the program was to understand impact of hydrate exploitation on seafloor stability and climate change along with assessment of the potential of methane hydrate as a potential future energy resource. The JIP included participation from Chevron, ConocoPhillips, Total, Schlumberger, Halliburton, Reliance Industries, JOGMEC, US mineral management service in collaboration with USGS, Rice University and Georgia Institute of Technology. The investigation (Ruppel et al 2008) revealed that drilling for gas hydrate in fine grained sediments can be done safely without disruption of the seafloor expected due to hydrate dissociation. The results also brought to light the importance of focussed gas flow through localised permeability zones like sand body or fractures in forming hydrate deposits with very limited lateral extent. The results also emphasized on the relative less importance of seafloor like mounds and hydrates in deciding coring sites for larger reserves at deeper depths. Coring/ drilling/ wire line operations were carried at water depths >500 m and down to a depth of 200 to 459 mbsf. As part of the JIP –II (leg II: year 2009), the primary goal was to collect logging while drilling (LWD) data through expected gas hydrate-bearing sand reservoirs in seven wells at three locations in the GoM. The JIP-II findings suggest that high-saturation gas hydrate sands free of trapped free gases are safe for exploitation since they do not present drilling hazards. The 2009 Gulf of Mexico Gas Hydrate Joint Industry Project Leg II featured the collection of a comprehensive set of logging-while-drilling data through expected gas-hydrate-bearing sand reservoirs in seven wells at three locations in the Gulf of Mexico. The discovery of thick hydrate-bearing sands at Walker Ridge and Green Canyon validates the integrated geological and geophysical approach used in the pre-drill site selection process, and provides increased confidence in assessment of gas hydrate volumes in the Gulf of Mexico and other marine sedimentary basins.

The Indian National Gas Hydrate Program (NGHP) undertook the second expedition on-board DV Chikyu in March-July, 2015 in the deep waters of the Krishna-Godavari Basin in collaboration with JAMSTEC and USGS. The objectives of the expedition was to confirm the presence of sand bearing hydrate reservoirs identified from seismic data and to calculate the reserves from the hydrate saturation percentage and sand body dimensions. Pressure coring, LWD, wireline logging, formation testing operations were carried out as part of the program. The NGHP-02 expeditions (Collett et al, 2019) confirms the predicted slope-basin interconnected depositional model with sand rich channel-levee facies saturated wih methane hydrate in the Krishna-Godavari basin. The exceptionally detailed petrophysical information acquired through closely spaced LWD and bore hole in the area B of L1 block gas hydrate accumulation have provided one of the most complete three dimensional petrophysical based views of any known gas hydrate reservoir system in the world.

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Methane hydrate has been identified as a potential new gas source for China and the South China Sea is believed to contain some of the world's most promising deposits.
In China, a substantial number of institutions have undertaken investigations into the possibility of using marine hydrates as a source of energy, and particularly the technology that would be needed to recover them. The methods considered include depressurization and thermal stimulation. Research has also focused on the security of methane-hydrate-bearing sediments during gas production and the related environmental impact (Song and others, 2014). In 2017, the China Geological Survey conducted a first production test and recovered 309,000 cubic metres of methane from marine hydrates in the Shenhu area of the South China Sea between 10 May and 9 July 2017 (Li and others, 2018). China extracted 861,400 cubic metres of natural gas from methane hydrate, known as "flammable ice", during an one-month trial production in the South China Sea. This production follows China's first experimental gas extraction from methane hydrate in 2017, during which a total of 309,000 cubic metres of natural gas was produced in a 60-day period.

5. Key knowledge and capacity-building gaps

There are obvious gaps in our knowledge of the global distribution and size of deposits of methane hydrates. The map in Figure 2 shows that, for much of the world, assessments of the presence of gas hydrates are largely based on extrapolation rather than direct observation. Likewise, estimates of the global amounts of hydrate present are largely based on estimates of the volume of the methane hydrate stability zone, regardless of evidence of the presence or not of gas to form them. Also, abiogenic methane generation by ocean crust serpentinization, a major process in the ocean, has been largely ignored. A recent review of gas hydrates in Europe has been published (Minshull and others, 2020) but there is still no updated review at the global level.

There are also major gaps in our understanding of how methane hydrates will behave in changing circumstances, especially changes of ocean temperature, the way in which methane hydrates may dissociate and the way in which any methane released will then behave, and its impacts on climate and slope stability. Futhermore, it remains to be determine whether the oxidation of methane venting from the seafloor, presumably some sourced from dissociating hydrates, contributes significantly to ocean acidification. These knowledge gaps have the possibility of being very significant in relation to the release of oceanic methane into the atmosphere and its consequent function as a greenhouse gas, even though the predominant opinion is that this possibility is limited (see section 4 above).

Capacities are clearly being developed in China, Japan and elsewhere to access methane stored as marine hydrates. At present, these are at the experimental/testing stage but could become important for States with limited access to natural gas.

6. Outlook

The outlook therefore depends very much on demand for natural gas in the context of reducing consumption of coal and other fossil fuels, on the success of experiments in accessing methane hydrates, and on the further identification of locations of significant methane hydrate deposits that may justify their exploitation.

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Chapter 28
Cumulative Effects

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Keynote points

- Increasing pressures on marine environments from multiple sources are resulting in biodiversity loss, habitat damage and fragmentation and disease.
- Effective implementation of ecosystem-based management requires an appreciation of how, and to what extent, human activities and natural events interact and affect different ecosystem components and their functioning. It also requires the identification of solutions to prevent and/or mitigate the pressures being caused by these interactions.
- Over the past two decades, many frameworks for assessing these interactions, known as cumulative effects, have been developed. These have used differing approaches and terminologies, and have been applied at differing scales.
- Although approaches vary, cumulative effect assessments (CEAs), conducted to date, have mostly involved three main steps: (i) collation of information on the intensity and footprint of activities that may be affecting marine ecosystems; (ii) identification of the responses of ecosystem components; and (iii) identification of management measures that could be applied in response.
- Despite their increase in use, assessments focused on particular regions, areas or values that follow the same general steps outlined above, are largely lacking from areas outside Europe and North America.
- This geographical bias in the implementation of CEAs highlights clear knowledge and capacity gaps, and the need for the development of approaches that: (i) can be implemented in regions where data are sparse; (ii) are easily implementable; and (iii) produce outputs that can be readily understood and translatable to decision-making processes, particularly in developing countries.

1. Introduction

The marine environment is currently subject to many pressures, many of which are derived from human activities. These include climate change, extraction of resources, pollution (from land and marine sources) and invasive species, resulting in biodiversity loss, habitat damage and fragmentation and disease (e.g. Evans and others, 2017). Ecosystem-based management aims to balance human activities with environmental stewardship to maintain ecosystem properties, functions and services.[300] This requires an appreciation of how and to what extent human activities and natural events interact and affect ecosystem components and their functioning. It also requires the identification of solutions to prevent and mitigate the pressures being caused by these interactions (Halpern and others, 2008; Levin and others,

[300] See also Chapter 29 of the present Assessment for an overview of assessments associated with marine spatial planning, and Chapter 30 for an overview of ecosystem-based management approaches.

2009, Ban and others, 2010; Curtin and Prellezo, 2010). These interactions are termed cumulative impacts or cumulative effects.

The terms cumulative impacts and cumulative effects are often used interchangeably to describe how pressures affect ecosystems. The use of standardized language is key to the transfer of knowledge, assessment approaches and expertise across management boundaries, stakeholders and organizations. A preference for the use of the term "cumulative effects" has been identified, noting that impacts are hypothesized and have either not been directly observed, or attributed (Murray and others, 2015). For consistency, the term "cumulative effects" is used in the present Chapter. There is as yet no universally accepted definition of cumulative effects and impacts, with definitions varying in literature, depending on what might be being assessed, and the context within which the assessment is being undertaken (e.g. Anthony, 2016; Spaling and Smit, 1993; Hegmann and others, 1999; Halpern and others, 2008; Johnson, 2016; Uthicke and others, 2016). Here we follow the premise that effects can be defined as a change to the environment, including its human components, while impacts represent the consequences of such change (Johnson, 2016).

Cumulative effects can be of four general types: additive, synergistic, antagonistic (compensatory), and masking (Sonntag and others, 1987; Hegmann and others, 1999; Crain and others, 2008; Halpern and others, 2008). Additive effects are incremental additions to the pressures caused by an activity, where each increment adds to previous increments over time. Synergistic effects, also referred to as amplifying or exponential effects, magnify the consequence of individual pressures to produce a joint consequence that is greater than their additive effect. Antagonistic or compensatory effects produce a joint consequence that is less than additive. Masking effects produce essentially the same consequence for the ecosystem or social component as would occur with exposure to one of the pressures alone. Impacts that can be considered as cumulative might result from a single activity repeatedly producing a single pressure, a single activity producing multiple pressures, multiple activities producing a single pressure, or multiple activities producing multiple pressures through time (Foley and others, 2017).

The topic of assessments of cumulative effects was not included in the First World Ocean Assessment (WOA I) (United Nations, 2017b), although the range of factors affecting ecosystem services were considered in each of its regional chapters and a summary of pressures affecting the marine environment was provided in its Chapter 54 (United Nations, 2017a). However, Chapter 54 did not attempt to undertake an assessment of the cumulative effects of those pressures, nor did it identify the frameworks within which such assessments could be conducted. The present Chapter, therefore, provides an overview of the key elements of assessments of cumulative effects, and provides an overview of approaches and their outcomes, including several regional examples of approaches in detail. The aim of this overview is to provide a baseline of the diversity of approaches and their use that can be used for establishing changes in approaches and applications in future global assessments.

2. Cumulative effects assessments

Over the past two decades, many frameworks for assessing cumulative effects on the environment have been developed using different approaches and terminologies (Stelzenmüller and others, 2018). Similarly, their focus has varied, with some taking a whole-of-system approach, where all existing stressors and their effects on broad components of the marine environment are included in the assessment. Others have focused on single stressors and single species or habitats (Korpinen and others, 2012; Marcotte and others, 2015; Coll and others, 2016). Of 154 studies reviewed by Stelzenmüller and others (2018), several key conclusions regarding the various approaches utilized were identified, including that (i) expert knowledge and qualitative data are sporadically or moderately used across assessments; (ii) the use of Geographic Information Systems (GIS) is almost a prerequisite for assessment; (iii) large gaps exist in addressing uncertainty throughout components of each assessment; and (iv) novel integrative methods, such as a combination of qualitative data and qualitative modelling to assess ecosystem state and pressures, were increasingly being developed for use in assessments.

Although approaches might vary, several common elements have been identified that should be incorporated into cumulative effect assessments (CEAs) aimed at advising management and planning (Halpern and others, 2008; Kappel and others, 2012; ICES, 2019). These elements can be broadly categorized in terms of information on the activities causing pressures that may be affecting marine ecosystems, information on measures that might be implemented to manage those activities and therefore pressures, and the responses of ecosystem components, which in turn depend on their resistance and recovery potential from the pressures being exerted.

The process used to date for undertaking a CEA is fundamentally based on a mapping process. This involves considering the spatial and temporal footprint of one or more pressures (including the frequency of that activity and associated pressures as a measure of intensity) in relation to those components of the marine ecosystem that are being or might be impacted (Elliott and others, 2020). It further considers the vulnerability of or risk to those ecosystem components (including their sensitivity), whilst taking into account any management measures that might be in place. This allows for the identification of residual pressures remaining after accounting for management, and the calculation of a measure of the anticipated cumulative effect (Halpern and others, 2008; Kappel and others, 2012; ICES, 2019). These various elements of information are identified in Figure 1. The connectivity and heterogeneity of ecosystem components, functions and processes, and the uncertainty in biophysical processes, together with varying levels of intensity of activities affecting the environment, determine the complexity of CEAs.

The key functional steps of a CEA are:

(i) Define the values of the marine system being assessed

This first step of an assessment identifies the values of importance in the location of the assessment and their spatio-temporal distribution within the assessment area. Values can be ecological, social, economic or cultural in nature.

(ii) Define the activities placing pressures on the marine system (stressors)

Identifying a tangible expression of the potential cumulative impacts involves confirmation that the system value and the pressure do indeed interact. This requires that disturbances and activities potentially placing pressures on the marine system in the area of the assessment be identified, and the nature of pressure (e.g. direct, indirect, continuous, pulse) and their spatio-temporal distribution be mapped and/or quantified. This is a key factor within CEAs. Many activities or disturbances concentrated in a small area over a short time can result in pressures or stressors that accumulate due to a crowding effect. An area may be resilient against some level of disturbance, but if that level is exceeded faster than the natural recovery rate, then the disturbance could exceed an ecological or societal threshold for a valued component (Johnson, 2016). Further, the effects of pressures can disperse from the activity area, resulting in a lagged effect on areas outside the immediate footprint of the activity. As a result, the extent, dispersal, frequency and persistence of pressures associated with an activity need to be accounted for when assessing exposure to risk (Borgwardt and others, 2019). In addition, all potential stressors within and adjacent to the area of the assessment should be considered in order to identify potential emerging risks.

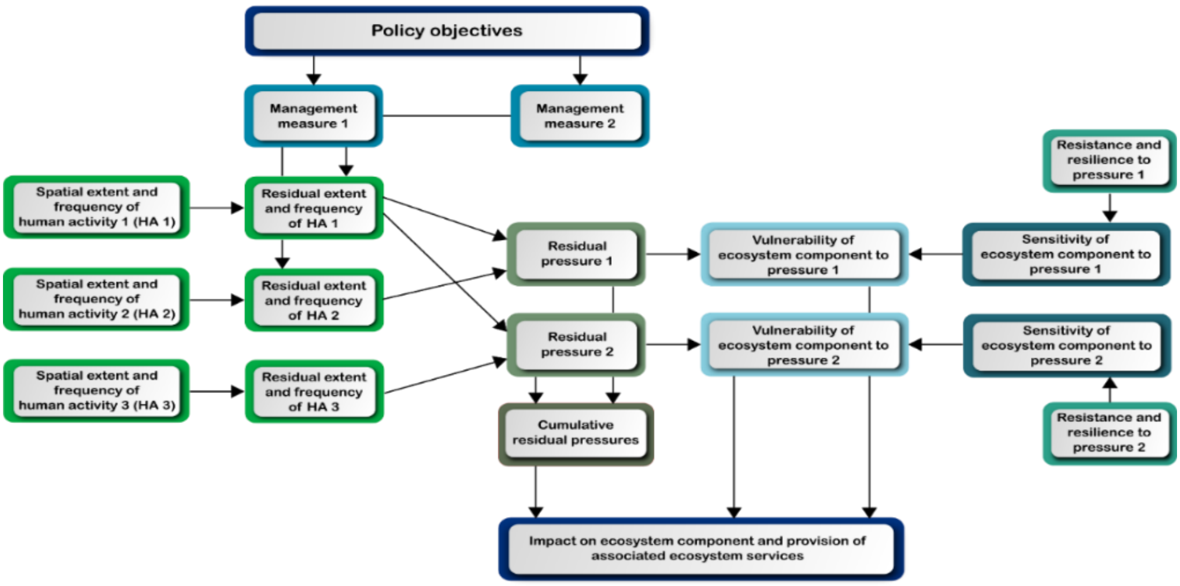

Figure 1. The elements of a cumulative effect assessment with a focus on quantifying effects associated with human activities on ecosystems. Adapted from ICES (2019).

There are many approaches that can be used to map and/or quantify the spatial and temporal extent of both values and stressors, such as GIS and spatial interpolation and dynamic models (e.g. Andersen and others, 2013; Robinson and others, 2013; Borgwardt and others, 2019; Dunstan and others, 2019). Because of the varying nature of values and stressors and their measurement, the data or information that might be available to contribute to the mapping process, it is unlikely that a single approach will be appropriate in all circumstances. Rather, the approach undertaken should be appropriate for the data available (including its complexity), capture the spatio-temporal components of the data appropriately, and address any uncertainties, biases or assumptions associated with those data.

(iii) Conceptually link pressures and values

Conceptual approaches (e.g. qualitative or quantitative models identifying impact pathways) can then be used to link the values identified and the various potential activities and stressors in the assessment area (e.g. Dambacher and others, 2009; Anthony and others, 2013). How components and processes in the marine environment are related, how natural and anthropogenic pressures can affect the system, and knowledge gaps and key uncertainties in the system are identified. Ideally, consideration of the nature of potential interactions between pressures caused by multiple stressors is included, recognizing that interactions may be nonlinear and that they may be synergistic, antagonistic or masking in nature (see section1 above). Understanding how values and pressures interact might be carried out initially using qualitative models that allow for the identification of the direction, nature and extent of interactions. Predictions of change can then be estimated through probabilistic modelling (e.g. Anthony and others, 2013). Undertaking such an approach allows for the degree of effect (i.e. severity) being placed on the value(s) to be determined, and therefore those interactions that are most important to focus efforts on in better understanding, mapping and quantifyingeffects.

(iv) Assess risk and uncertainty

Once the pathways for the effects of pressures on values are understood, the scale of the effect on the value can be quantified, so that the level of exposure resulting from different stressors are integrated across their individual spatial extents - their "zones of influence" (e.g. Figure 2; Anthony and others, 2013). The risk to the value associated with impacts caused by the pressure and associated uncertainty can then be estimated, while noting that, often, the limited understanding of both the value and the pressures is, in itself, also a source of uncertainty. For example, often the spatial and temporal patterns of pressures are not fully known nor are the responses of particular values to pressures that might vary through space and time (Stock and Micheli 2016). Identification of sources of uncertainty and their influence on assessment results can be challenging in itself, so appropriate sensitivity analyses that explore the influence of all stressors and their interactions should be carried out (Stock and Micheli 2016). Estimation of risk needs to be capable of capturing the complexity of the system components, the interactions with the activities and the uncertainties associated, and then incorporate the relevant spatial and temporal distributions of any consequences, both positive and negative in nature (e.g. Gregory and others, 2012; Stock and Micheli, 2016).

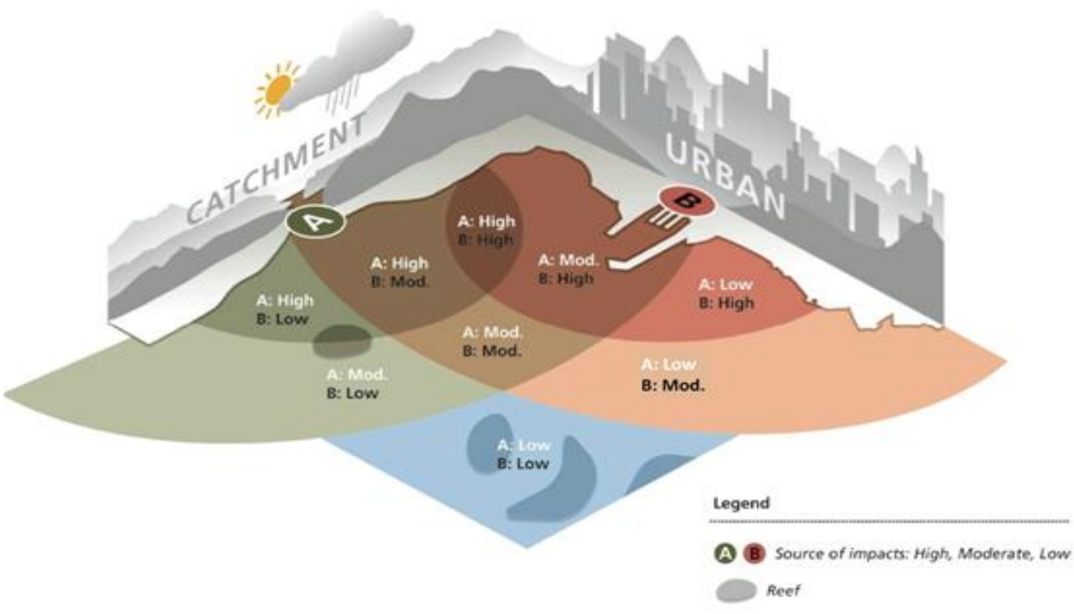

Figure 2. A conceptual model illustrating zones of influence for two examples of point sources: (A) river run-off from catchments and (B) urban or port development. The probabilities of change for each ecosystem value and the amount of ecosystem value potentially impacted (with those probabilities accounting for uncertainties) are calculated within each zone of influence. From Anthony and others (2013).

(v) Validation

Finally, where possible, the networks of interactions, maps of risk and cumulative effects should be verified observationally (though, in practice, this has occurred relatively rarely; see Halpern and Fujita (2013)). In order to facilitate such validation, risk assessments need to be reported in such a way that they can be observable; that is, measured and mapped in the field.

One framework that is useful for developing quantitative models for estimating effects, and that is also useful for the purpose of communication with policy makers and other decision makers, is the Driver-Pressure-State-Impact-Response (DPSIR) framework (Smeets and Weterings, 1999; Elliott and others, 2017). This framework is based on the concept that drivers (underlying natural and human-caused forces) exert pressures (immediate factors) on the environment that lead to changes in the state of the environment. To be operational, a CEA should also explicitly include an evaluation of the effectiveness of management measures (Cormier and others, 2018; Stelzenmüller and others, 2018), particularly in, first, quantifying the effects of any management measures on pressures and their resulting impacts and, second, identifying how management measures might be modified to further reduce those pressures and resulting impacts. As yet, however, most CEAs lack linkages between an assessment of cumulative effects and the management measures that might regulate the activities causing the respective pressures (Hayes and others, 2015; Cormier and others, 2017). As a result, many CEAs provide limited linkages between planning processes and regulatory frameworks that might identify where a precautionary approach might need to be implemented or improvements to management process are needed (ICES 2019). Further, most widely accepted CEA methods consider that the provision of ecosystem services and estimates of sociocultural effects are outside the remit of a CEA (ICES 2019).

3. Regional applications of CEAs on the marine environment - distribution and approaches

Implementation of CEAs within marine systems has increased rapidly over the last couple of decades, with applications in regional marine assessments, planning and regulatory processes (Halpern and others, 2015; ICES, 2019). However, despite their increased use, assessments following the same general steps outlined in Section B are largely lacking from areas outside Europe and North America (Korpinen and Andersen, 2016; Table 1; Figure 3).

Recently, Korpinen and Andersen (2016) undertook a review of CEAs, in an effort to provide an overview of the methods and practices associated with CEAs in the marine environment. In particular, the review aimed to determine if different estimate variables used in CEAs were comparable, and whether validation of the CEAs was reliable. Similar methodological approaches were identified in half of the studies reviewed, with those studies based on the method of Halpern and others (2008), although relatively few addressed the major uncertainties with the use of such approaches as outlined in Halpern and Fujita (2013). The review identified several key areas in which CEAs needed to be advanced, including validating or benchmarking pressures, inclusion of accurate measures of temporal components to human activities (many assumed that activities were long lasting and overlapped in time), and accounting for historical impacts that have already modified the marine environment.

Building on this review, we have undertaken a review of literature published publicly in the peer review literature since 2016 (by searching Scopus for the keywords “cumulative effect” and “cumulative impact”) to provide an updated summary of assessments. In so doing, we provide an overview of each approach and the outputs from each CEA (Table 1).

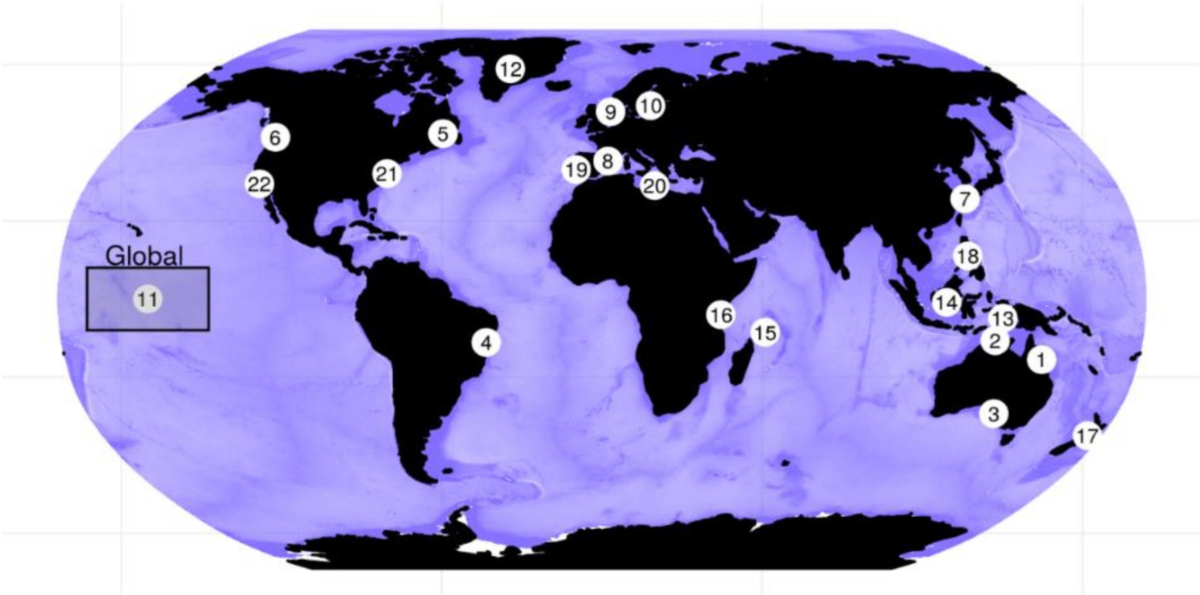

Figure 3. Global distribution of cumulative impact assessments implemented in marine ecosystems and published 2016-2019, providing an update to those detailed in Korpinen and Andersen (2016). Numbers align with the summaries provided in Table 1.

Key insights gained from an updated review are that:

- Assessment approaches need to be contextually based. So, while approaches should include the functional steps outlined here, development of approaches to CEAs need to consider the scale (and resolution) at which the assessment is being conducted, the values being assessed, the data available for undertaking a CEA, the uncertainties associated with those data, the specific management objectives in undertaking the assessment and the format of outputs produced, particularly their suitability for informing planning and/or management.
- Assessments need to incorporate the extent, spatial and temporal variability in data and associated uncertainty (including that associated with data quality), not only to ensure robust outputs from CEAs, but also to focus where knowledge gaps might lie, and where future efforts should be placed for improving assessments and reducing uncertainties.
- Most CEAs lack experimentally or observation-based measures of sensitivity of ecosystem components to the effects of stressors, so the outputs of assessments should be verified observationally.
- Many assessments continue to provide single point assessments or temporal averages of cumulative effects, rather than repeated temporal assessments that

might provide information on changes in cumulative effects through time (i.e. trends).

- In order to ensure uptake into the decision-making processes, CEAs should incorporate linkages between an assessment of cumulative effects and the management measures that might regulate the activities causing the respective pressures. Many assessments continue to lack these linkages. In association, few assessments consider evaluation of the implementation of management measures on activities causing the respective pressures and cumulative effects on the environment.
- Assessments linked to management and regulatory processes, in most cases, consider only the effects of activities within the area under regulation and do not account for the dispersal of effects beyond the area being assessed (i.e. regional and/or ecosystem-scale effects). It is, therefore, important that spatial separation of activity location and pressure effect is considered (see also Stephenson and others, 2019).
- Clear communication of risk and the uncertainties associated with estimates of risk is needed for maximal uptake of CEAs into decision-making processes. Assessments need explicitly to describe the causes and consequences of deleterious effects to help managers, stakeholders, scientists and engineers understand the causal pathways of risk (see also Nicol and others, 2019).
- Implementation of CEAs is geographically biased to Europe and North America, although it is encouraging to see publications of assessments from areas in which no assessments had been identified in Korpinen and Andersen (2016). The jurisdictions of many developing economies are still yet to see any level of formal assessment beyond the general coverage of global analyses such as those by Halpern and others (2015). This highlights clear capacity gaps and the need for the development of approaches that (i) can be implemented in regions where data is lacking; (ii) can incorporate non-traditional data sources such as community observations (e.g. citizen science), and traditional knowledge; (iii) are easily implementable (both in terms of skills and time); (iv) can be readily updated as new information or pressures are realized; and (v) produce outputs that can be readily understood and translatable to decision-making processes.

Detailing the many approaches to CEA implemented in the marine environment globally is beyond the scope of the present Chapter. Here we provide some further detail on examples of varying frameworks implemented in assessing cumulative effects from the Southern and Northern Hemisphere, and provide some further insights into developments in areas where CEAs have been implemented to a lesser degree.

3.1. Great Barrier Reef, Australia

The Great Barrier Reef (GBR) has been identified as being under a range of pressures that vary across local to global scales, including those associated with climate change, (cyclonic) storms and flooding, nutrient and sediment run-off from land use, pollutants (including pesticides, marine debris, plastics, nano-particles, noise and light), human uses of the marine environment and disease (Uthicke and others, 2016). Overall reef health has been identified as declining for some time (De'ath and others, 2012) and mass bleaching events that occurred in 2016, 2017 and 2020 have reduced its health even further (Smith and Spillman, 2020). Some sources have concluded that the northern portion of the GBR has been permanently altered as a result of these pressures (Hughes and others, 2017).

Development of CEAs for the GBR has been an iterative process. The first formal CEA, conducted in 2012, used a combined cumulative impact and structured decision-making (CISDM) framework that used both qualitative and probabilistic models to consider the influence of a subset of cumulative stressors (nutrients, turbidity and sedimentation, habitat erosion and climate change) on coral reefs and seagrass ecosystems (Anthony and others, 2013). The framework incorporated a decision-making process that allowed for exploration of hypothetical management interventions, consequences and trade-offs.

This CISDM approach has been further developed to incorporate statistical, ecotoxicological, conceptual, semi-quantitative and quantitative mechanistic models, and structured decision analyses to assess cumulative effects on coral reef environments (Uthicke and others, 2016). Outputs from the framework include risk and exposure maps, and the assessment of pressure and value thresholds for specific locations and ecological communities of interest. The application of the framework resulted in the recognition that (i) linear changes are rare in ecosystems (i.e. change is not necessarily additive); (ii) ecological thresholds and responses to multiple pressures are likely to change over ecologically relevant time frames, through acclimation (which can ameliorate effects) or dynamically compounding effects (that amplify responses); and (iii) predictions without experimental or field confirmation of responses may lead to false conclusions and suboptimal investment in management processes.

The approach of Uthicke and others (2016) goes beyond simply spatially layering the distribution of stressors and assuming that the cumulative effects are linearly additive in nature, as it allows for mechanistic understanding of non-linear interactions (through the development of full response curves that take into account antagonistic and synergistic interactions) with management implications. Application of this CEA framework (the Reef 2050 Cumulative Impact Management Policy; CIMP[301]), with a proposed set of guidelines for its implementation (Dunstan and others 2019), has only recently occurred. [302]. The involvement of the Great Barrier Reef Marine Park Authority (the management agency responsible for the GBR) in the development of the CIMP has seen it underwritten into all future planning and approval processes at the regional level, as well as at the level of specific development applications. This first (illustrative) application of the guidelines linked data collected on shallow coral reef systems with spatial data on the distribution of pressures through structural equation models, indicating a strong context dependence for the cumulative effects (Dunstan and others, 2019). This highlighted the role of long-term monitoring in informing assessments when evaluating cumulative effects.

3.2. North Sea

The North Sea is one of the most impacted marine ecosystems in the world ocean (Halpern and others, 2008), with multiple anthropogenic stressors associated with global and regional

[301] http://www.gbrmpa.gov.au/our-work/reef-strategies/Reef-2050-policies#:~:text=The%20Reef%202050%20Cumulative%20Impact%20Management%20Policy%20and%20Net%20Benefit,to%20guide%20their%20practical%20application.

[302] http://hdl.handle.net/11017/3389

developments, including coastal development and habitat loss, eutrophication, pollution and fishing, affecting it (Emeis and others, 2015). In addition, the North Sea is a climate change hotspot (Burrows and others, 2011; Holt and others, 2012) with dramatic changes in food web structure and functioning reported in association with trends in sea level, ocean temperatures and acidification (Reid and others, 2001; Beaugrand, 2003; Weijerman and others, 2005; McQuatters-Gollop and others, 2007; Kenny and others, 2009; Lynam and others, 2017). In particular, the fish community of the North Sea has been strongly impacted by fishing and climate change, with rapid and substantial changes reported since 2000 (Engelhard and others, 2014; Fock and others, 2014; Sguotti and others, 2016; Frelat and others, 2017).

Assessments investigating effects of human activities on ecosystem components of the North Sea have largely comprised modelling studies focused on the effect of different demersal fishing practices, and derived aggregated measures of benthic disturbance by such practices (Stelzenmüller and others, 2015; Rijnsdorp and others, 2016; Hiddink and others, 2019). Only within the last decade has there been an increasing focus on assessing the combined effect of human activities other than fishing on the marine environment. (Stelzenmüller and others, 2010; Fock, 2011; Foden and others, 2011). This is not only due to limitations associated with data that might be available for CEAs, but also the complex socio-ecological interlinkages in the North Sea region, in no small part due to the multinational jurisdictions.

More recently, a greater emphasis has been placed on the development of approaches that not only allow for the assessment of the cumulative effects of human activities, but also assess those effects at considerably larger spatial scales than previously considered (Knights and others, 2015; Piet and others, 2019) in order to produce more targeted advice for management (Piet and others, 2017; Cormier and others, 2018). Approaches have included exposure-effect risk assessments based on sector–pressure–ecological component linkage matrices (Knights and others, 2015; Piet and others, 2019) and spatial mapping of activities/stressors and ecosystem components, combined with linkage pathways determined by expert elicitation (Andersen and others, 2013), similar to that described by Halpern and others (2008). Results from such assessment have identified key areas where cumulative effects are greatest, and the stressors associated. As yet, however, a North Sea-wide assessment has not been undertaken.

An emerging approach to assessing cumulative effects within the region, particularly in the context of management or regulation, comprises a framework which combines the conceptual structuring of cause-effect pathways with a quantitative assessment of effects (Cormier and others, 2018). This approach highlights the need to assess the effectiveness of management measures in reducing human pressures in order to understand the prevailing cumulative pressure load on distinct ecosystem components.

3.3. Other regions

As identified by the review presented here, few CEAs have been conducted outside North America and Europe (Table 1). Examples of CEAs conducted elsewhere include those in the Asian region, where an expert based step-wise decision logic process was used to score the intensity of ten pressures (including urbanization; coastal, anchorage and port infrastructure; sewage discharge; aquaculture; a gas platform; a saltern; and tourism) on Jiaozhou Bay in the

People's Republic of China (Wu and others, 2016). The weighted outputs were then combined with distance measures calculated using GIS software to produce maps that represented the sum of the cumulative effects. In Hong Kong, China, a similar approach was taken to look at the potential implications for the survivorship of the local population of Indo-Pacific humpback dolphins (*Sousa chinensis*) (Marcotte and others, 2015). In this case, however, the weighting was done in terms of the severity of each effect on dolphin survival.

Beyond these explicit examples of CEAs, other related or precursor assessments exist for Asian and Latin American locations, highlighting that a wider number of CEAs could be undertaken in these regions. For example, the Integrated Fisheries Risk Analysis Method for Ecosystems (IFRAME) approach developed by Zhang and others (2011), used to look at the performance of fisheries management strategies in terms of the goals of an ecosystem approach to management, could easily be extended beyond fisheries to other human activities. This approach explicitly considers aspects of the local fish stocks, habitats, biodiversity measures and fisheries economic indicators. Importantly, it considers the kinds of pressures fisheries place on ecosystems. It is at this point that the approach could be extended to other activities as a means of creating a CEA. Dynamic process-based models explicitly bringing together multiple human activities, including fisheries, aquaculture, urban development, marine transport, mining, forestry, agriculture and tourism, to explore the implications for the future management, development or expansion of sustainable aquaculture in Patagonian Chile could also be used as a basis for CEA (Steven and others, 2019).

4. Outlook

Most CEAs undertaken to date have focused on assessing activities and effects that have already occurred in the marine environment. There is a growing enthusiasm to move to assessments that allow foresighting/forecasting and prediction, so as to inform future planning of activities or adaptive and anticipatory management approaches (e.g. Lukic and others, 2018; see also Chapter 29 of the present assessment on marine spatial planning). The global economic contribution by marine industries is projected to double by 2030 (OECD, 2016), reaching as much as 3 trillion United States dollars, with exponential (or similar) increases in their footprint and interactions (McCauley and others, 2015; Plagányi and Fulton, 2017). Avoiding undesirable outcomes and a degradation in the values of marine systems will require informative CEAs that feed into adaptive management and evidence-based decision making. Dynamic research languages, methods and models spanning across disciplines will be required in order to achieve this; the development of which is not straightforward and will require substantial effort, particularly in forecasting each stressor into the future in a spatially and temporally explicit way, and accounting for the changing nature of interactions among the stressors. Although a unified and broadly applicable forward-looking CEA methodology is probably unfeasible at least in the near future, due to the inherent difficulties in addressing key uncertainties in future projections. The improvement of guidelines and best practices to facilitate such CEA approaches will provide a useful step forward in this regard.

Whether forward or rearward looking, there is growing agreement that the methods associated with CEAs need to expand from consideration of the multiple effects of single development activities or the accumulation of effects of multiple similar activities within a single industrial sector, to the combined effects of all pressures on marine ecosystems. Modelling frameworks such as those detailed above have identified that the responses of marine systems are often non-linear and synergistic and antagonistic effects play important roles in shaping the environment (Crain and others, 2008; Hunsicker and others, 2016; Uthicke and others, 2016). There is a need for improving capacity in the use of conceptual and statistical modelling approaches that allow for mechanistic understanding of non-linear interactions between stressors, non-additive effects on marine environment, and responses of the marine environment as a result. Again, it is recognized that the development of such approaches is not straightforward and will require substantial effort. Improvement of guidelines and best practices to facilitate such CEA approaches and commitment to building capacity in their application and use will provide a useful step forward in this regard.

Meta-analyses (e.g. Crain and others, 2008) are helping researchers to understand the prevalence of additive, synergistic and antagonistic interactions, while statistical approaches are helping to identify the presence and nature of non-additive interactions (e.g. Teichert and others, 2016). In addition, there have been significant advances in the handling of uncertainty in assessments (e.g. Rochet and others, 2010; Foster and others, 2014; Gissi and others, 2017) and some progress in defining thresholds and reference points to use in assessments, though these can be somewhat subjective as they are defined by societal objectives (e.g. Samhouri and Levin, 2012; Samhouri and others, 2012; Large and others, 2015; Samhouri and others, 2017). Incorporation of uncertainty not only allows for more robust interpretation of the outputs of assessments, it also facilitates an adaptive management process and identifies research priorities to fill knowledge gaps for continuing improvement to management.

Ultimately, to increase the geographical spread of CEA, future effort has to address the development of approaches that can be applied, particularly in data-poor situations and that produce outputs that can be readily understood and translated into decision-making processes (Stelzenmüller and others, 2020). This would better equip decision makers to deal with the dynamic nature of rapidly changing marine ecosystems, where the mixes and relative dominance of the different pressures will change through time and space.

Table 1. Summary of cumulative effects assessments published in the literature 2016–2019 by country/region. Map numbers are presented in Figure 3.

Map No.	Country	Region	Assessment approaches	Assessment objectives	Assessment results	References
1	Australia	South Pacific Ocean	Qualitative conceptual models; Bayes nets; Statistical models; Mechanistic models; Index calculation; Literature reviews	Map scientific understanding of coral habitats and identify gaps; Identify limitations of extant assessment methods; Assess the impact of prawn trawling; Identify impacts affecting reef habitats and communities; Assess response of coral to ocean warming and sedimentation; Identify under climate change scenarios the cumulative effects of multiple range shifting species and evaluate management responses	Overall the Great Barrier Reef is continuing to decline in state; Considerations for conducting CEAs (including uncertainties and biases) and recommendations for advancing CEAs, including developing assessment frameworks for application across a range of activities and area; Identifying knowledge gaps; Redistribution of multiple species can induce trophic cascades and negatively impact ecosystem dynamics and productivity	Grech and others (2011); Marzloff and others (2016); Uthicke and others (2016); Bessell-Browne and others (2017); Richards and Day (2018); Dunstan and others (2019)
2	Australia	South Pacific Ocean, Indian Ocean	Spatial mapping	Evaluate the cumulative patterns in sea turtle bycatch	A bycatch “hotspot” was identified in the Gulf of Carpentaria where multiple species were impacted by commercial fisheries	Riskas and others (2016)
3	Australia	Indian Ocean	Spatial mapping	Assess cumulative effects on marine environment while capturing uncertainty in expert	Assessing experts’ uncertainty makes CEA more transparent and robust for management implementation	Jones and others (2018)

				elicitation		
4	Brazil	South Atlantic Ocean	Spatial mapping; Index calculation	Assess exposure of coral reefs to cumulative effects of human activities	Exposure to cumulative effects varied spatially and in terms of the types of stressors coral reefs were exposed to. Areas of highest exposure were closest to population centres	Magris and others (2018)
5	Canada	North Atlantic Ocean	Species distribution models	Assess the impact of ocean warming and decreases in oxygen on three marine species	Species distributions were projected to change substantially across 20-30 years in varying ways	Stortini and others (2017)
6	Canada/USA	North Pacific Ocean	Spatial mapping; Statistical models	Assess the impacts of dissolved oxygen concentrations and bottom trawling along a depth gradient; Assess the impacts of sea shore armoring; Assess the impacts of marine noise	Bottom trawling influences deep-water benthos even where communities are being shaped by strong environmental gradients; Shoreline armoring can contribute to cumulative effects; Marine mammals are predicted to avoid or be injured by loud marine noise	De Leo and others (2017); Dethier and others (2016); Ellison and others (2016)
7	China	North Pacific Ocean	Literature review; Statistical models Numerical models	Qualitative review of potential stressors contributing to fishery declines; Assess the cumulative effects of metals and polycyclic aromatic hydrocarbons on bacterioplankton communities; Assess the cumulative effects of restoration projects on	Ecosystem based management is needed for sustainable development of fisheries; Individual and cumulative effects of Cadmium and PHE on bacterial assemblages were temporally variable and antagonistic in the early stages of exposure; Restoration projects improved water quality but were often implemented within single objective frameworks and did	Qian and others (2017; Zhao and others (2016); Ma and others (2017)

				water quality	not account for other activities reducing water quality	
8	Europe/Africa	Mediterranean Sea and Black Sea	Meta-analysis; Expert elicitation; Estimation of uncertainty; Regression models; Index calculation; Spatial mapping; Mechanistic models; Statistical models	Map and calculate cumulative impacts associated with a range of human activities; Invasive species and effects on biodiversity values	Current conservation initiatives are inadequate to deal with cumulative threats in Tunisia EEZ; Estimates of uncertainty of impacts highly variable with impacts on only a few areas of the Adriatic/Ionian Seas robustly identified; The cumulative effects of extraction and dumping of marine sand are overlooked; The modelled importance of drivers of observed degradation on coralline outcrops did not agree with expert elicitation outputs.	Coll and others (2016); Katsanevakis and others (2016); Ben Rais Lasram and others (2016); Corrales and others (2017); Depellegrin and others (2017); Gerakaris and others (2017); Gissi and others (2017); Trop (2017); Bevilacqua and others (2018); Brodersen and others (2018); Corrales and others (2018)
9	Europe	North Atlantic Ocean	Biological traits analysis; Spatial mapping; Expert elicitation; Meta-analysis; Spatial analysis; Index calculation	Assess the cumulative impact of five marine sectors on benthic communities; Assess the influence of climate change on area-based management tools in high seas areas; Assess the cumulative effects of noise on two species	Sensitivity of habitats to activities varies with placement of hard structures onto benthic habitats causing significant changes in biological and functional traits; Climate change is projected to reduce the usefulness of area-based management tools in high sea areas; High exposure risk areas were identified for the two species	Merchant and others (2017); Johnson and others (2018); Kenny and others (2018)
10	Europe	Baltic Sea	GIS-based viewshape model	Conduct visual impact assessment of	Sheltered coastal areas of complex geomorphological	Depellegrin (2016)

				cumulative pressures caused by existing and planned anthropogenic activities	features have highest potential visual impacts	
11	Global	Global	Literature review; Meta-analysis; Spatial analysis; Statistical models	Review of CEAs across a range of anthropogenic activities and including social and management objectives; Assess the capacity of large MPAs to protect ecosystems from cumulative impacts; Assess vulnerability of deep-sea ecosystem services to deep sea mining; Assess the cumulative effects on the marine environment generated through oil sands production and transport	Considerations for conducting CEAs (including uncertainties and biases) and recommendations for advancing CEAs, including developing assessment frameworks for application across a range of activities and areas; Identifying knowledge gaps	Borja and others (2016); Briscoe and others (2016); Hazeem and others (2016); Lucke (2016); Lundquist and others (2016); Davies and others (2017); Foley and others (2017); Green and others (2017); Le and others (2017); Willsteed and others (2017); Faulkner and others (2018); Stelzenmüller and others (2018)
12	Greenland	Arctic Ocean	Spatial mapping	Assess cumulative effects of multiple stressors on biodiversity values	There is high overlap between stressors and key species along the west coast of Greenland, highlighting this area in need of future management and protection.	Andersen and others (2017)
13	Indonesia	South Pacific Ocean	Expert-elicitation; Bayesian belief networks	Assess the interactions of social, economic and environmental factors influencing fishing activities and	Complex interrelationships between community perceptions of fishing and tourism and associated conflicts influenced the social economic	Hoshino and others (2016)

				effectiveness of customary marine tenure	and environmental outcomes of customary marine tenure.	
14	Indonesia	Indian Ocean	Semi-quantitative risk scoring	Assess the cumulative risk to marine ecosystem of a range of human activities	Fishing, climate change and coastal development pose the greatest risk to marine ecosystems	Battista and others (2017)
15	Ireland	North Atlantic Ocean	Statistical models	Assess the impact of vessel and construction-related activity on marine mammals	The occurrence of three species was reduced in association with vessel and construction-related activity	Culloch and others (2016)
16	Kenya	Indian Ocean	Statistical models	Assess the cumulative effects of the presence of tourist boats on a population of Indo-Pacific dolphins	The presence of tourist boats affected the behavioural budgets of dolphins although at current levels the cumulative effects were not significant	Pérez-Jorge and others (2017)
17	New Zealand	South Pacific Ocean	Literature review; Meta-analysis; Expert elicitation	Assess interdependencies in science-governance-society to identify risks in marine ecosystems; Assess the importance and magnitude of impacts by various activities and stressors on ecosystem services	Considerations for identifying risks and recommendations for risk assessments; Total cumulative impacts were severe for all ecosystem services considered with climate change, commercial fishing, sedimentation and pollution contributing the most	Thrush and others (2016), Singh and others (2017)
18	Philippines	North Pacific Ocean	Semi-quantitative risk scoring	Assess the cumulative risk to marine ecosystem of a range of human activities	Fishing and climate change pose the greatest risks to marine ecosystems	Battista and others (2017)
19	Portugal	North Atlantic Ocean	Spatial mapping	Assess the interactions between a range of human activities and the marine	The Portuguese maritime space is experiencing high cumulative impacts caused by human activities, particularly near the	da Luz Fernandes and others (2017)

				environment	coast	
20	South Africa	Atlantic Ocean, Indian Ocean	Statistical Models	Describe pelagic bioregions for defining regions of marine spatial planning	Bioregional analysis identified three key bioregions and a number of subregions as a framework for ecosystem reporting and systematic conservation planning	Roberson and others (2017)
21	USA	North Atlantic Ocean	Mechanistic models	Simulate the effects of multiple stressors on marine living resources	Temperature increases have the highest impacts on the system productivity	Ihde and Townsend (2017)
22	USA	North Pacific Ocean	Spatial mapping; Sstatistical models	Map potential impacts of single and multiple stressors across the Marine Protected Area (MPA) network; Assess the appropriateness of scientific activities on habitats and communities in MPAs; Assess the cumulative effects of storm events and trampling on intertidal ecosystems	Intense land- and ocean-based impacts affect the majority of MPAs with climate stressors having the greatest impacts; Recommendations for a decision-making framework for assessing scientific activities; Impacts associated with storm and trampling occurred across similar species thereby identifying vulnerable species, with disturbances having additive effects	Micheli and others (2016); Mach and others (2017); Saarman and others (2018)

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Chapter 29
Developments in Marine Spatial Planning

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Keynote points

- The growing scale of human activities and the associated impacts on the marine environment mean that conflicts are increasingly occurring between different uses of the ocean. Marine spatial planning is an effective way of resolving such conflicts.
- Over the past two decades, marine spatial planning has been instituted to a growing extent in many jurisdictions, in a variety of forms: some are simply zoning plans; others include more complex management systems.
- The legal status of marine spatial planning varies between jurisdictions: in some it is guidance to be taken into account; in others it has legal force constraining specific management decisions.
- In general, marine spatial planning has been most effective where it has been developed with the involvement of all relevant authorities and stakeholders.

1. Introduction

As noted in the summary of the First World Ocean Assessment (WOA I) (United Nations, 2017), "human activities now have so many and such great impacts on the ocean that the limits of its carrying capacity are being (or, in some cases, have been) reached". The causes of these impacts include both the intensification and extension into new areas of traditional uses of the sea and also the development of new uses. Increasingly, the use of ocean space cannot be taken for granted, and uses will tend to conflict with each other, especially in coastal zones. The present Chapter discusses the role of marine spatial planning (MSP) as an approach aimed at planning and managing such potential conflicts.

The demands for goods and services from areas of the sea within national jurisdiction often exceed the capacity of those areas to meet all the demands. In the absence of special regulatory regimes, marine resources can be subject to excessive exploitation, and other uses of the sea (such as inputs of waste) can degrade the marine environment. The externalities of such exploitation and uses are often not considered within relevant market systems, and there can be a need to identify efficient trade-offs in the allocation of sea uses (Tuda, 2014). A public process may, therefore, be desirable to reconcile all these factors.

At the same time, there has been increasing realization of the importance of the ocean for achieving sustainable development. Many countries have developed programmes to ensure the sustainable expansion of use of their marine resources ("the blue economy") in order to achieve economic development in the context of the Sustainable Development Goals[303] (INTOSAI, 2019).

[303] See United Nations General Assembly resolution 70/1.

1.1. Marine spatial planning in the First World Ocean Assessment (WOA I)

Marine spatial planning (MSP) was not treated as a standalone topic in the First World Ocean Assessment (WOA I), though its relevance was noted in the chapters on ecosystem services, land-sea physical interactions, marine renewable energy and offshore hydrocarbon development, and fisheries (UN 2017). Marine spatial planning was defined as "the public process of analysing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic, and social objectives that are usually specified through a political process" (UN 2017, Chapter 15). It was noted that MSP is linked to a number of other tools and approaches that have the potential to assist in managing conflicts among diverse stakeholders through participation, such as ecosystem-based management, marine protected areas and the ecosystem approach to fisheries (UN 2017).

2. Types of marine spatial planning

There is not as yet wide agreement about the nature of MSP or how it should be evaluated (Plasman, 2008). However, the relationship between MSP and terms such as ecosystem-based management, sea use management, and ocean zoning has been clarified (Ehler and Douvere, 2009).

The concept of MSP covers a spectrum of processes. At its most basic, it may involve simply the production of a plan allotting zones to different activities. At the other end of the spectrum, it may provide a complex system for planning activities in the ocean, including elements of planning, management, licensing and enforcement (see reviews by Collie and others 2013; Jones and others 2016). Decisions on what type of MSP is appropriate in what areas take account of the range and intensity of pressures on the ocean, the national and local administrative frameworks and the level of economic development (Douvere and Ehler, 2009).

Many countries have already implemented some forms of development control over land, which constrain the abilities of landowners to develop and change the use of their properties. The precise extent of such controls varies (OECD, 2017). Most countries also have systems set up to regulate coastal and maritime activities. A review by the OSPAR Commission for the Protection of the Marine Environment of the North-East Atlantic identified the following aspects as those that could be covered by MSP: coastal defences and land reclamation; dumping; fisheries; harbour works and navigational dredging; marine aquaculture; seabed minerals other than oil and gas; nature protection; navigation; offshore oil and gas; pipelines and cables; recreation (including bathing and pleasure boats); underwater cultural heritage; wind and wave energy; and wrecks and other historic features (OSPAR, 2009).

In addition, many countries have instituted systems to promote the use of the sea and marine resources for economic development. This is especially the case for exploration for, and exploitation of, offshore hydrocarbons (see chapter 20) and for marine renewable energy installations (see chapter 22). However, the socio-economic aspects of MSP can extend well beyond simple planning of the location of offshore installations and can also cover consideration of the way in which to enhance the maritime sectors of the coastal economy and the gross domestic household incomes in the coastal communities (Jay, 2017).

It is clear from this wide range of regulatory and economic-development systems that a need arises to integrate these controls, so that they are not in conflict and allow a coherent approach. This is where MSP is useful (Ehler and Douvere, 2009).

Given the wide range of potential elements to be covered in MSP, and the spectrum of types of MSP, the resulting MSP systems vary widely, but attempts have been made to synthesize good practices (e.g. Foley and others, 2010). One such attempt is the development of the guide "Marine spatial planning: A step-by-step approach toward ecosystem-based management" by the United Nations Educational, Scientific and Cultural Organization (UNESCO) (Ehler and Douvere, 2009).

3. "Marine spatial planning: A Step-by-Step Approach toward Ecosystem Management"

Although initial thinking around the planning of multiple uses in coastal and ocean zones occurred during the 1980s (see section 5.4 - China) interest in MSP started to developed rapidly in the early 2000s. The United Nations Educational, Scientific and Cultural Organization realized that marine spatial planning could make a useful contribution both to the Man and Biosphere Programme and the work of the UNESCO Intergovernmental Oceanographic Commission (Ehler, 2007). In 2006, a workshop on MSP was organized, which led to the development of a guide to marine spatial planning (Ehler and Douvere, 2009).

The guide recommends ten steps for the MSP process. These steps are not a linear process – feed-back loops, and opportunities for review and revision as the process is implemented should be built in from the beginning (Ehler and Douvere, 2009):

Step 1: Identifying need and establishing authority: This includes formulating clearly why MSP is needed, and establishing appropriate authority to plan for and to implement MSP. In most MSP initiatives around the world, a new authority is often established for MSP, while implementation is carried out through existing authorities and institutions;

Step 2: Obtaining financial support: This includes preparing a financial plan that estimates the costs involved in developing and implementing MSP, and identifying sources to meet those costs. The identification of alternative sources tends to be necessary as agencies are often given responsibilities to undertake MSP activities without receiving additional funds. In many cases, some form of fee or charge on the activities authorized under the plan will be appropriate;

Step 3: Organizing the process through pre-planning: MSP requires substantial preparation, including to assemble a multidisciplinary team to develop a work plan, defining the boundaries, time frame, principles, goals and objectives, and identifying risks and developing contingency plans;

Step 4: Organizing stakeholder participation: Involving key stakeholders in the development of MSP is essential, in particular because MSP aims to achieve a number of social, economic and ecological objectives and should therefore reflect as many expectations, opportunities or conflicts in the area under consideration. This step includes defining who should be involved, and when and how they should be involved in the MSP process;

Step 5: Defining and analysing existing conditions: It is essential to know a sea area to create a useful marine spatial plan for it. The preparation of inventories of relevant information is therefore important to the creation of an MSP. The inventories should include information about ecological, environmental and oceanographic conditions, and on human activities in the area, which would be mapped on to the area being planned. Then, conflicts and compatibilities among existing human uses and between those uses and the protection and preservation of the marine environment need to be identified;

Step 6: Defining and analysing future conditions: This includes evaluating the likely future development of the sea area if no changes are made ("business as usual"), estimating the effect of new demands for ocean space, and identifying alternative scenarios for the future of the area. The outcome of this step is the selection of a preferred scenario towards which MSP will work;

Step 7: Preparing and approving the spatial management plan: Within this step, a marine spatial management plan should be developed to identify specific management measures that can deliver the preferred scenario, specifying criteria for selecting measures, and developing a zoning plan, then evaluating and approving the spatial management plan through a formal process;

Step 8: Implementing and enforcing the spatial management plan: At this stage, the planning phase ends and the implementation phase begins. Relevant institutions would carry out actions towards implementation, and ensure compliance with the marine spatial management plan, including through enforcement actions. These activities require continuing new information on what is actually happening in the sea area being planned, and action by a wide range of institutions to gather, evaluate and respond to that information;

Step 9: Monitoring and evaluating performance: As with all policy activities, there is a need to revisit the conclusions that have been adopted and see what progress is being achieved. For MSP, an assessment of the state of the environmental system is relevant in addition to the measurement of the performance of management measures;

Step 10: Adapting the marine spatial management process: The results from the monitoring and evaluation would be used to adapt MSP and management so that the actions dictated by the plan have their intended effects.

Marine spatial planning may need to include, or be accompanied by, an investment and development plan to provide the infrastructure, equipment and (above all) the skilled people needed to ensure the desired development of the "blue economy" (Schultz-Zehden and others, 2019). A review of the relevant science and technology can also be helpful (Pinarbası and others, 2017). Involvement of stakeholders is also important. Studies are emerging on the practicalities of engaging stakeholder (for example, Twoomey and O'Mahony, 2019).

4. Tools for marine spatial planning

Marine spatial planning covers a range from a process to produce a plan for a given marine area to a suite of systems for managing human impacts on the ocean through the planning, management, licensing, regulation, surveillance and enforcement of human activities. Management approaches are considered in Chapter 30 of the present Assessment.

As noted above, information about ecological, environmental and oceanographic conditions of the sea area for which MSP is being developed is an essential basis for this work. **Habitat mapping** is therefore a necessary tool: if the current state of the natural marine environment is not known in some detail, the possible effects of both policies and individual projects can be little more than guesswork. For the benthic layer, improvements in echo-sounding techniques – in particular in allowing whole swathes of seabed to be explored in a single sweep – have permitted since the early 2000s much better resolution of seabed exploration. Geophysical techniques (multibeam, side-scan, seismic) may allow the recognition of the nature of the seabed (mud, sand, gravel or rock), the nature of the rock and the thickness of sedimentation to be ascertained thoroughly. The collection of information about the plants and biota that it supports is then a second level, which together with the information on the seabed will give an overall picture of the area in question. These techniques are providing a mass of new information to support MSP and other marine policymaking (Colenutt and others, 2013). Online geospatial mapping tools are facilitating access to open source information relevant to MSP approaches (e.g. Menegon and others 2018).

Habitat mapping does not give a comprehensive view of the ecosystem componentss that comprise the various habitats, including the functioning and connectivity of ecosystem components. In more developed MSP systems, therefore, an **ecosystem overview** is usually one of the bases of the planning system. An example of this is the Ecosystem Overview of the Pacific North Coast Integrated Management Area (Lucas and others, 2007). This report covered geology, meteorology and climate, physical and chemical oceanography, plankton, marine plants, invertebrates, fish, marine mammals, marine turtles and seabirds.

Similarly, where fisheries are included as part of the MSP process, it may be desirable to incorporate temporal and spatial knowledge of fish stocks and their exploitation. In France, a **method for incorporating fishers' knowledge** has been developed to ensure that these aspects can be brought into the MSP process (Trouillet and others, 2019).

Strategic Environmental Assessment (SEA) aims to ensure that relevant aspects are considered effectively in the development of policies, plans and programmes, because it is often at this more general level that decisions are taken that constrain specific projects.. Originally focused on environmental aspects, it has broadened to cover social and sustainability issues as well (Fundingsland Tetlow and Hanusch 2012).

In China, the technique grew out of the long-established administrative process of environmental impact assessment for specific projects, and was then embodied in the 2002 revision of the law on environmental assessment, which provided for assessment of integrated plans for land use and regional development, development of drainage areas and marine areas (Zhu and others, 2005).

In Europe, the technique grew out of the Espoo Convention,[304] and is outlined in the 2003 Protocol.[305] The Protocol provides for six stages: screening, to determine whether SEA is

[304] Convention on Environmental Impact Assessment in a Transboundary Context; United Nations, *Treaty Series*, vol. 1989, No. 34028.
[305] Protocol on Strategic Environmental Assessment to the Convention on Environmental Impact Assessment in

needed to implement a plan or programme; scoping to determine what information is relevant to the environmental report; preparing an environmental report to identify, describe and evaluate the likely effects of a planned activity; informing and consulting the public, relevant authorities and any States likely to be affected; feeding the SEA into the decision-making process; and monitoring the effects of plans and programmes after their implementation. SEA is recognized by the World Bank as a key means of integrating environmental and social considerations into policies, plans and programmes (World Bank, 2013), and incorporated into the management of development support by a number of States in line with the 2005 Paris Declaration on Aid Effectiveness (OECD, 2006).

At the level of an individual project, **Environmental Impact Assessments** (EIA), aim to ensure that environmental consequences are taken into account before a decision is made to start physical changes in the environment (e.g. Morgan 2012). A detailed description of the form of this adopted for States across the whole of Europe can also be found in the Espoo Convention.

If the socioeconomic aspects are to be included, **surveys of the maritime industrial sectors** that are local to the plan will be needed. There may be problems, however, in correlating the relevant sectors with the area for which the plan is being prepared, since fishing vessels may be based at distant ports and other out-of-area industries may impact on the plan zone. To incorporate wider socioeconomic aspects, it can be appropriate to include a **social survey** of communities involved with the sea area to be covered by the MSP process. In addition to employment, such a survey may also (depending on the area) need to include cultural aspects, indigenous rights and traditions and other traditional involvement of the communities with the sea (Sullivan and others 2015).

5. Progress in implementing marine spatial planning

5.1. Overview

All across the world, governments have developed – or, more commonly, are developing – marine spatial plans. A “Joint Roadmap to accelerate Maritime/marine spatial planning processes worldwide” was adopted during the Second International Conference on Maritime Spatial Planning, organized by the Intergovernmental Oceanographic Commission (IOC) and the European Commission in March 2017 in Paris. This foresees the creation of an international forum for discussion and exchanges on cross-border MSP at the international level. Three workshops of the International MSP Forum have already taken place: in Brussels, in May 2018; La Réunion,in March 2019; Vigo, Spain, in May 2019 and in Riga, in November, 2019. These meetings build on a wide exchange of good practices and interactive discussions in order to work towards the creation of international guidelines on transboundary MSP (IOC, 2019).

A summary of the worldwide inventory of marine spatial planning provided by the IOC (IOC, 2020) is provided in Table 1.

Table 1. Number of countries with full or partial MSP approved or planned, started or in progress, by region. Source: IOC, 2019. **Note:** The 22 coastal States of the European Union (marked *) are committed to full coverage of MSP in their waters by 2021.

a Transboundary Context; United Nations, *Treaty Series*, vol. 2685, No. 34028.

Region	Countries with full or partial (for some aspects or some areas) MSP approved	Countries with MSP planned, started or in progress
Africa		Angola, Ghana, Kenya, Madagascar, Mauretania, Mauritius, Morocco, Namibia, Seychelles, South Africa
Asia	China, Philippines, Viet Nam	Indonesia, Myanmar, Thailand
Australia/Oceania	Australia, Kiribati, New Zealand, Palau	Fiji, Solomon Islands, Tonga, Vanuatu
Europe	Belgium,* Germany,* Latvia,* Netherlands,* Norway, United Kingdom of Great Britain and Northern Ireland	Bulgaria,* Croatia,* Cyprus,* Denmark,* Estonia,* Finland,* France,* Greece,* Iceland, Ireland,* Italy,* Lithuania,* Malta.* Poland,* Portugal,* Romania,* Russian Federation, Slovenia,* Spain,* Sweden*
Middle East		Israel, United Arab Emirates
The Americas	Antigua and Barbuda, Belize, Canada, Mexico, United States of America	Colombia, Dominica, Grenada, Jamaica, St Kitts, St Lucia, St Vincent and the Grenadines, Trinidad and Tobago

In the Baltic Sea, efforts are being made to develop transboundary MSP. The Regional Baltic MSP Roadmap 2013–2020 outlines the steps planned for developing and implementing maritime spatial plans throughout the region by 2020. In order to facilitate a coherent MSP process, the Helsinki Commission has developed guidelines for the implementation of an ecosystem-based approach in MSP in the Baltic Sea area on transboundary consultations, public participation and cooperation, and transboundary MSP output data structure (HELCOM, 2016).

Further development of MSP is also being undertaken in the Republic of Korea[306] and in Peru and Ecuador[307].

Given the many varying approaches to MSP that have been implemented across regions, here we provide further detail on examples of approaches to MSP through a series of case studies, selected to give a view of different continents and different issues.

5.2. Case study – Australia

Australia made an impressive start on MSP with the creation of the Great Barrier Reef Marine Park (GBRMP) in 1975. Legislation defined the Great Barrier Reef Region and established the GBRMP Authority that manages and protects the park. The GBRMP has governance

[306] The Republic of Korea introduced the Marine Spatial Planning and Management Act and in association a National Marine Spatial Framework Plan in 2019.
[307] See http://www.fao.org/in-action/coastal-fisheries-initiative/activities/latin-america/en/ and https://www.pe.undp.org/content/peru/es/home/projects/iniciativa-de-pesquerias-costeras---america-latina.html

arrangements whereby the Authority liaises and coordinates policies with other departments of the Commonwealth of Australia and the Queensland government. The park is managed on the basis of ecologically sustainable principles, a zoning plan that includes multiple-use areas and provides protection of biodiversity values through a network of no-take zones for 33 per cent of its area and for at least 20 per cent of every bioregion (Vince, 2014). The Great Barrier Reef Zoning Plan provides the cornerstone for management within the GBRMP (Kenchington and Day, 2011; GBRMPA, 2019), but many other integrated spatial and temporal management tools and strategies are also in place (Day and others, 2019; see also Chapter 28). Key challenges to the management of the GBRMP are those associated with global pressures, such as ocean warming as a result of climate change and resulting impacts on reef ecosystems (see Chapter 7E of the present Assessment; see also the case study in Chapter 28 (Cumulative effects, section 3.1).

Elsewhere in Australia, progress has been less straightforward. Efforts were started in 1998 to develop an "integrated oceans strategy" later renamed as a "national oceans policy". To begin with, the aim was a "full integration" between the various levels of government (particularly States and Commonwealth) and across the relevant sectors. However, that would have required changes in legislative arrangements, which had been settled in 1979 (OAGA-OCS, 1980), and so that model was not pursued. The national oceans policy provided a comprehensive review of each marine sector and the state of the waters. In 2004, a South-East Regional Marine Plan was released, covering waters from southern New South Wales to eastern South Australia, including Victoria and Tasmania. This foresaw collaborative action over the next decade, leading to a review in 2014 (NOO, 2004). However, little of the specific action foreseen in the plan developed, and the review was not held. In 2005, a new start was made at Commonwealth level, focusing on marine bioregional plans (MBPs) for Commonwealth waters. These MBPs were based on conservation values, which are: key ecological features, protected species (and habitats for such species), and protected places. They describe the marine environment and conservation values of each marine region, set out broad biodiversity objectives, identified regional priorities and outlined strategies and actions to address these priorities by bringing together scientific knowledge and information and they are intended to offer guidance for the relevant sectoral decisions (Vince and others, 2015). In taking forward these commitments, the main effort has been focused on the creation of a National Representative System of Marine Protected Areas (MPAs). A review of the management plans for most of the designated MPAs (which cover 3.2 million km^2, about 36 per cent of the waters within the Commonwealth Government's marine jurisdiction) was completed in 2015 (Beeton and others, 2015). However, the outcome has attracted criticism from academic sources (OSCA, 2017)

5.3. Case study – Canada (Pacific coast)

Canada first developed a comprehensive approach to ocean management in the Oceans Act (Statutes of Canada, 1996, c.31). Canada's Oceans Strategy (2002) provided policy direction for implementing the Oceans Act based on the principles of sustainable development, integrated management and the precautionary approach. Five priority areas for marine planning were identified in an Oceans Action Plan (2005), including an area later known as the Pacific North Coast Integrated Management Area (PNCIMA). In 2005, some of the First Nations on the Pacific Coast began considering MSP as one of a number of issues of common interest. This led eventually to the creation of the Marine Plan Partnership (MaPP) for the Pacific Coast, which brought together the Provincial Government and (eventually) 16 First Nations. The MaPP plans are not considered as having a legal function, but set guidelines in partnership between 16 First Nations and the Province of British Columbia. The plans have a zoning regime which identifies areas important for biodiversity, general use and for the marine industry. Four subregional plans have been synthesized into a regional action framework for the whole planning area (Rodriguez, 2017). The Canadian Department of Fisheries and Oceans organized a thorough ecological overview of the area, providing much of the basic material to support development of PNCIMA planning (Lucas and others, 2007). By 2010, a non-binding trilateral agreement was established between the Government of Canada , First Nations, and the Province of British Columbia. The PNCIMA Plan was endorsed by the Canadian Government, First Nations and the Province of British Columbia in early 2017. The Plan provides a framework for ecosystem-based and adaptive collaborative management of marine activities and resources. A key priority under the plan currently under development is the design of a Marine Protected Area (MPA) network which will guide the establishment of future MPAs and other area-based conservation measures.

5.4. Case study – China

In China, marine functional zoning (MFZ) is considered as a form of MSP and was introduced by the Chinese government in 1988 (Feng and others, 2016; Kang and others, 2017). The development of MFZ can be regarded as moving through three phases and has been institutionalised through the Law on the Administration of the Use of Sea Areas, which was enacted in 2001. This law established principles for sea-use authorization, user fees and marine functional zoning systems. According to the law, MFZ is based on dividing sea areas (including islands) into different spatial areas for human activities, in the light of their geographical and ecological features, natural resources, current usage and socioeconomic development needs (Fang and others, 2018).

The first phase in the development of MFZ was from 1989 to 1993 and involved a pilot MFZ project implemented in the Bohai Sea in 1990. Coastal provinces then developed and implemented their provincial MFZ from 1991 to 1997. The State Oceanic Administration (SOA) developed the first national MFZ maps in nearshore areas of the territorial sea in 1993.

The second phase of MFZ was from 1997 to 2002 and began with the release of a Technical Directive for Marine Functional Zoning to guide MFZ. A first MFZ plan was adopted in 1997 by the local government of the city of Xiamen. Based on the experience of the first phase, the SOA organized the second phase of MFZ in 1998. This phase lasted until 2010. During this phase, in 1998, SOA instructed all 11 coastal provinces of China to formulate a provincial MFZ plan. In 2001, these were completed and, in 2002, the MFZ plans of seven coastal provinces were approved. The MFZ plans of all 11 coastal provinces of China were approved by 2008 (Fang and others, 2018).

The third phase of MFZ began in 2011 and will last until 2020. In this phase, the MFZ is divided into three levels so that the entire maritime area of China is covered (Huang and others, 2019). At the first level, the seas of China are divided into five geographic regions: the Bohai Sea, the Yellow Sea, the East China Sea, the South China Sea, and the Taiwan Straits. The second level is the MFZ at the provincial level, and the third level is the municipal level MFZ (IOC, 2020).

The MFZ has helped China to better plan development of its seas and coasts (Fang and others, 2018; Huang and others, 2019). However, there have been a number of challenges in its implementation. Better coordination between maritime and land planning, improved resolution of conflicts between stakeholders, enhanced monitoring and evaluation, and more effective participation of stakeholders have all been identified (Feng and others, 2016; Liu and Xing, 2019). In practice, MFZ is a zoning tool for multiple marine spatial users (Feng and others, 2016; Kang and others, 2017). In assessing the MFZ, Huang and others (2019) found that the MFZ formulation and implementation process is essentially top-down management, which led to two issues: low applicability due to deficiencies in marine spatial zone classification; and lack of consistency due to lower (municipal) levels having to work within different sea-use areas specified on smaller scale maps set by the provincial authorities. Currently, the MFZ lacks implementation plans and does not ensure management of cumulative impacts of the different sectors. Its implementation does not seem to have stopped the degradation of coastal and marine natural resources and ecological systems, thus leaving the environment still polluted (Kang and others, 2017).

5.5 Case study – European Union

Following on from the Marine Strategy Framework Directive (2008), the European Union decided in 2014 to adopt a directive requiring its coastal member States to develop and implement maritime spatial plans for their waters (EU, 2014). The national legislation for this was to be adopted by 2016, and Maritime Spatial Plans for all the waters covered by the directive are to be in place by 2021. The Plans are not to include coastal waters covered by town and country planning systems, and are not to deal with land/sea interactions, though the results of national decisions on these are to be reflected in the Plans. The planning is to take into account all the relevant human activities and uses, including: aquaculture areas, fishing areas, installations and infrastructures for the exploration, exploitation and extraction of oil, of gas and other energy resources, of minerals and aggregates, and for the production of energy from renewable sources, maritime transport routes and traffic flows, military training areas, nature and species conservation sites and protected areas, raw material extraction areas, scientific research, submarine cable and pipeline routes, tourism and underwater cultural heritage. Member States are required to arrange for public participation in the planning process, to share information and generally to cooperate with each other and with relevant third countries – especially through existing regional seas organizations (EU, 2014).

The areas to be covered by individual plans are left to the judgement of the member States. For example, in France, a high-level National Strategy for the Sea and Coast, which was approved by a decree of the Prime Minister in February 2017. In accordance with this National Strategy, there is to beand as part of this a Strategy Document for each of four sea and coastal basins (Eastern Channel and North Sea; Atlantic (North) and Western Channel; Atlantic (South); and Mediterranean) are to be developed. Each of these strategy documents is to have four parts: situation review, challenges and a vision for the sea basin in 2030; strategic objectives defined from an economic, social and environmental perspective, together with related performance indicators; evaluation procedure for assessing implementation of the strategy document; and an action plan. The first two parts have now been produced for each basin and the remaining parts are due over the next few years. Taken together, these documents set the framework for all relevant decisions by national, regional and local authorities (FMTES, 2017).

5.6. Case study – South Africa

The framework for MSP in South Africa was developed through an initiative of the South African government – Operation Phakisa (“phakisa” means “hurry up” in Sesotho) – aiming to unlock the country's ocean economy as a mechanism to fulfil the National Development Plan 2030. Within Operation Phakisa, MSP was identified as a focus area, which, in turn, fast-tracked the development of the Marine Spatial Planning Act 2019 (RSA, 2019). This Act provides for the development of marine spatial plans and the establishment of institutional arrangements for their implementation and governance of the use of the ocean by multiple sectors. The accelerated pace of the development and enactment of MSP legislation in South Africa (less than three years from first draft to promulgation) stemmed from a concern to achieve speedily larger-scale (exclusive economic zone scale) marine spatial planning. ..

During the detailed planning and roll-out of Operation Phakisa, and while the MSP Act was being drafted, the national Government also published the National Framework for MSP (RSA, 2017). This policy provided high-level direction for undertaking MSP in the context of the country's legal framework – including existing planning regimes – in order to ensure consistency in ocean space planning. The framework also highlighted the need for coordination with terrestrial and coastal planning. To simplify spatial planning, South Africa's EEZ has been divided into western, eastern and southern marine areas, and the Prince Edward Islands, for which statutory marine spatial plans are to be developed. The Government aims to publish the first marine area plans by 2021. The national Government has recognized the importance of data and information for spatial planning and has initiated projects simultaneously to fill data gaps and to provide spatial data infrastructure to support MSP and ocean economy planning (RSA, 2017).

The establishment of MSP in South Africa is constructed on a legacy of environmental policies that were inherently supportive of area-based management, and specifically spatial planning of environmental resources. South Africa chose a consociational democracy as the basis for its political system after apartheid (i.e. post 1994) (Karume, 2003). As a result, most post-1994 environmental legislation embraces cooperative, participatory approaches, including the need for negotiated spatial planning or zonation. This is evident in legislation for terrestrial protected areas, and spatial planning for terrestrial areas (RSA, 2004; RSA, 2013b). In 2008, the National Environmental Management: Integrated Coastal Management Act (RSA, 2009) established cross-sectoral mechanisms for government of coastal space, thus introducing administrative (and explicitly spatial) boundaries such as coastal public property and development set-back lines. In this way, spatial planning (or zoning) became a key component within the national framework for integrated coastal management (ICM) extending to the outer limit of the EEZ (e.g. RSA-DEA, 2014; RSA, 2013a). Although considered progressive and bold (Taljaard and others, 2019; Colenbrander and Sowman, 2015), many barriers for implementation remain, including lack of political support, lack of resources and lack of clarity regarding jurisdiction over private and communal land, and limited civil-society involvement in decision-making (Sowman and Malan, 2018).

The MSP legislation in South Africa is new and its implementation is untested and, as of yet, unchallenged in case law. Its testing in courts of law is a certainty given its intention to allocate the use of space, as it relates to highly valued marine resources that are often contested by multiple users for multiple, often conflicting, uses. Operation Phakisa, with its emphasis on MSP, is also encouraging community-based, bottom-up initiatives such as the "Algoa Bay Project" (Dorrington and others, 2018). The role of these initiatives within the national framework for MSP is not yet clear.

5.7. Case study – Viet Nam

Research on ICM and MSP began in Viet Nam in 1996. From 2010 to 2013, by implementing a regional project on coastal spatial planning, Viet Nam improved MSP capacity and undertook MSP in the coastal areas of Quang Ninh and Hai Phong provinces. With the assistance of various donors, including Partnerships in Environmental Management for the Seas of East Asia (PEMSEA) and the National Oceanic and Atmospheric Administration (NOAA), Viet Nam applied an MSP approach to the functional zoning of Hon Mun, Bai Tu Long Bay and Cu Lao Cham MPAs, and coastal-use zoning for ICM on the Da Nang coast (Nguyen and Hien, 2014). At the same time, through a project funded by the Global Environment Fund and executed by the Ministry of Agriculture and Rural Development of Viet Nam, seven coastal provinces (Nghe An, Thanh Hoa, Binh Dinh, Phu Yen, Khanh Hoa, Soc Trang and Ca Mau) initiated MSP across the period 2012 to 2018. The creation of formal institutions specifically for MSP began in 2012 with the Viet Nam Law of the Sea. In 2015, the Viet Nam Law on Sea and Island Natural Resources and Environment provided for integrated planning of the sustainable use and exploitation of coastal resources. This was followed by the Viet Nam Law of Planning, enacted in January 2017. This legislation provides that MSP shall be the basis of all relevant planning, and that all other sectoral planning in the coasts and seas of must follow it. Development of MSP covering all the coasts and seas of Viet Nam is underway.

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Chapter 30
Developments in Management Approaches

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Keynote points

- The ecosystem approach is one of the most significant approaches to ocean management, consisting of the environmental, social and economic management of human interactions with oceans and coasts at multiple scales (i.e. transboundary, regional, national and local).
- While there is general agreement that the ecosystem approach provides an effective framing of ocean management, further research and capacity-building is needed to realize its full potential benefits across the oceans.
- Management has two different levels of governance, namely, decision-making processes that provide a framework to make decisions and implement policy focused on the conservation and sustainable use of marine resources; and management tools (area-based and non-area based) that can be used to regulate and modify human activity in a particular system.
- The implementation of the 2030 Agenda for Sustainable Development[308] requires management grounded in the ecosystem approach in order to achieve the integrated set of global priorities and objectives set out in its Sustainable Development Goals (SDGs). This will allow for the integration of the interactions, benefits and trade-offs between the SDGs and support achievement of each of the ocean-related targets.
- There is a growing trend towards incorporating the cultural values of the ocean into management.

1. Introduction

1.1. The need for management of the marine environment

The past decade has seen a step-change in the development of management approaches for ocean resource management and sustainability. The present Chapter aims to provide an overview of the nature of this change as well as examples of selected good practices worldwide, including decision-making processes and their tools. To understand these changes, it is important to recognize that approaches to ocean management have deep roots in local and indigenous communities, as well as in science, having evolved incrementally from initial attempts to deal with specific environmental issues, such as pollution from land-based sources in the 1960s, to more integrated approaches, such as integrated coastal zone management (ICZM) starting in the 1970s. Modern approaches to ocean management now

[308] See United Nations General Assembly resolution 70/1.

cover many different tools, tailored to regionally specific issues at a range of scales. The needs and nature of ocean management are influenced by social, cultural, economic and governance contexts, including the norms and value systems that impact on approaches to decision-making between government, industry and civil society at multiple levels. In general, ocean management is expanding from coasts and regional seas to include the regulation of increasing human activities in deeper waters of the exclusive economic zone (EEZ) and the continental shelf (e.g. via marine spatial planning (MSP); see Chapter 29 of the present Assessment). Areas beyond national jurisdiction (ABNJ) are currently the focus of negotiations at the United Nations in the context of the intergovernmental conference on an international legally binding instrument under the United Nations Convention on the Law of the Sea[309] on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction (see Chapter 31 of the present Assessment). In applying the many different forms of management, an understanding of these approaches and their success to date is, therefore, necessary.

The Chapter commences with one of the most significant emerging paradigms for ocean management, the ecosystem approach, which is now universally accepted at global, regional and national scales (SCBD, 2004) as a strategy for integrated management. The ecosystem approach embraces the need for engagement of all relevant sectors of society and has motivated increasing levels of support for "bottom up" community-led approaches to ocean management that take into consideration traditional rights and social justice and apply participatory processes. These trends are juxtaposed in a stocktake of global approaches to management, organized according to area-based and non area-based examples. The bottom-up approaches are complemented by the top-down approaches, developed through international, regional and national governance initiatives. This shows a diversity of ocean management interventions, designed to address a wide range of issues, from global wetlands conservation to networks of marine protected areas (MPAs). Adaptive management integrating flexible strategies that mitigate and adapt to shifts in marine ecosystems associated with climate change is also analysed in the context of region-specific issues, capacity-building, gaps and future research.

1.2. Summary of the First World Ocean Assessment (WOA I)

The First World Ocean Assessment (WOA I) (United Nations, 2017) did not explicitly include management approaches as a stand-alone chapter, with high-level commentary on management approaches integrated into individual chapters instead. Recognizing the importance of providing a consolidated overview of the many approaches to marine management and their application, a chapter specifically focused on ocean management has been included in the present Assessment.

1.3. Overlaps/interactions with other Chapters

Management tools broadly apply across all marine uses and users and so the present Chapter is relevant to all other Chapters in the present Assessment, in particular, Chapter 15 on

[309] United Nations, *Treaty Series*, vol. 1833, No. 31363.

capture fisheries, Chapter 16 on aquaculture, Chapter 22 on renewable energy, Chapter 28 on cumulative effects and Chapter 29 on marine spatial planning.

2. Management approaches

2.1. Introduction to the ecosystem approach

The ecosystem approach consists of an integrated approach with three main pillars, that is, the environmental, social and economic management of human interactions with oceans and coasts at multi-level scales (i.e. transboundary, regional, national and local) incorporating both top-down and bottom-up perspectives. The Parties to the Convention on Biological Diversity (CBD) (UNEP, 2000), in decision V/6, described the ecosystem approach as "a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use of biodiversity in an equitable way". As such, the ecosystem approach has been widely accepted and implemented as an effective management mechanism (see, for example, the European Union Marine Strategy Framework Directive[310] and the Integrated Ecosystem Assessment implemented by the United States National Oceanic and Atmospheric Administration (NOAA)).[311]

There is a plethora of legislative instruments covering all aspects of marine use and requiring both vertical and horizontal integration (Boyes and Elliott, 2014). Top-down management approaches generally include policy and legislative instruments focused on implementing international conventions, agreements and instruments, and meeting national priorities for marine spaces. Bottom-up management tools, including customary or indigenous ecosystem-based and stakeholder-based approaches to resource management (Thornton and Maciejewski Scheer, 2012; Turner and Berkes, 2006), are generally driven by a local-level need to implement effective management at the local scale. Bottom-up management tools can be motivated by social, economic or environmental aspects specific to an area, such as the need to address point source pollution impacts through targeted management.

Box 1 – The 12 principles of the ecosystem approach as defined by the CBD Guidelines (COP decisions V/6 and VII/11), which include implementation guidelines for each principle.

Principle 1: The objectives of management of land, water and living resources are a matter of societal choice.

Principle 2: Management should be decentralized to the lowest appropriate level.

Principle 3: Ecosystem managers should consider the effects (actual or potential) of their activities on adjacent and other ecosystems.

Principle 4: Recognizing potential gains from management, there is usually a need to understand and manage the ecosystem in an economic context. Any such ecosystem-management programme should:

(a) Reduce those market distortions that adversely affect biological diversity;
(b) Align incentives to promote biodiversity conservation and sustainable use;
(c) Internalize costs and benefits in the given ecosystem to the extent feasible.

Principle 5: Conservation of ecosystem structure and functioning, in order to maintain ecosystem services, should

[310] See https://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/marine-strategy-framework-directive/index_en.htm.
[311] See https://www.integratedecosystemassessment.noaa.gov/.

be a priority target of the ecosystem approach.

Principle 6: Ecosystems must be managed within the limits of their functioning.

Principle 7: The ecosystem approach should be undertaken at the appropriate spatial and temporal scales.

Principle 8: Recognizing the varying temporal scales and lag-effects that characterize ecosystem processes, objectives for ecosystem management should be set for the long term.

Principle 9: Management must recognize that change is inevitable.

Principle 10: The ecosystem approach should seek the appropriate balance between, and integration of, conservation and use of biological diversity.

Principle 11: The ecosystem approach should consider all forms of relevant information, including scientific and indigenous and local knowledge, innovations and practices.

Principle 12: The ecosystem approach should involve all relevant sectors of society and scientific disciplines.

The CBD implementation guidelines above acknowledge that there are often limitations in current understanding and, in such cases, a precautionary approach should be followed.[312] The precautionary approach, as reflected in Principle 15 of the 1992 Rio Declaration on Environment and Development,[313] which states that, where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation, has been incorporated into an increasing number of international treaties and other instruments, reflecting a trend towards making the precautionary approach part of customary international law (see, for example, Advisory Opinion of the Seabed Disputes Chamber of the International Tribunal of the Law of the Sea, ITLOS (2011), para. 135). .

2.2. Implementation of the ecosystem approach to management

The ecosystem approach can be operated and implemented in a single sector, for example, ecosystem-based fisheries management (EBFM) (Cowan and others, 2012), ecosystem approaches to fisheries (EAF) and the ecosystem approach to aquaculture (EAA, Brugère and others, 2019) or multiple sectors such as integrated coastal zone management (ICZM) (UN Environment, 2018). Over the last decade, specific implementations of the ecosystem approach have resulted in management mechanisms moving towards establishing methods for operation and implementation (Zhang and others, 2011, Link and Browman, 2017). Despite this, there are still large gaps in implementation and incomplete uptake across sectors and regions. For example, there are still significant differing opinions on the implementation of EBFM from different stakeholders, such as policymakers and managers, scientists, conservationists and ecologists (Trochta and others, 2018). It is, therefore, necessary to create frameworks and criteria for ecosystem assessment (Harvey and others, 2017; Zador and others, 2017), particularly based on demonstrated best practices. Developing methods to increase stakeholder engagement is also essential for ensuring successful implementation (Oates and Dodds, 2017).

Management generally occurs in two different levels of governance: (i) decision-making processes that provide a framework for making decisions and implementing policy focused on

[312] CBD decision VII/11, annex I, implementation guideline 6.2.

[313] *Report of the United Nations Conference on Environment and Development, Rio de Janeiro, 3−14 June 1992*, vol. I, *Resolutions Adopted by the Conference* (United Nations publication, Sales No. E.93.I.8 and corrigendum), resolution 1, annex I. See also https://www.cbd.int/doc/ref/rio-declaration.shtml.

the conservation and sustainable use of marine resources, such as MSP, EAF and ICZM; and (ii) management tools (area based and non-area based) that can be used to manage or regulate human activity in particular systems, such as marine protected areas (MPAs) and zoning (Maestro and others, 2019), fisheries closures (Hall, 2002), Particularly Sensitive Sea Areas (PSSAs) (Basiron and Kaur, 2009) and fisheries management tools (Pope, 2002) (see also section 3 below).

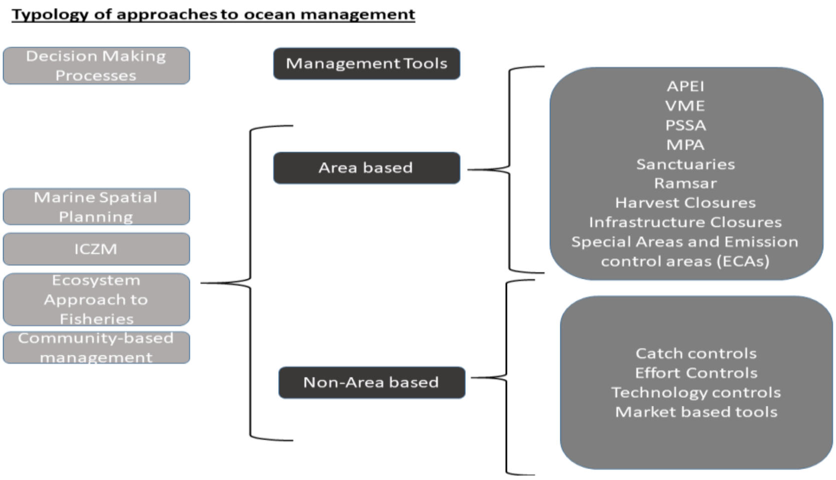

Figure 1. Illustrative typology of approaches to ocean management.

2.3. Community-based and cultural-based management

One area where ocean management based on ecosystem approaches continues to develop is in the way in which it supports engagement with communities and their culture. The Millennium Ecosystem Assessment identified cultural ecosystem services as the non-material benefits that people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation and aesthetic experiences (Milcu and others, 2013; Diaz and others, 2018). As already noted, the principles of the ecosystem approach include decentralization of management to the lowest appropriate level and involvement of all relevant sectors of society. Management approaches should also recognize that the cultural services provided by the marine

environment also include specific values and benefits derived from sites of anthropogenic origin, including archaeological and historical sites (shipwrecks, prehistoric submerged sites etc. known as underwater cultural heritage). Such sites or locations can exhibit a variety of values, including historical and archaeological significance, sacred nature (war grave or tomb), or cultural importance (myth and folklore). These are benefits provided by the cultural footprint within the marine ecosystem. Hence, there is growing recognition that many marine ecosystem services are a hybrid of culture and nature in combination, appreciated holistically by coastal communities. For example, management of Papahānaumokuākea Marine National Monument, Hawaii, is framed by a native Hawaiian understanding of the ocean as a cultural seascape, where all natural resources are cultural resources, connected through ancestral stories and perpetuated through traditional practices, including wayfinding and voyaging (Kikiloi and others, 2017). Despite an anthropogenic emphasis, community-based and cultural-based management approaches respect the intrinsic value of nature for its own sake.

Equally, recognition of the limitations of top-down management approaches, and increased understanding of the rights, tenures, traditional and indigenous customary uses of inshore marine environments, have catalysed widespread recognition of the strength and sustainability of community-based management (CBM) or “bottom-up” approaches to marine conservation. Community-based management recognizes local community stewardship, knowledge and practices in monitoring, assessing and managing marine resources and through participatory, collaborative governance structures led by or involving local communities and systems of authority (Turner and Berkes, 2006). Many CBM schemes often develop from long-standing local institutions, such as the Alaska Eskimo Whaling Commission (Meek, 2013) and its self-organized aboriginal whaling captain associations that are now engaged in cross-scale (local to international) and community-based management. In the Southern Hemisphere, dugong management is shared by State and Territory agencies and communities in the Torres Strait between Australia and Papua New Guinea, through a system of indigenous rangers and Papua hunters (Miller and others, 2018). Such systems of shared management may be framed by a general understanding of the ecosystem approach but, at the local level, communities shape management approaches within their social and cultural values and the cultural benefits of their traditional practices (Delisle and others, 2017). As another example, networks of locally managed marine areas (LMMA) in the Pacific build community resilience by supporting village-level management and sustainable use of marine resources (Govan, 2009; Veitayaki, 2003).

Growing recognition of the importance of marine ecosystem services to coastal communities and culture will undoubtedly intensify as these communities face pressures associated with climate change, particularly sea level rise and both temporary and permanent coastal inundation (Goodhead and Aygen, 2007; see also Chapter 9 of the present Assessment). Cultural information is increasingly regarded as an integral part of ecosystem-based management, both in the context of community-based management and for safeguarding the cultural dimension of the marine environment. Such information may be very diverse and intangible, relating to, for example, traditional marine resource use, sea routes, ancient navigational skills, maritime identities, legends, rituals, beliefs and practices, aesthetic and inspirational qualities, cultural heritage, places of spiritual and sacred and/or religious importance.[314] This may mean that these cultural values and practices are challenging to incorporate into planning and management. Nonetheless, the cultural dimension of the sea can be integrated and mapped as a precursor to management. Once taken on board, culture can be potentially powerful, not simply as a factor to be managed and monitored, but as the foundation upon which management incorporating ecosystem approaches may be developed in the context of sustainable development.

3. Advances in ocean management approaches

The last decade has been characterized by the proliferation and expansion of new and existing approaches to the management of the oceans and seas. This has been manifested by the regulation of human activity in specified areas to achieve conservation or resource management policy objectives. Although all areas of the marine environment might be managed in some way (e.g. fisheries, tourism, oil and gas extraction), this often consists of a patchwork of policies and legislation that results in piecemeal approaches to protection (Boyes and Elliott, 2014). While the management processes and tools described in this section tend to have a spatial dimension, they share a common set of characteristics, namely:

- Scale- from international to regional to local scales.
- Driving factors- e.g. whether motivated by conservation or economic development.
- Sectoral dimensions - e.g. single sector, multi-sector or cross sector.
- Implementation measures - e.g. hard measures (legally binding) or soft measures (voluntary).
- Top down or bottom-up approaches to management.

In this assessment, we have concentrated on management approaches that alter some aspect of human use. Other tools, such as the description of Ecologically or Biologically Significant Marine Areas (EBSAs)[315] under the Convention on Biological Diversity (CBD)[316] do not change use but provide information that may play a role in decision-making processes. They should be distinguished, however, from “decision making processes”, such as fisheries stock assessments, Integrated Ecosystem Assessments (IEA) and Strategic Environmental Assessments (SEA), as EBSAs are a purely scientific and technical process exercise and do not include management measures, even though they have the potential to inform policy and management decisions.

[314] A number of cultural practices relating to the sea have been inscribed in the UNESCO Representative List of the Intangible Cultural Heritage of Humanity; see https://ich.unesco.org/en/lists.

[315] See https://www.cbd.int/ebsa/.

[316] United Nations, *Treaty Series*, vol. 1760, No. 30619.

3.1. Decision-making processes for management

Decision-making processes are used to identify the most appropriate policy and management objectives of competent authorities tasked with developing and implementing management approaches or strategies (Table 1). Governments, industry, communities and civil society identify the outcomes they wish to achieve, i.e. the management objectives, and then use one of the potential approaches to identify how and where to achieve these outcomes. The outcomes described cover the different aspects of sustainable development, including environmental, economic and social aspects. They may be global, regional, national and subnational/community-led. Common examples are MSP, IEA, SEA, EAF and EBFM, systematic conservation planning (SCP) (McIntosh and others, 2017), community-based resource management (see section 2.3), source to sea approaches,[317] and ICZM.

At the regional level, examples of such approaches can be found in the context of the OSPAR,[318] Helsinki,[319] Barcelona[320] and Bucharest[321] regional seas conventions. These Conventions use an area-based approach to assess the status of the environment and control activities, aimed at ensuring good environmental status of marine assets. The organizations established under those Conventions have working groups that are focusing on MSP, fisheries management and ICZM.

The concept of adaptive management or adaptive resource management is shared across the decision-making processes listed (Dunstan and others, 2016), but the actual process used is often determined by the policy objectives (see also Section 4). Within adaptive management frameworks, management measures or actions are implemented sequentially over time, taking into account future conditions and uncertainties associated with the responses of the resource being managed (Schultz and others, 2015). Conservation objectives are often met using systematic conservation planning and community-based approaches at local levels in order to support local communities in the sustainable use and conservation of marine resources (Berkes and others, 2000; Nguyen and others, 2016). In contrast, the ecosystem approach to fisheries aims to provide a holistic approach to managing fisheries and other living marine resources by taking into account relevant human activities and their interactions with the ecosystem, with the purpose of maintaining health, productivity and resilience in order to ensure the continued delivery of ecosystem services and societal goods and benefits (Cowan and others, 2012). However, even with these more holistic processes, there are still issues around integrating multiple sectors (Jones and others, 2016).

[317] https://www.siwi.org/publications/implementing-the-source-to-sea-approach-a-guide-for-practitioners/

[318] Convention for the Protection of the Marine Environment of the North-East Atlantic; United Nations, *Treaty Series*, vol. 2354, No.42279.

[319] Convention on the Protection of the Marine Environment of the Baltic Sea Area; United Nations, *Treaty Series*, vol. 2099, No.36495.

[320] Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean; United Nations, *Treaty Series*, vol. 1102, No. 16908.

[321] Bucharest Convention on the Protection of the Black Sea Against Pollution.

Table 1. Decision-making processes and their associated attributes, including primary drivers (economic, environmental or social/cultural), sectors (single sector or multi sector), implementation measures (source of authority to establish), direction (top down via government or bottom up via communities) and scale (global to local scales).

Management approach	Example in practice	Relevant authority	Primary driver			Sector			Measures		Direction			Spatial scale			
			Economic	Environmental	Social wellbeing/cultural	Single	Multi	Cross	Legally Binding	Voluntary	Top-down	Bottom-up	Both	Global	Regional	National	Sub-national
Decision-making processes																	
	Marine spatial planning (via zoning, consenting, licencing and policy-led mechanisms)	Competent national authorities/ local authorities	x	x	x		x	x	x				x		x	x	x
	Integrated coastal zone management (ICZM)	Competent national/local authorities	x	x	x		x	x	x	x			x		x	x	x
	Systematic Conservation	Competent national/local		x		x	x		x		x					x	

	Planning	authorities															
	Integrated Ecosystem Assessment (IEA)	Competent national/local authorities	x	x		x	x		x		x					x	
	Ecosystem approach to fisheries	Competent national/local authorities	x	x		x			x		x				x	x	x
	Community-based management plans	Competent national/local authorities	x	x	x	x	x		x	x		x					x
	Strategic Environmental Assessment (SEA)	Competent national/local authorities	x	x	x	x	x		x		x				x	x	x

3.2. Area-based management tools

Area-based management tools provide a spatial context to management approaches where, usually, the area has been defined as having distinctive characteristics that warrant measures that are different to the management of surrounding sea areas. Examples of area-based management tools that change or regulate aspects of human use of the marine environment include Marine Protected Areas (MPAs), Particularly Sensitive Sea Areas (PSSAs), Areas of Particular Environmental Interest (APEI), World Heritage Sites (WHS), fisheries closures, infrastructure closures and designations under the Convention on Wetlands of International Importance especially as Waterfowl Habitat (Ramsar Convention).[322] Applying these tools worldwide, and the use of terminology, is highly variable, due in part to local hazards, risk and vulnerability and the need for resilience building (Fanini and others, 2020). Despite this variability, there is general consistency in overall goals to improve pathways towards sustainability, and some of these tools could be used as "other effective area-based conservation measures".[323] The following paragraphs, while not exhaustive, highlight a number of examples of area-based management tools in current use.

MPAs provide specific protection mechanisms to specific areas of the ocean. They have been identified as one of the tools that should be implemented in achieving Aichi Biodiversity Target 11[324] and Sustainable Development Goal (SDG) 14.5.[325] The indicators and global targets for MPAs as identified under the CBD are currently under revision through the process of negotiation of the CBD post 2020 global biodiversity framework. MPAs can take many forms, covering varying spatial scales and providing varying levels of marine environmental protection. Examples of MPAs include the 94,000 km^2 South Orkney Islands Southern Shelf MPA (2009) and the 1.5 million km^2 Ross Sea MPA (2017) designated by the Commission for the Conservation of the Antarctic Marine Living Resources;[326] the OSPAR network of MPAs of a total surface area of 864,337 km^2;[327] the Specially Protected Areas of Mediterranean Importance (SPAMIs) under the SPA/BD Protocol to the Barcelona Convention, including the 87,500 km^2 Pelagos Sanctuary for the Conservation of Marine Mammals established by a tripartite agreement between France, Monaco and Italy (2001),[328] and the European Union Natura 2000 Network, the largest coordinated network of protected areas in the world, spanning the marine territory of 23 European Union countries and, at the end of 2018, covering more than 551,000 km^2.[329] MPAs have increased rapidly in both number and size in recent years, largely in response to internationally agreed targets under the CBD and the 2030 Agenda for Sustainable Development,[308] and are an important tool for marine conservation (Humphreys and Clark, 2020). Currently, the global MPA coverage in areas within national jurisdiction has reached 18 per cent, which amounts to 8 per cent coverage of the entire ocean. In contrast, only 1 per cent of

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[322] United Nations, *Treaty Series*, vol. 996, No. 14583; see also https://www.ramsar.org.

[323] A definition and voluntary guidance for OECMS was adopted at the Convention on Biological Diversity Conference of Parties (COP) 14 (https://www.cbd.int/doc/decisions/cop-14/cop-14-dec-08-en.pdf).

[324] See United Nations Environment Programme, document UNEP/CBD/COP/10/27, annex, decision X/2; Target 11 "By 2020, at least 17 per cent of terrestrial and inland water areas and 10 per cent of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, are conserved through effectively and equitably managed, ecologically representative and well-connected systems of protected areas and other effective area-based conservation measures, and integrated into the wider landscapes and seascapes".

[325] See United Nations General Assembly resolution 70/1; SDG 14.5 "By 2020, conserve at least 10 per cent of coastal and marine areas, consistent with national and international law and based on the best available scientific information".

[326] See https://www.ccamlr.org/en/science/marine-protected-areas-mpas.

[327] As of 1 October 2018, the OSPAR Network of MPAs comprised 496 MPAs, including 7 MPAs collectively designated in ABNJ; see *2018 Status Report on the OSPAR Network of MPAs*, OSPAR Commission, 2019; see also https://ospar.org.

[328] See www.rac-spa.org/spami.

[329] See https://www.eea.europa.eu/data-and-maps/dashboards/natura-2000-barometer.

areas beyond national jurisdiction (ABNJ) has been established as protected areas (UNEP-WCMC, IUCN, 2019).

With respect to incorporating community and indigenous values into area-based management, examples can be found in Canada's MPAs in the Arctic (including Anguniaqvia niqiqyuam in the Amundsen Gulf, Tarium Niryutait in the Beaufort Sea, Tuvaijuittuq off the northwest coast of Ellesmere Island, Nunavut). Anguniaqvia niqiqyuam was the first Canadian MPA with conservation objectives based on traditional and indigenous knowledge. These sites were identified as ecologically important areas that provide habitat for species of cultural importance and contribution to social and cultural values.[330]

Other examples of area-based management tools are provided for under conventions that seek to protect specific areas of diversity, habitat or heritage. In Ramsar-designated areas, for example, the broad aim is to halt the worldwide loss of wetlands and to conserve those that remain through wise use and management. As of February 2019, 2,341 sites have been designated under the Ramsar Convention,[322] comprising 252.48 million hectares of internationally significant wetlands. A recently designated site is the Qurm Nature Reserve in Oman, which has successfully protected 106.83 hectares of coastal wetland ecosystems through specific planning and management, as a result of its designation as a Ramsar-listed site. Programmes include encouraging the development of nature-based tourism and community engagement in active management of the wetlands, which has resulted in an increased economic value of the Qurm Nature Reserve[331] to the community.

Other mechanisms that use area-based management include implementation of offshore exclusion zones or closures to facilitate infrastructure installation and operation, for example, pipelines, offshore windfarms and telecommunication cables. These areas are restricted primarily for public health and safety although, indirectly, have resulted in the protection of marine habitats and biodiversity.

Area-based management tools of particular sectors, such as shipping, encompass the seventeen areas designated by the International Maritime Organization as PSSAs,[332] including the Great Barrier Reef, the Torres Strait, the Florida Keys, the Papahānaumokuākea Marine National Monument, the Galapagos Islands, the Wadden Sea and Western European waters. The protection afforded in these areas includes routeing measures and anchoring bans, mandatory reporting requirements and strict application of discharge and equipment requirements for ships, such as oil tankers as set out under the International Convention for the Prevention of Pollution from Ships (1973), as modified by the Protocol of 1978 and the Protocol of 1997 (MARPOL).[333] Four of these areas (Great Barrier Reef, Papahānaumokuākea Marine National Monument, Galapagos Islands, Wadden Sea) are also protected as marine World Heritage Sites (see below).

The Regional Environmental Management Plan adopted by the International Seabed Authority for the Clarion-Clipperton Zone in Eastern Central Pacific included the establishment of an initial set of

[330] See https://cases.open.ubc.ca/the-cultural-and-conservation-significance-of-anguniaqvia-niqiqyuam-marine-protected-area-mpa-north-west-territories-canada/.
[331] See https://rsis.ramsar.org/ris/2144.
[332] See https://www.pssa.imo.org/.
[333] See http://www.imo.org/en/About/Conventions/ListOfConventions/Pages/International-Convention-for-the-Prevention-of-Pollution-from-Ships-(MARPOL).aspx.

nine Areas of Particular Environmental Interest as "no mining areas", based on expert recommendations. These areas were intended to protect the biodiversity and ecosystem structure and functioning of the Zone from the potential impacts of seabed mining (Jones and others, 2019; see also Chapter 19 of the present Assessment).

Marine protected areas may also be used in combination with fisheries management tools and sanctuaries (no take zones which may be within MPAs). Sanctuary areas and seasonal and year-round fisheries closures[334] and exclusion zones provide area-based management mechanisms that seek to improve species population and biodiversity recovery. For example, the International Whaling Commission has established two sanctuaries, both of which prohibit commercial whaling: the Indian Ocean Sanctuary which was established in 1979 and covers the whole of the Indian Ocean south to 55°S; and the Southern Ocean Sanctuary which was established in 1994 and covers the waters around Antarctica.[335]

Seasonal and year-round fisheries closures support the maintenance or recovery of overexploited species, preserve livelihoods of local communities, protect habitats and key ecological processes such as spawning, and prevent the exploitation of living resources in ABNJ prior to specific rule setting as a precautionary measure. Examples include the identification of vulnerable marine ecosystems (VMEs) and spatial closures by RFMO/As, no-trawl zones in the United Kingdom of Great Britain and Northern Ireland to protect fish stocks and habitats, dynamic spatio-temporal closures in Australia to manage catches associated with migratory species, and the closure of Arctic waters to commercial fishing under the Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean, pending a scientific assessment of the sustainability of such fisheries.

Area-based management is also used to safeguard marine sites of significance due to their cultural value, or the way the marine seascape combines cultural and natural attributes. World Heritage Sites under the 1972 United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Convention (UNESCO, 1972) provide an international example. Since the inscription of the first marine site on the UNESCO World Heritage List in 1981, 50 marine sites across 37 countries have been recognized for their unique marine biodiversity, ecosystems or geological processes or incomparable beauty.[336] The largest is the French Austral Lands and Seas, designated in 2019, covering 67,296,900 hectares. Following this is the Phoenix Islands Protected Area in Kiribati at 408,250 km², inscribed in 2010.[337] Four of these sites, the Papahānaumokuākea Marine National Monument in Hawaii, St. Kilda in Scotland, United Kingdom of Great Britain and

[334] See, inter alia, new European Union regulation No 2019/1022 establishing a multiannual plan for the fisheries exploiting demersal stocks in the western Mediterranean Sea to face generalized regional fisheries overexploitation; the regulation provides, inter alia, for the establishment of 3-month closure areas for the protection of juveniles to be determined spatially and temporally by each Member State; see https://www.consilium.europa.eu/en/press/press-releases/2019/06/06/first-ever-multi-annual-management-plan-for-fisheries-in-the-western-mediterranean-becomes-reality/.

[335] See https://www.iwc.int/sanctuaries.

[336] See https://whc.unesco.org/en/marine-programme/.

[337] Also, the number of marine World Heritage Sites declared as "in danger" has been reduced from three to two sites. The Belize Barrier Reef Reserve System was removed from the List of World Heritage in Danger in 2018 due to the effective implementation of national policy, specifically relating to the adoption of forests (protection of mangroves) regulations, a moratorium on oil exploration and other petroleum operations within the entire maritime zones of Belize, and further revision and amendment of the Environmental Impact Assessment (EIA) checklist and the corresponding ongoing revision of the EIA regulations.

Northern Ireland, Ibiza in Spain and Rock Islands Southern Lagoon in Palau, are internationally recognized for their mixed cultural and natural outstanding universal value. In a national context, all of the National Marine Sanctuaries in the United States of America include protections for historical, archaeological, and cultural resources throughout the sanctuary system, and in fact have several sanctuaries designated specifically for their collections of historic shipwrecks (e.g. Thunder Bay sanctuary, Monitor sanctuary, Mallows Bay sanctuary)[338]. In Scotland, the MPA concept has been developed to introduce MPAs around significant historic wreck sites (Historic Environment Scotland, 2019). Similarly, many national heritage laws provide for the designation of protection zones around underwater archaeological and historical sites, including measures such as prohibition of fishing, anchoring and scuba diving without special authorization (e.g. Greek law No. 3028/2002 on the protection of antiquities and cultural heritage in general). Finally, special reference should be made to the recognition of the wreck site of RMS Titanic as an international maritime memorial by United States law and the International Agreement on RMS Titanic between the United Kingdom and the United States that entered into force in 2019.[339]

[339] See https://www.gc.noaa.gov/gcil_titanic.html; see also IMO Circular (MEPC.1/Circ.779, 31 January 2012) on pollution prevention measures in the area surrounding the wreckage of RMS. Titanic. Since 2012, the wreck site of the Titanic falls within the scope of protection of the 2001 UNESCO Convention on the Protection of the Underwater Cultural Heritage (United Nations, *Treaty Series*, vol. 2562, No. 45694) which applies to all traces of human existence having a cultural, historical or archaeological character that have been underwater for at least 100 years; see http://www.unesco.org/new/en/culture/themes/underwater-cultural-heritage/the-heritage/did-you-know/titanic/.

Table 2. Area-based management tools and their associated primary drivers (economic, environmental, social/cultural), sectors (single sector or multi-sector), implementation measures (source of authority to establish), direction (top down via government or bottom up via communities) and scale (global to local scales)

Management approach	**Example in practice**	**Relevant authority**	**Primary driver**			**Sector**			**Measures**		**Direction**			**Spatial scale**			
			Economic	**Environmental**	**Social wellbeing/cultural**	**Single**	**Multi**	**Cross**	**Legally Binding**	**Voluntary**	**Top-down**	**Bottom-up**	**Both**	**Global**	**Regional**	**National**	**Sub-national**
Area-based tools																	
	Areas of Particular Environmental Interest (APEI)	International Seabed Authority	x	x		x			x		x			x			
	Vulnerable Marine Ecosystems (VMEs)	RFMO/As, Competent national authorities		x		x			x		x				x		
	Particularly Sensitive Sea Areas (PSSAs)/Areas to be Avoided (ATBA)	IMO	x	x		x			x		x			x			
	Fisheries closures/ Fisheries Restricted Areas	FAO, RFMO/As, EU, Competent national authorities		x		x			x		x				x	x	x
	Whale sanctuaries	IWC		x		x			x		x			x			
	Infrastructure closures: pipeline (e.g. oil, gas, waste, freshwater) and	IMO, Competent national authorities	x			x			x		x					x	

	cable closures (e.g. telecommunications, grid)																
	National marine conservation zones/priority areas for conservation	Competent national authorities		x		x			x		x					x	x
	Aquaculture closures	Competent national authorities	x	x		x			x		x					x	x
	World Heritage Sites (WHS), including those recognized for their mixed cultural and natural outstanding universal value	UNESCO		x	x		x		x		x					x	
	Marine Protected Areas (MPAs)	CBD Aichi Targets, Regional Seas Conventions (RSC), Competent national authorities		x		x			x		x				x	x	
	Protection zones around archaeological and historical sites	Competent national authorities			x				x		x					x	
	Ramsar sites	Ramsar Convention		x		x			x		x				x	x	
	Species specific sanctuaries (e.g. shark, dugong)	Competent national authorities		x		x			x		x				x	x	
	Co-location (e.g. ocean	Competent national	x	x			x			x	x					x	x

	energy, aquaculture etc.)	authorities															
	Special areas and emission control areas	MARPOL/IMO		x		x			x		x				x	x	x
	Community-based spatial closures	Local government/ communities		x	x	x		x		x		x					x
	Traditional management approaches, including indigenous rangers programmes	Community leadership/authority, competent national or local authorities	x	x	x	x	x		x	x		x					x

3.3. Non area-based management tools

The management of the ocean is not limited to area-based approaches, although, paradoxically, all management measures are applied across a spatial area even if required or sanctioned at larger scales. Many activities are dealt with through a range of other measures, such as regulation of chemicals and pollution events, management of transboundary migratory species and the application of technical measures in fisheries management (see Chapter 15 of the present Assessment).

Non area-based tools are primarily sectoral in nature and regulate specific sectoral activity of a specific sector to achieve a specific outcome. For example, global emissions controls are applied to international shipping vessels (global sulphur cap),[340] while catches within fisheries can be restricted through catch limits and/or limits on effort (through quota-based systems, hook limits, capacity limits, etc). Technology-based measures can also be applied to fisheries to restrict catches of non-target species (e.g. turtle exclusion devices) and market-based approaches (e.g. accreditation schemes, seafood sustainability or eco-labelling) can be applied across an entire fishery, whether at a global, regional, national or subnational scale.

Non area-based tools are also widely used by domestic law for managing cultural heritage at sea, such as the requirement to report discoveries and obtain a licence before carrying out any activities directed towards the excavation, removal or disturbance of underwater cultural heritage.

At the international level, the United Nations Convention on the Law of the Sea[309] sets out the jurisdictional framework for the duty to protect objects of an archaeological and historical nature at sea (see Article 303 of the Convention; Strati, 1995). The 2001 UNESCO Convention on the Protection of the Underwater Cultural Heritage elaborates this duty into specific rights and obligations within the various maritime zones as defined by the United Nations Convention on the Law of the Sea, by providing, inter alia, a system of reporting/notification and consultation for the protection of underwater cultural heritage found in the exclusive economic zone and on the continental shelf as well as in the Area. In addition, the Rules annexed thereto concerning activities directed at underwater cultural heritage lay down general principles of protection along with technical rules, such as standards for conservation and management.

[340] See http://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx.

Table 3. Non area-based management tools and their associated primary drivers (economic, environmental or social/cultural), sectors (single sector or multi sector), implementation measures (source of authority to establish), direction (top down via government or bottom up via communities) and scale (global to local scales)

Management approach	**Example in practice**	**Relevant authority**	**Primary driver**			**Sector**			**Measures**		**Direction**			**Spatial scale**			
			Economic	**Environmental**	**Social**	**Single**	**Multi**	**Cross**	**Legally Binding**	**Voluntary**	**Top-down**	**Bottom-up**	**Both**	**Global**	**Regional**	**National**	**Sub-national**
Non area-based tools	Catch and/or effort controls	Regional/national competent authorities	x	x		x			x		x				x	x	x
	Technology controls	Regional/national competent authorities	x	x		x			x		x				x	x	x
	Market-based tools	Regional/national competent authorities	x	x		x			x	x		x			x	x	x

	Underwater cultural heritage protection mechanisms	National competent authorities		x	x	x			x		x					x	x

4. Management tools to support mitigation of and adaptation to climate change, including building resilience

In undertaking the ecosystem approach, decision-making processes are also required to consider knowledge of climate impacts and mitigation and adaptive responses. In this regard, identifying the adaptation pathways that might be undertaken to progress climate resilience is important for determining which management processes and tools can incorporate the uncertainty and unpredictability of environmental impacts and responses across spatio-temporal scales (Holsman and others, 2019; Wise and others, 2014). The choice of different adaptive measures that might be implemented to achieve greater resilience can vary greatly, and is contingent on the decision-making processes that frame them. As an example, ecosystem-based disaster risk reduction contributes to the adaptability of ICZM and protected area management, particularly in the case of vulnerable communities and countries (Ferrario and others, 2014; Satta and others, 2017). Alternative strategies might apply mitigation and compensation measures,[341] such as the blue carbon initiative. Effective mitigation approaches should also enhance linkages with adaptation finance, technology transfer and capacity-building, while adaptive responses should consider environmental, social and economic aspects in order to identify effective mechanisms that balance the needs and maximize benefits to all.

The global application of marine protected area networks helps to promote mitigation and adaptation to climate change (Dudley and others, 2010; Roberts and others, 2017) by supporting ecosystem resilience. By building resilience, ecosystems have a greater ability to cope with perturbations and recover from adverse circumstances, thereby maintaining ecosystem functions and provision of services necessary to human well-being (Chong, 2014).

Resilience-based management (alongside area-based management tools) uses knowledge of current and future drivers influencing ecosystem function (e.g. coral disease outbreaks, changes in land use, trade or fishing practices) to prioritize, implement and adapt management actions that sustain ecosystems and human well-being (Mcleod and others, 2019). To support the maintenance of ecosystem resilience, managers must reduce local stressors (e.g. pollution, destructive fishing pressures), while fostering key resilience processes (e.g. recovery, reproduction, recruitment and connectivity) (Anthony and others, 2015; Graham and others, 2013). This requires managing the causes and consequences of the endogenic (local) pressures and responding to the consequences of the exogenic (global) pressures, given that responding to the causes of the latter requires global action (Elliott, 2011). For example, marine protected area networks can be designed for climate resilience by maintaining a diversity and redundancy of species, habitats and functional groups and pathways of connectivity and reducing stressors, and by including adaptive processes can accommodate uncertainty and change (Mcleod and others, 2019). Coral resilience and associated ability to recover from bleaching events across Hawaii's MPA network is supported through active management of herbivore fish aimed at maintaining and/or increasing herbivore biomass, abundance and functional diversity (Chung and others, 2019).

[341] These follow a hierarchy of management measures: preventative measures (such as stopping pollutants from entering the sea); mitigation measures (reducing the direct impacts); and compensation, for example by compensating the user (such as fishers for a loss of catch), the resource (such as by re-stocking fishes or replanting mangroves), or the habitat (by creating new habitats to compensate those lost by building infrastructure) (Elliott and others, 2016).

Along with MPA networks, there is a diversity of adaptation measures that can be carried out at the community and institutional level. These include tools such as cross-sectoral coordination, flexible fishing licences, seasonal rights, transboundary management or enhanced institutional cooperation which can be applied in conjunction with market and livelihood diversification and resilience-building tools such as emergency preparedness, early-warning systems, remittances and post-disaster recovery plans (Poulain and others, 2018). In applying specific management tools, trade-offs should also be considered, as these tools can trigger contrasting effects on different sectors or countries. In the Arctic, for example, transboundary cooperation engages new actors and sectors, for example, polar tourism, but also brings new risks, such as shipping and mineral exploration and exploitation. In the Mediterranean, transcontinental cooperation (Europe-Africa) is needed to embrace regional adaptation measures to deal with contrasting local needs and adaptive capacities of European and African countries (Karmaoui, 2018, Hidalgo and others, 2018).

5. Key region-specific issues

The implementation of the ecosystem approach through decision-making processes and management tools in the marine environment has progressed at different paces in different regions. Regions with higher skill-levels, financial capacities and resources have seen considerable progress in the implementation of the ecosystem approach. For example, rapid environmental change in the Arctic Ocean, driven by large-scale warming, has necessitated a shift by the Arctic Council from a focus on soft-policy scientific assessments to legally binding agreements negotiated by member countries. These agreements have also become necessary as a result of the increasing opportunities for industrial uses of the Arctic Ocean, and their attendant risks, including shipping activities, Arctic tourism, the transfer of alien species and mineral exploitation on the continental shelf of Arctic coastal States. These rapid changes have prompted countries to adjust their policies to better respond to fast-emerging social, economic and environmental challenges resulting from climate change. Canada, for example, amended its Oceans Act in 2019 to be able to apply precautionary principles and allow interim protection for an area for a period of up to five years, through the use of a Ministerial Order provision that freezes the footprint of human activities, meaning that no new or additional human activities will be allowed to occur in the area for the duration of the order. In 2019, the Tuvaijuittuq marine protected area was the first area created through the use the Ministerial Order provision and was created to protect the oldest and thickest sea ice in the Arctic Ocean as an important summer habitat for species as ice cover continues to decline in the Arctic.

In regions with more limited capacity, it is more difficult to implement the ecosystem approach. Many marine and coastal areas in such regions are confronting decades, if not centuries, of degradation as a result of a lack of management practices or controls and due to the fact that restoration approaches are being implemented reactively. In South America (Gianelli and others, 2018; Reis and D'Incao 2000), implementation of ecosystem approaches to fisheries has struggled with both limits to institutional and to scientific capacity, which has limited success to areas with favourable enabling conditions. Similar capacity challenges are seen in the management of MPAs (Gerhardinger and others, 2011), although engagement with local knowledge holders has seen improvements in outcomes (Gerhardinger and others, 2009).

Much of the recent growth in the surface areas of MPAs can be accounted for by a small number of countries that have established large marine protected areas. Although the data reflect progress towards the conservation of biodiversity and marine resources, protection is still focused on waters under national jurisdiction and those countries with the capability and capacity to identify and implement MPA networks. However, the designation of an MPA is not necessarily reflective of active management and protection, since many of them lack adequate management plans and associated enforcement measures (UNEP-WCMC, IUCN, 2019; Maestro and others, 2019). Similarly, the uneven geographical distribution of MPAs limits their effectiveness, connectivity, coherence and representativeness.

Finally, climate change is becoming a key driver in prioritizing restoration approaches in many parts of the world, including the restoration of mangrove forests in Indonesia and in a number of small island developing States in the Pacific Ocean, aimed at protecting local communities from coastal inundation (FAO, 2016) and increasing resilience to future changes, and the restoration of parts of the Great Barrier Reef in Australia following multiple bleaching events (RRAP Consortium, 2018). The restoration of coral reefs in the Caribbean and oyster reefs worldwide employed small-scale techniques, such as micro-fragmentation, to address local-scale damage (Gilby and others, 2018). However, such approaches are often still limited in their scale. Further examples of climate adaptation and disaster risk reduction include the measures undertaken by Grenada, Ecuador and Colombia with respect to mangrove restoration and coastal protection; the United Kingdom with respect to coastal realignment; Mexico with respect to sustainable fishing and mangrove rehabilitation; and Vanuatu with respect to coral reef restoration (CBD, 2019). The forthcoming United Nations Decade on Ecosystem Restoration (2021–2030)[342] aims to accelerate this trend (Waltham and others, 2020).

6. Capacity-building

Most management approaches require information that cuts across natural and social sciences. In many regions, especially in developing countries, scientists and practitioners are simply not sufficiently trained to implement existing or new approaches to management, particularly those involving the ecosystem approach. Increased capacity, not only in understanding management approaches, but also in having the tools to implement them, will support governments and other stakeholders to understand the suite of options available for marine management and governance in their jurisdictions. Hence, there are several key capacity-building and technology-transfer requirements in this field. First, there is a need for training and expertise in marine management and governance linked to the required science, including training in policy drivers, as well as policy-relevant science and policy repercussions of science, that is, how relevant science can be used in developing policy and what adaptations/revisions need to be made to policy as new scientific information becomes available. Second, there is a large scope for learning within and between nations and regions (i.e. knowledge and technology transfer), especially since some approaches have worked well in some conditions, such as MSP programmes under the Convention for the Protection, Management and Development of the Marine and Coastal Environment of the Western Indian Ocean (Nairobi Convention). In this regard, increased capacity in transboundary cooperation

[342] See United Nations General Assembly resolution 73/284.

is needed, with science-based management as a core element. Third, there is also a large scope for learning across the breadth of different policies, including how policy was derived, especially for new practitioners but also as continuing professional development for more experienced professionals.

Knowledge of the key stages in implementing the planning and policy process for marine management, as well as the metrics for measuring and monitoring the effectiveness of management measures, are key requirements for countries starting to implement management approaches. Also important, in this regard, is an understanding by scientists and other stakeholders (including the public) of policymaking and management of public behaviour, including related economic aspects. To achieve these goals, both formal and non-formal approaches to education are required. In addition, transfer of knowledge on decision-making processes and tools across sectors should be promoted in order to ensure that the ecosystem approach can be applied holistically across marine sectors.

Gill and others (2017) indicated that staff and budget capacity are the strongest predictors of conservation impacts. In this study, MPAs with adequate staff capacity had ecological benefits 2.9 times greater than those with inadequate capacity. Creating MPAs without adequate investment will, therefore, result in suboptimal conservation outcomes. Limited resources in some cases may increase the need for citizen science programmes that can complement and/or support monitoring limitations (e.g. in the United Kingdom for shore biota monitoring and beach litter monitoring/clean-up programmes, and Reef Check, MangroveWatch and the Manta Trust) in their global programmes (see also section 7.1 below). These techniques can be deployed worldwide as best practices for greater benefit.

7. Gaps and future perspectives

7.1. Data and information for management needs

Marine management approaches, processes and tools are often hampered by lack of data of appropriate quality and quantity (Borja and others, 2017). Recent developments in the use of big-data methods, innovative use of data and information in policy approaches and the linking of databases help to provide information in such situations. However, understanding of ecological cause and effect related to socioeconomic priorities, as reflected in modelling expertise and scientific support systems for decision-making (recognizing the complexity of coastal and marine systems), is still limited across many regions. Sharing of knowledge (e.g. OBIS) and open access to information and data streams, particularly across sectors, should be encouraged in order to ensure that the data collected are made available to all (e.g. “collect once, use many times”). Enhanced collaboration and connectivity of monitoring programmes will assist, not only in the sharing of capacity across sectors and institutions, but also in providing for more efficient approaches to monitoring and provision of data and information. Data from citizen science are increasingly becoming an important source of monitoring information, where they are validated and accepted by the academic community (Bennett, 2019) to provide key information on environmental state and trends (e.g. Edgar and Stuart-Smith, 2014).

Challenges that still need to be addressed include the gathering of data for marine management in a cost-effective manner. The role of technology in marine conservation and management will become increasingly important, especially the collection and use of data from remote sensing and satellites. In sectoral and spatial management, for example, Automatic Identification System (AIS) and Vessel Monitoring System (VMS) data are used to manage shipping and fishing activities, particularly for mapping. Novel analytical approaches, such as machine learning, are increasingly being applied to identification of illegal activities in these sectors (Longépé and others, 2017) and to monitor fishery catches (Lee and others, 2008).

7.2. Management requirements

Marine management requires the best available science for maintaining and protecting the natural system, while also providing benefits for the private sectors and for society. More research is needed on ecological adaptation/resilience, inter alia, and the prediction of ecosystem response trajectories. These variables should be built into management approaches that cover the scale of both the impact and the response of marine ecosystems, which implies the need for a greater recognition of human intervention in the marine environment as measured against baselines and for using thresholds and targets for unacceptable change. However, this is a major challenge and there is often no baseline or, because of climate change, baselines are moving. Establishing better interconnected monitoring programmes across institutions is also needed. Areas beyond national jurisdiction present a major challenge in this regard, particularly in deep sea ecosystems that are poorly surveyed.

Management approaches are underpinned by detailed governance mechanisms, such as policies, polities, administration and legislation. Improving the science-policy interface by enhancing capacity is necessary and particularly important where the knowledge base of informing decision-making is quickly expanding and emerging. Greater coordination is needed in this regard between social and natural sciences, between scientists and policymakers and between science and civil society, including industry, as is inclusion of traditional knowledge, culture and social history into management. Such cross-sectoral understanding is important for management that is truly holistic.

7.3. Incorporating multiple values into management

The present Chapter has shown an evident trend in management approaches from focusing on predominantly ecological aspects to the inclusion of diverse links between ecological and societal/economic/cultural aspects of the marine environment. Management would be better equipped to achieve the fundamental goal of protecting and maintaining natural systems if it also recognized the wide range of ecosystem services and benefits derived from our oceans. Protecting and preserving the marine environment depends on engaging those who live or work with the sea, and who gain benefits from it, to address deleterious behaviours, to restore systems inadvertently damaged, and to mitigate the impacts of a changing climate.

However, the values that people place on the marine environment and its services vary not only in quantity but also in character. Challenging to most management systems is the need to accommodate Mthe multiplicity of values, where real or perceived benefits cannot be equated with each other, or reconciled. The best opportunities to understand and address multiple values are those that engage affected communities in the management approach, and hence the need to combine ecosystem-based management with community-based management that is sensitive to the cultural dimensions of the sea. Such hybrid systems are more capable of balancing all three pillars of sustainable development (environmental, economic and social) and, as such, are likely to be more successful.

8. Outlook

While the present Chapter has identified a plethora of approaches to the management of the marine environment, there is still much that can be done to improve and enhance progress, including with regard to the successful integration of the Sustainable Development Goals (SDGs), especially SDG 14, into management objectives and programmes. There is also a need for increased integration of measures to manage anthropogenic pressures not currently the focus of management measures, for example anthropogenic noise.

The implementation of the 2030 Agenda for Sustainable Development requires management grounded in the ecosystem approach in order to achieve the integrated set of global priorities and objectives set out in its SDGs. This will allow for the integration of the interactions, benefits and trade-offs between the SDGs and support achievement of each of the ocean-related targets. Overall, the progress made to date, notwithstanding existing actions for the implementation of SDG 14, is insufficient. Accelerated action, in particular in respect of SDG 14 targets that mature in 2020, is necessary on an urgent basis, including for targets 14.2, 14.4, 14.5 and 14.6.[308] Although SDG 14 does not explicitly include any reference to marine cultural aspects, the outcome of the United Nations Conference to Support the Implementation of Sustainable Development Goal 14, “Our ocean, our future: call for action”, includes the need to develop comprehensive strategies to raise awareness of the natural and cultural significance of the ocean.[343] Similarly, the SAMOA Pathway recognizes the cultural connection of the communities of small island developing States to the ocean and the importance of traditional knowledge in the sustainable development of ocean-based economies.[344]

The outputs of the United Nations Decade of Ocean Science for Sustainable Development (2021–2030)[345] and the concurrent United Nations Decade on Ecosystem Restoration[342] will support the implementation of SDG 14 and provide many of the necessary data sources to apply management processes and tools, and will increase ocean literacy[346]. These initiatives have the potential to progress the tools needed for current and future decision-making, improve overall understanding of issues and solutions for ocean management and increase societal engagement in decision-making and solution applications. Integration of the protection of the underwater cultural heritage in the United Nations Decade of Ocean Science for Sustainable Development[347] is also pertinent to support the tangible and intangible

[343] See United Nations General Assembly resolution 71/312, annex.
[344] The SIDS Accelerated Modalities of Action (SAMOA) Pathway; see United Nations General Assembly resolution 69/15, annex; https://sidsnetwork.org/samoa-pathway/
[345] See United Nations General Assembly resolution 72/73.
[346] https://oceanconference.un.org/commitments/?id=15187 and http://ioc-unesco.org/index.php?option=com_oe&task=viewEventAgenda&eventID=2200
[347] See United Nations General Assembly resolution 72/73, para. 292; see also Ocean Decade Heritage Network,

resources and cultural benefits provided by oceans (UNESCO, 2019; Trakadas and others, 2019).

While it is implicit in the context of marine management, the present Chapter has not covered the detailed nature of marine governance, nor the challenges associated with the sectoral and often fragmented nature of administrative bodies (e.g. Boyes and Elliott, 2014, 2015). In order to be effective across wider scales and for species that span large scales, both area and non area-based management approaches will need to overcome the often fragmented and complex governance regimes worldwide.

Effective management of marine resources will also need to extend beyond areas under national jurisdiction to ABNJ, where challenges are greater due to the complexities of the legal regime. This gives added significance to the current negotiations at the United Nations on an international legally binding instrument under the United Nations Convention on the Law of the Sea for the conservation and sustainable use of marine biological diversity of ABNJ (see Chapter 31 of the present Assessment). Similar discussions have been initiated at UNESCO on the expansion of the scope of application of the World Heritage Convention to provide for the protection and management of marine sites of outstanding universal value in high seas areas (UNESCO, 2016; UNESCO, 2019).

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Chapter 31
Developments in the Understanding of Overall benefits from the Ocean to Humans

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Keynote points

- Ocean resources provide main sources of livelihoods to millions of people across the globe. They also provide a wide range of ecosystem services or benefits including oxygen production, food provision, carbon storage, minerals, genetic resources and cultural and general life support services. However, these ecosystem services from marine and coastal ecosystems are deteriorating at an alarming rate, due to several human pressures, including climate change.
- Human activities are directly or indirectly affecting ecosystem services and thus can reduce or erase benefits that otherwise would be provided. As human activities in the marine environment are expected to increase in the future, in particular in areas beyond national jurisdiction, they will not only exert growing pressure on natural resources, but may also threaten marine biodiversity and thus the benefits people obtain from ecosystem services.
- International law as reflected in the United Nations Convention on the Law of the Sea[348] plays a crucial role in the conservation and the sustainable use of the ocean and its resources and in safeguarding the many ecosystem services that the ocean provides both for current and future generations. Actions and efforts should primarily focus on implementation and regulatory gaps, especially in areas beyond national jurisdiction.
- This gives added significance to the current negotiations at the United Nations on the elaboration of an international legally binding instrument under the United Nations Convention on the Law of the Sea on the conservation and sustainable use of marine biological biodiversity of areas beyond national jurisdiction.
- The distribution around the world of the benefits drawn from the ocean is still very uneven. Gaps in capacity-building and resource and financial constraints hamper less developed countries in taking advantage of what the ocean can offer them.
- Capacity-building and shared scientific knowledge, collaboration to develop and transfer innovative marine technology will empower States to fully participate in and benefit from the conservation and sustainable use of the ocean and its resources and assist them in meeting their obligations.

1. Introduction

[348] United Nations, *Treaty Series*, vol. 1833, No. 31363.

Ocean resources provide the basis for the livelihoods of millions of people across the globe, and also provide a range of critical ecosystem services, including oxygen production and carbon storage, several biodiversity related services, like harvesting of living resources, coastal protection and genetic resources (Mohammed, 2012) and cultural and amenity services (Whitmash, 2011). The most commonly valued services are tourism and recreation, and storm protection (Mehvar and others, 2018). Fisheries alone provide multiple benefits to millions of people, including those living in poverty in coastal communities of low-income countries. Fish and other seafood are a major source of food, protein and micronutrients for many vulnerable communities. It is also estimated that, in 2016, 59.6 million people were employed in the primary sector of capture fisheries and aquaculture, with a great majority in low-income countries (although this figure includes some inland activities). With the addition of those who work in associated processing, marketing, distribution and supply industries, it is estimated that fisheries and aquaculture support nearly 250 million livelihoods (FAO, 2018).

Benefits from marine and coastal ecosystems can be categorized in several ways. Traditionally, these benefits have been understood in terms of "goods" (i.e. products, resources, harvests from nature with a market value), "services" (i.e. processes that sustain all forms of life but that do not have a market value), and "cultural benefits" (i.e. spiritual, religious heritage, with no explicit market value). Whilst goods have a direct use (consumptive) value, determined through market prices, services and cultural benefits have an indirect use (non-consumptive) value that can be determined through the application of a variety of valuation techniques (See Figure 1).

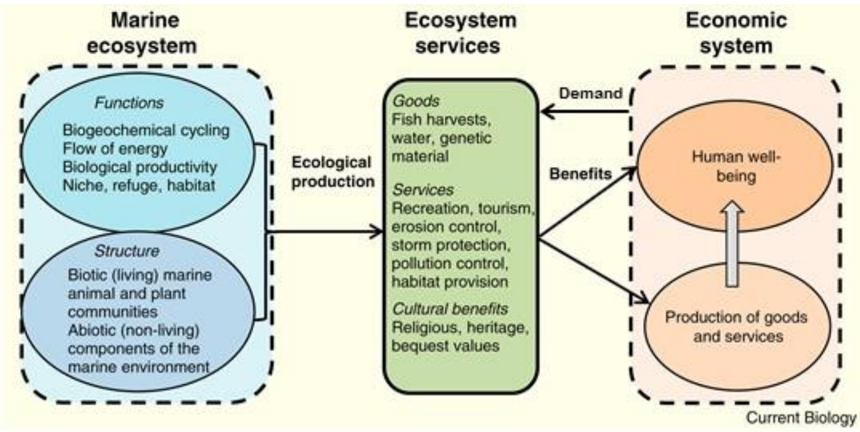

Figure 1. How marine ecosystems generate economic benefits.
The structure and functioning of marine ecosystems lead to the ecological production of ecosystem services. Some of these goods, services and cultural benefits directly impact human well-being, whereas others indirectly impact the welfare of humans through supporting or protecting valuable economic assets and production activities

Source: Adapted from Barbier, 2017.

The seminal Millennium Ecosystem Assessment (2005) proposed a different classification of benefits obtained by humans from ecosystems, which it simply called "ecosystem services". These are disaggregated as Provisioning, Regulating, Cultural and Supporting, the latter category being needed for the existence of the previous ones. Provisioning services, such as the food, fuel and fibre extracted from ecosystems, are akin to consumptive benefits and have a use value, while other services, such as regulating the climate, absorbing carbon dioxide, maintaining life cycles and landscapes, creating income and employment opportunities and cultural identity, are mostly immaterial (i.e. non-consumptive in nature, with a non-use value).

1.1. Provisioning services of marine and coastal ecosystems

The ocean provides a multitude of direct and indirect benefits of value to humans. The most direct benefit that marine and coastal ecosystems provide is through their primary productivity and its resulting products, such as fish, plants, animals, fuel, timber (e.g. mangroves), biochemicals, natural medicines, pharmaceuticals, raw materials (sand, corals), and to a lesser extent, freshwater and fibre. In 2016, 79.3 million tonnes of marine fish[349] were caught, and 28.7 million tonnes of marine aquaculture species[349] were farmed, supplying together an average 14.6kg of seafood per person on earth (FAO, 2018). Seafood is essential for food security - it provides more than 20 per cent of the average per capita animal protein intake for 3 billion people, and more than 50 per cent in some developing countries (FAO, 2018).

1.2. Regulating services of marine and coastal ecosystems

Oceans also perform fundamental regulating services. They influence biologically mediated processes, e.g. carbon fixation and oxygen release, enabling climate mitigation and regulation. Similarly, coastal fringes perform a key role in sequestering carbon. These services have an indirect use value to humans as they enable the maintenance of favourable and stable climate conditions (e.g. temperatures, precipitations) to which livelihood activities have adapted (e.g. crop cultivations), the preservation of human health, and infrastructures and other assets on which livelihoods depend. The role of coastal ecosystems in controlling pests and animal populations through trophic-dynamic relations and supporting pollination helps to keep at bay pests and diseases that can impact cultivations, aquaculture activities and, potentially, human health.

Coastal ecosystems play an important role in the prevention of coastal erosion and can act as both shoreline stabilization and protection against storms, attenuating the strength of the waves and reducing the vulnerability of coastal settlements to sea surges and flooding events. For example, it was estimated that the Indian Ocean tsunami of 2004 caused greater damage to areas that had been converted to shrimp ponds and other uses than those where the mangrove had remained intact (EJF, 2006) and that, overall, the thicker the mangrove fringes are, the greater the protection to economic activity they offer (Hochard and others, 2019). Though to a lesser extent, coral reefs, seagrass beds and other vegetated coastal ecosystems can also have a significant impact in dissipating wave action and offering shoreline protection (Spalding and others, 2014) provided that they are in “healthy” state themselves..

1.3. Supporting services of marine and coastal ecosystems

Photosynthesis occurring in marine and coastal ecosystems enables the conversion of solar energy into plants and animals and the maintenance of the net primary productivity of these ecosystems. Coastal ecosystems perform a key role in maintaining biodiversity and suitable reproductive habitats and nursery grounds for aquatic species. The ecological niches and

[349] Excludes aquatic mammals, crocodiles and related, seaweed and other aquatic plants.

refuge for wild animals and plants they provide directly support the provisioning services of marine and coastal ecosystems. For example, seagrass beds in the Mediterranean are estimated to contribute 30 to 40 per cent of the value of commercial fisheries landings and approximately 29 per cent of recreational fisheries expenditure (Jackson and others, 2015). Coastal ecosystems also act as pollution sinks and enable the storage and recycling of nutrients, and support water cycling.

1.4. Cultural services and other social benefits of marine and coastal ecosystems

The aesthetic, cultural religious and spiritual services from the ocean ("cultural services") cover a wide range of practices. These services are essential in the maintenance and creation of social capital, education, cultural identity and traditions (human and social capital). All around the world, many beliefs and rituals are rich in references to the sea. Research on marine and coastal cultural ecosystem services is, however, still limited (Garcia Rodrigues and others, 2017, Blythe and others, 2020; Diaz and others, 2018).

Some cultural practices form integral parts of the traditional use of the ocean (such as ways of building boats or harvesting shellfish, and stone fish traps found across the coast of South-East Asia, Australia and the Pacific Islands). The diversity and technological sophistication of these structures attest to indigenous traditional knowledge of the ocean and its resources (Jeffery, 2013; Rowland and Ulm, 2011) Traditional watercraft like the Hawaiian voyaging canoe *Hōkūle`a* provide an active platform for the restoration and maintenance of Pacific non-instrument navigation and cultural identity. Numerous other voyaging canoes have been constructed in the Pacific and, in many places, the knowledge of traditional wayfinding has been preserved. Fautasi races in Samoa and dragon boat races in China merge history and cultural traditions with health, fitness and contemporary competition. People have long incorporated water-related activities as habitual or significant parts of their lives. Non-consumptive ocean activities also include swimming, diving, kayaking, surfing, sailing and wildlife viewing.

Finally, for many indigenous communities, fishing and the sharing of fish form essential parts of traditional foodways, which support socio-cultural cohesion and identity as well as linked ceremonial and cultural practices (Loring and others, 2019; Leong and others, 2020).

Other cultural activities represent ways of reacting to the ocean (such as dances to celebrate the ocean or religious practices to safeguard against danger on the ocean). These practices can constitute an important part of the cultural heritage of a people. One example is the role of whale hunting for the indigenous peoples of the western seaboard of Canada and the United States of America, as discussed in WOA I. One tribe in Washington State, United States of America, the Makah, has been pursuing special authorization to resume some whale hunting since 2005. In November 2019, a hearing was held into their request and, in February 2020, a revised environmental impact assessment was published. They fear that, without the special authorization, this element of their culture would remain a connection to the past without any present reinforcement. (NOAA, 2015; NOAA, 2020).

Heritage is also a part of the cultural services provided by the ocean, providing significant, though often unquantified, social and economic benefits (Firth, 2015). The iconic nature of underwater cultural heritage, such as historic shipwrecks, captures archaeological and historical information, revealing unique aspects of past human seafaring and behaviour, to be shared through museums, documentaries and public research. Shipwrecks can also yield valuable information about the sociocultural, historical, economic, and political contexts at various scales of reference (local, regional, global) between the date of the vessel's construction (e.g. hull design, rig, materials used, its purpose, etc.) and its eventual demise in the sea (e.g. due to warfare, piracy/privateering, intentional abandonment, natural weather events, etc.) (Gould, 1983). The remains of prehistoric and historic landscapes submerged by changing sea levels and the continuing destruction of important coastal sites by exposure and erosion are important reminders of climate change in the human past and of the impact of the climate crisis today (Harkin and others, 2020).

Wreck site tourism plays a role in the recreational diving industry. Services memorializing vessel losses, such as wreath-laying ceremonies at submerged warship gravesites, expresses a deep connection to sacrifice at sea. The diversity of cultural services arising from shipwrecks, and other historic structures in the sea, is complemented by the role that underwater cultural heritage can play as artificial reef, providing habitats that are important for nature conservation, sea angling and commercial fishing, for example (Firth, 2018).

Finally, there is the sense of place engendered in onlookers by the ocean. The sense of openness and exposure to the elements can be very important to those who live by the sea or visit it as tourists. As discussed in Chapter 8B of the present Assessment, on human health and the ocean, there is growing evidence that the sense of openness engendered by the ocean can improve human health. The ocean has also been an important source of inspiration to artists, composers and writers, often reflecting economically important aspects of society. Some studies reveal the deep emotional attachment of people to the marine environment (e.g. the Black Sea in Fletcher and others, 2014, and the North Sea in Gee and Burkhard, 2010), and the importance of maintaining this relationship to preserve both nature and culture (Fletcher and others, 2014). However, despite progress to date, marine research and management have until recently largely neglected the critically important role of "sense of place" and its role in influencing the success and efficacy of management interventions (van Putten, 2018; Hernandez and other, 2007).

Opportunities for income generation and employment opportunities, for education and recreation and for scientific and artistic information and inspiration, are also part of the wider range of social benefits that marine and coastal ecosystems provide, and upon which the well-being of populations, regardless of their distance from the shore, hinges directly and indirectly.

2. Benefits and their distribution

While some benefits from the ocean are very central and ensure the existence of life on earth, like the production of oxygen, and the uptake of carbon dioxide and heat, most services are related to specific ecosystems or elements therein and are thus not fairly distributed. Moreover, not all States have the capacity to participate fully in and benefit from the ocean and its resources. This might be either because they do not have access to ocean, like landlocked States, or do not have the financial means to develop maritime industries, which is the case for many developing countries. Some States do not have the capacity to access areas beyond national jurisdiction or even parts of their own exclusive economic zone. For example, in areas beyond national jurisdiction, the collection of marine genetic resources, their sequencing and potential commercialization are currently concentrated within a small number of countries (Blasiak and others, 2019; Harden-Davies, 2019; Levin and Baker, 2019; Blasiak and others, 2018).

One of the main provisioning services, living resources, is not only unevenly distributed, with productivity hotspots concentrated in the upwelling areas of the world (Kämpf and Chapman, 2016), but a very substantial proportion of capture fisheries are carried out by relatively few fishing vessels from few States. Vessels from 25 States took 42 per cent of the global catch in 2016 (FAO, 2018). Thus, profits are not necessarily going to the countries with the exclusive economic zone producing the fish. McCauley and others (2018) found that vessels flagged to higher-income nations, for example, are responsible for 97 per cent of the trackable industrial fishing on the high seas and 78 per cent of such effort within the national waters of lower-income countries.

Economic assessments of cultural ecosystem services benefits are increasingly undertaken applying environmental valuation methods to recreational use like tourism, marine recreational fishing, whale watching, and enjoying seascape (Hanley et al 2015, Aanesen et al 2018, Spalding and others, 2017) as well as non-use values (i.e. existence and bequest values) of coral reefs and other marine biodiversity (Aanesen et al 2015, Navrud et al 2017). Tourism rely particularly on specific characteristics such as coral reefs (Brander et al 2007) and specific activities like cruise tourism, and are concentrated in certain areas like the Caribbean and the Mediterranean but increasingly also in polar areas (see Chapter 8C).

The International Seabed Authority has been established as the organization through which States Parties to the United Nations Convention on the Law of the Sea organize and control activities in the Area (i.e. all activities of exploration and exploitation of the mineral resources of the seabed and ocean floor and subsoil thereof beyond the limits of national jurisdiction) for the benefit of mankind as a whole and to provide for the equitable sharing of financial and other economic benefits from activities in the Area (Article 140). However, in addition to economic benefits from deep seabed mining, the benefits from leaving ecosystems intact should also be considered in the context of Article 140, thus integrating redistribution (international solidarity) with ecological preservation (intergenerational solidarity) (Tladi, 2015, Feichtner, 2019).

Specific revenue-sharing obligations are also included in Article 82 of the Convention, which provides for a system of payments or contributions in kind by coastal States with respect to the exploitation of the non-living resources of the continental shelf beyond 200 nautical miles. Such payments or contributions are to be made through the International Seabed Authority for distribution to States Parties to the Convention, on the basis of equitable sharing criteria (Spicer and McIsaac, 2016).

3. Disbenefits to humans

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services conceptual framework defines nature’s contributions to people as all the positive contributions or benefits (including ecosystem services) and occasionally negative contributions, losses or detriments, that people obtain from nature (Pascual and others, 2017). The negative contributions of nature, which in some fields have become known as ecosystem disservices, are beginning to be incorporated into ecosystem service assessments (Campagne and others, 2018).

Ecosystem disservices or disbenefits are functions or properties of ecosystems that are unpleasant or cause harm, either by reducing ecosystem services or directly affecting humans (Lyytimäki, 2014; Shackleton and others, 2016). Direct effects on humans are, for example, caused by floods and storm surges, which can lead to economic losses of several billion to over 100 billion United States dollars annually (Kousky, 2014). Direct harm to humans can also come through seafood-borne diseases, mainly caused by harmful algal blooms such as Amnesic Shellfish Poisoning, Paralytic Shellfish Poisoning, Diarrhetic Shellfish Poisoning, Neurotoxic Shellfish Poisoning and Ciguatera Fish Poisoning. Besides the negative impact on human well-being, these diseases also cause economic losses due to hospitalization expenses and lost productivity (Sanseverino and others, 2016). Harmful algal blooms can also cause losses in terms of fisheries and aquaculture production. Natural and sedimentation can negatively affect human activities, including shipping.

Despite the recognition of the occurrence of negative contributions from nature, the increase in these occurrences and magnification of these events are, most of the times, related to anthropogenic activities and pressures. For instance, coastal flooding normally affects human settlements misallocated in low and susceptible coastal areas. Likewise, some algae blooms are due to contaminants from human activities.

4. Threats to ocean ecosystem services

Human activities are directly or indirectly affecting ecosystem services and thus can reduce or erase benefits that otherwise would be provided. These threats are the pressures which are detailed in Chapters 9–28 of the present Assessment. As human activities in the marine environment are expected to increase in the future, in particular in areas beyond national jurisdiction, they will not only exert growing pressure on natural resources, but may also threaten marine biodiversity and thus the benefits people obtain from ecosystem services (Altvater and others, 2019). Relatively little is understood about how social and ecological processes interact to determine marine ecosystem benefits (Outeiro and others, 2017). While the co-production process can sustain desirable ecosystem service flows, it can also produce trade-offs which constrain flows of ecosystem services or exacerbate the provision of disservices, with negative impacts on human well-being at a range of scales (Pope and others, 2016). These impacts, which can be categorized as extractive (e.g. fishing, mining, offshore hydrocarbon exploration and extraction, offshore and marine renewable energy installation and mangrove exploitation) and non-extractive threats (e.g. ocean warming and acidification, eutrophication, pollution, and habitat destruction and conversion), interact, often with compounded effects (McCauley and others, 2015; Sumaila and others, 2016; Simas and others, 2014; O-Hagan and others, 2015; Greaves and others, 2016).

5. Safeguarding ocean benefits through regional and international cooperation and improved implementation of international law as reflected in the United Nations Convention on the Law of the Sea

5.1. United Nations Convention on the Law of the Sea, its implementing agreements and related instruments

The United Nations Convention on the Law of the Sea,[348] which sets out the legal framework within which all activities in the oceans and seas must be carried out, plays a crucial role in the conservation and sustainable use of the ocean and its resources and in safeguarding the many ecosystem services that the ocean provides for both current and future generations.

Integration of the environmental, social and economic dimensions is at the core of the Convention, which establishes a delicate balance between the need for economic and social development through the use of the oceans and their resources and the need to conserve and manage those resources in a sustainable manner and to protect and preserve the marine environment. It also provides a framework for international cooperation in the conservation and sustainable use of the oceans and its resources, which can take place through intergovernmental institutions, or bilaterally among States (United Nations, 2017b).

The integrated approach to ocean management as reflected in the Convention is essential for promoting sustainable development, as sectoral and fragmented approaches lack coherence and may lead to solutions that have a limited impact on the conservation and sustainable use of the oceans and their resources. At the international level, it is important that this integrated approach guides the regulatory work and capacity-building activities of international organizations in the framework of their competences and that such organizations effectively respond to the increasing need for coordination and cross-sectoral cooperation. At the same time, at the national level, the integrated approach requires that a comprehensive legal framework for ocean matters be put in place and that institutional mechanisms enabling inter-agency cooperation be set up and improved.

The Convention is, in many fields, supplemented by more specific, sectoral instruments. In addition to its two implementing agreements, the 1994 Agreement relating to the Implementation of Part XI of the United Nations Convention on the Law of the Sea of 10 December 1982[350] and the 1995 Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks,[351] there are numerous other international legal instruments both at the global and regional levels covering many aspects of ocean use, including the conservation and sustainable use of oceans and their resources.

Such instruments include, inter alia, global treaties relating to sustainable fisheries management, including the 2009 FAO Agreement on Port State Measures to Prevent, Deter and Eliminate Illegal, Unreported and Unregulated Fishing, pollution from ships, maritime safety, atmospheric pollution, the release of hazardous substances into the environment, the protection of certain species or habitats and the conservation and sustainable use of biodiversity, the working conditions of seafarers, fishers and other maritime workers, and the protection of underwater cultural heritage. A number of regional treaties are also included in this framework, including those that establish regional fisheries management organizations and arrangements (RFMO/As) as well as regional seas conventions and action plans. In addition, a number of soft law instruments also address relevant issues, including technical guidelines on fisheries, such as the FAO International Guidelines for the Management of Deep Sea Fisheries in the High Seas, the FAO Code of Conduct for Responsible Fisheries or the IOC-UNESCO Step by Step Approach for Marine Spatial Planning toward Ecosystem-based Management. While these guidelines are universal, they highlight best practices and regional specificities and, therefore, support individual countries in the implementation of global ocean agendas. Components of a working system for global ocean management are

[350] United Nations, *Treaty Series*, vol. 1836, No. 31364.
[351] Ibid., vol. 2167, No. 37924.

also supported by soft law mechanisms providing guidance for international action, such as the Rio Declaration on Environment and Development of the United Nations Conference on Environment and Development[352] and the 2030 Agenda for Sustainable Development[353] and its Sustainable Development Goals, in particular SDG 14 (Life below water).

Effective conservation and sustainable use of the ocean and its resources will be achieved only with the full and effective implementation of the whole of this body of international law. Actions and efforts should focus primarily on implementation gaps. All States are challenged by the implementation of such a comprehensive legal framework, in particular, developing countries. Many small island developing States and least developed countries lack the detailed knowledge and skilled manpower needed for ocean management, particularly in light of their limited resources and capacity compared to the large ocean areas under their jurisdiction. Capacity and technologies for planning and managing land-based activities that have impacts on coastal and marine environments, as well as those activities occurring in coastal and marine environments, will ensure that economic benefits can be maximized in an environmentally sustainable manner.

WOA I noted that capacity-building and shared scientific knowledge and the transfer of marine technology, taking into account the Intergovernmental Oceanographic Commission Criteria and Guidelines on the Transfer of Marine Technology, will empower States to fully participate in and benefit from the conservation and sustainable use of the ocean and its resources and assist them in meeting their obligations (United Nations, 2017a).

The situation has not changed drastically since then. Human, institutional and systemic capacities, as well as financing, continue to be the primary limiting factors, in particular for developing countries. Resource capacity, including financial capacity, remains a significant constraint in relation to the protection and preservation of the marine environment and marine scientific research, whilst technology constraints are often an impediment to effective implementation of a State's obligations (United Nations, 2017b; see also Chapter 30 of the present Assessment).

Gaps also exist with regard to the material or geographical scope of relevant instruments. For example, while some aspects of marine debris, plastics and microplastics are covered by several global, regional and national instruments, none, other than some regional action plans on marine litter, and sector-specific measures such as MARPOL Annex V, are specifically dedicated to these issues. At the same time, while there is widespread coverage by regional instruments relevant to the implementation of aspects of the United Nations Convention on the Law of the Sea and the Fish Stocks Agreement (United Nations, 2017b), still some gaps remain.

Special challenges are encountered in the enforcement of effective management measures in areas beyond national jurisdiction, primarily due to a lack of cross-sectoral coordination but also to regulatory gaps (Altvater and others, 2019; Chapter 30 of the present Assessment). These issues are currently being discussed at the United Nations in the context of the intergovernmental negotiations on the elaboration of a legally binding instrument under the United Nations Convention on the Law of the Sea on the conservation and sustainable use of

[352] *Report of the United Nations Conference on Environment and Development, Rio de Janeiro, 3–14June 1992*, vol. I, *Resolutions Adopted by the Conference* (United Nations publication, Sales No. E.93.I.8 and corrigendum), resolution 1, annex I.
[353] See United Nations General Assembly resolution 70/1.

marine biodiversity in areas beyond national jurisdiction.

Sustainable Development Goal (SDG) 14 can be a strong driver for strengthening ocean governance and enhancing policy coherence, whilst providing an impetus for collective global accountability for the oceans under the 2030 Agenda for Sustainable Development. In target 14.c of SDG 14, States committed to "enhance the conservation and sustainable use of oceans and their resources by implementing international law as reflected in UNCLOS".[354] Increasing participation in international instruments and addressing challenges of implementation, including resource and capacity constraints, strengthening intersectoral cooperation, coordination and information-sharing at all levels and developing new instruments to address emerging challenges in a timely fashion, will be key elements in accelerating the implementation of this target (United Nations, 2019).

5.2. The third implementing agreement of the United Nations Convention on the Law of the Sea on the conservation and sustainable use of marine biodiversity in areas beyond national jurisdiction, currently under consideration

Efforts to strengthen the international legal framework through the elaboration of new instruments include, in particular, the intergovernmental conference convened by the General Assembly to elaborate the text of an international legally binding instrument on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction. More specifically, following a decade of work in the framework of a working group and then a preparatory committee, the United Nations General Assembly decided in its resolution 72/249 of 24 December 2017 to convene an intergovernmental conference, under the auspices of the United Nations, to consider the recommendations of the Preparatory Committee established by its resolution 69/292 of 19 June 2015 on the elements and to elaborate the text of an international legally binding instrument under the United Nations Convention of the Law of the Sea on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction, with a view to developing the instrument as soon as possible.

The Conference convened three substantive sessions from 2018 to April 2020 to address the topic identified in the package agreed in 2011, namely the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction, in particular, together and as a whole, marine genetic resources, including questions of the sharing of benefits, measures such as area-based management tools, including marine protected areas, environmental impact assessment and capacity-building and the transfer of marine technology. Negotiations are at a critical juncture. Regrettably, however, in accordance with General Assembly decision 74/543 of 11 March 2020, the fourth session, initially scheduled for March/April 2020, was postponed due to the COVID-19 pandemic.

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[354] See United Nations General Assembly resolution 71/313, annex. The indicator to monitor progress against target 14.c, indicator 14.c.1, calls for an assessment of the number of countries making progress in ratifying, accepting and implementing through legal, policy and institutional frameworks, ocean-related instruments that implement international law, as reflected in the United Nations Convention on the Law of the Sea, for the conservation and sustainable use of the oceans and their resources. Recently, a new methodology for the measurement of such progress has been developed. Data to be collected based on the approved methodology will provide, for the first time, a baseline of the current state of implementation of the Convention and its implementing agreements with respect to the conservation and sustainable use of the oceans and their resources. See further DOALOS, *Information Note. Development of a methodology for Sustainable Development Goal Indicator 14.c.1*, 4 October 2019.

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7E. Ian Butler (Convenor); Hilconida Calumpong (Lead Member), Karen Evans (Sub-chapter Lead Member), Hazel Oxenford, Hiroya Yamano, Alex Rogers, Raquel Silva Peixoto, Kemraj

Parsram

7F. Erik Cordes (Convenor); Malcolm R. Clark, Karen Evans (Sub-chapter Lead Member), Sebastian Hennige, Georgios Kazanidis

7G. Colin David Woodroffe (Convenor); Qiao Bing, Hilconida Calumpong (Lead Member), Ronaldo Christofoletti, Dana E. Hunt, Pablo Muniz, Tymon Zielinski (Sub-chapter Lead Member), Moriaki Yasuhara, José H. Muelbert,

7I. Hugh Kirkman (Convenor); Hilconida Calumpong (Lead Member), Sanae Chiba (Co-Lead Member), Elizabeth Sinclair, Paul Lavery, Nahid Abdel Rahim Osman, Konstantinos Topouzelis, Kiho Kim

7J. José Rosa Filho (Convenor); Hilconida Calumpong (Lead Member), Sanae Chiba (Co-Lead Member), Nahid Abdel Rahim Osman, Colin David Woodroffe, Phillip da Silva, Seon Hamer, Mario Soares, Mohammad Zahedur Rahman Chowdhury, Nahid Abdel Rahim Osman

7K. Judith Weis (Convenor); Hilconida Calumpong (Lead Member), Luis M. Pinheiro, Katherine Segarra, Alan Simcock (Sub-chapter Lead Member), Oscar O. Iribarne

7L. Lisa A. Levin (Convenor); Peter Auster, Hilconida Calumpong (Lead Member), Malcolm R. Clark, Jason Hall-Spencer, Russell Hopcroft, Jeroen Ingels, Anna Metaxas, Bhavani Narayanaswamy, Joshua T. Tuhumwire (Sub-chapter Lead Member), Moriaki Yasuhara, J. Murray Roberts

7M. Grant R. Bigg (Convenor); Maurizio Azzaro, Hilconida Calumpong (Lead Member), Karen Evans (Sub-chapter Lead Member), Huw Griffiths, Moriaki Yasuhara

7N. Malcolm Ross Clark (Convenor); Hilconida Calumpong (Lead Member), Angelo Fraga Bernardino, J. Murray Roberts, Bhavani Narayanaswamy, Paul Snelgrove, Joshua T. Tuhumwire (Co-Lead Member), Jason Hall-Spencer, Karen Stocks, Chunsheng Wang

7O. Jeroen Ingels (Convenor); Diva Amon, Angelo Fraga Bernardino, Punyasloke Bhadury, Holly Bik, Hilconida Calumpong (Lead Member), Malcolm R. Clark, Thomas Dahlgren, Daniel O.B. Jones, Craig McClain, Clifton Nunnally, Paul Snelgrove, Joshua T. Tuhumwire (Sub-chapter Lead Member), Moriaki Yasuhara, Fuji Toyonobu

7P. Peter Croot (Convenor); Hilconida Calumpong (Lead Member), Osman Keh Kamara (Co-Lead Member), Joseph Montoya, Tracey Sutton, Michael Vecchione, Tymon Zielinski (Co-Lead Member), Fernanda De Oliveira Lana

7Q. Ana Colaço (Convenor); Angelika Brandt, Hilconida Calumpong (Lead Member), Ana Hilario, Nuno Lourenço, Bhavani Narayanaswamy, Imants George Priede, Michael Vecchione, Joshua T. Tuhumwire (Co-Lead Member), Hiromi Kayama Watanabe, Ashley Rowden, Imants George Priede, Tomo Kitahashi

7R. Nadine Le Bris (Convenor); Hilconida Calumpong (Lead member), Sanae Chiba (Sub-chapter Lead Member), Ana Colaço, Elva Escobar, Anna Metaxas, Nomikou Paraskevi, Julia Sigwart, Verena Tunnicliffe, Hiromi Kayama Watanabe

7S. Howard S.J. Roe (Convenor); Hilconida Calumpong (Lead Member), David Freestone, Laurence Kell, Brian E. Luckhurst, Chul Park (Co-Lead Member), Tammy Warren

8B. Michael Moore (Convenor); Martin Edwards, Sarah Bella Galil, Osman Keh Kamara (Co-Lead Member), Essam Yassin Mohammed (Co-Lead Member), Alan Simcock (Lead Member), Anastasia Strati (Co-Lead Member), Dick Vethaak

8C. Alan Simcock (Convenor and Lead member); Austin Becker, Marcelo Bertellotti, Tony Charles, Leandra Gonçalves, Miguel Angel Iñíguez Bessega, Osman Keh Kamara (Co-Lead Member), Paula Keener, Jenna Lamphere, Candace May, Ishmael Mensah, Essam Yassin Mohammed (Co-Lead Member), Tanya O'Gara, Christina Pita, Jean Edmond Randrianantenaina, Maria Sahib, Regina Salvador, Anastasia Strati (Co-Lead Member), Jean-Claude Tibe, Gregory Wetterau, Robert Boysen,

9. Carlos Garcia-Soto (Convenor and Lead Member); Denise Breitburg, Monica Campillos, Patricia Castillo-Briceno, Sanae Chiba (Co-Lead Member), Matthew Collins, Ganix Esnaola, Karen Evans (Co-Lead Member), Louise B. Firth, Thomas Frölicher, Jason Hall-Spencer, David Halpern, Karen L. Hunter, Gabriel Ibarra, SungYong Kim, Roxy M. Koll, Kathleen McInnes, Jon Saenz, Ca Thanh Vu (Co-Lead Member), Bess Ward, Tymon Zielinski (Co-Lead Member)

10. Thomas Malone (Convenor); Archis Ambulker, Maria Bebianno (Co-Lead Member), Paula Bontempi, Michael Krom, Harri Kuosa, Joseph Montoya, Alice Newton, Yapo Ossey, João Sarkis Yunes, Walker Smith, Lars Sonesten, Georgios Sylaios, C. Taylor Armstrong, Juying Wang (Lead Member), Kedong Yin

11. Ralf Ebinghous (Joint Convenor), Bjorn Einar Grøsvik (Joint Convenor), Ida-Maja Hassellöv (Joint Convenor), Colin Moffat (Joint Convenor), Lars Sonesten (Joint Convenor), Penny Vlahos (Joint Convenor), Maria Bebianno (Lead Member), Bjørn Einar Grøsvik (Joint Convenor); Colin Moffat; Ralf Ebinghaus (Joint Convenor); Ida-Maja Hassellöv; Eric P. Achterberg, Babajide Ibitayo Alo, Carlos Francisco Andrade, Miguel Caetano, Peter Croot, Kissao Gnandi, Gi Hoon Hong, Suk Hyun Kim, Rainer Lohmann, Alan Simcock (Co-Lead Member), Monika Stankiewicz, Christos Tsabaris, Joshua T. Tuhumwire (Co-Lead Member), Juying Wang (Co-Lead Member), Bi Tra Boniface Nene, Kida Rose Ninsemon, Arsonina Bera, Qiao Bing, Isabel Natalia Garcia Arevalo, Jae Ryoung Oh, Julio Esteban Guerra Massón, Robin Anderson, Michael Angelidis, Judith Weis, Lars Sonesten

12. François Galgani (Joint Convenor), Aleke Stöfen-O'Brien (Joint Convenor), Archis Ambulkar, Maurizio Azzaro, Maria Bebianno (Lead Member), Joan Bondareff, Huw Griffiths, Martin Hassellöv, Christos Ioakeimidis, Jenna Jambeck, Paula Keener, Fernanda de Oliveira Lana, Iryna Makarenko, Chelsea Rochman, Qamar Schuyler, Paula Sobral, Konstantinos Topouizelis, Joshua T. Tuhumwire (Co-Lead Member), Dick Vethaak, Ca Thanh Vu (Co-Lead Member), Penny Vlahos, Juying Wang (Co-Lead Member), Judith Weis, Arsonina Bera, Alan Deidun, Bjørn Einar Grøsvik, Ahmed Md. Kawser, Qamar Schulyer

13. Ca Thanh Vu (Convenor and Lead Member); Paulette Bynoe, Trang Duong, Matt Eliot, Frank Hall, Roshanka Ranasinghe, Matthieu de Schipper, Joshua T. Tuhumwire (Co-Lead Member), Sylvain Monde, Tuan Le Nguyen

14. Ca Thanh Vu (Convenor and Lead Member); Sam Bentley, Lionel Carter, Catherine Creese, Robert Dapa, Regina Folorunsho, Alan Simcock (Co-Lead Member), Alix Willemez, Matchonnawe Hubert Bakai, Bi Tra Boniface Nene, Victor Hugo Masson Fiallos, Gheorghe Ftadeev-Brat

15. Porter Hoagland (Convenor); Megan Bailey, Lena Bergström, Alida Bundy, Karen Evans (Co-Lead Member), Manuel Hidalgo, Andrew Frederick Johnson, Enrique Marschoff (Lead Member), Essam Yassin Mohammed (Co-Lead Member), Henn Ojaveer (Co-Lead Member), Fernanda de Oliveira Lana, Franklin Ormaza-Gonzalez, Imants George Priede, Ylenia Randrianisoa (Co-Lead Member), Zacharie Sohou, Burcu Bilgin Topçu, Chang-Ik Zhang, Hector Lozano-Montes, Lynn Waterhouse

16. Rohana Subasinghe (Convenor); Pedro José Barón, Malcolm Beveridge, Enrique Marschoff (Lead Member), Doris Oliva, Renison Ruwa (Co-Lead Member)

17. Hilconida Calumpong (Convenor and Lead Member), Franciane Pellizzari, Isabel Sousa Pinto, Renison Ruwa (Co-Lead Member), Jörn Schmidt (Co-Lead Member), Adam Hughes, Paula Bontempi

19. James R. Hein (Joint Convenor), Pedro Madureira (Joint Convenor); Maria Bebianno (Co-Lead Member), Ana Colaço, Luis M. Pinheiro, Richard Roth, Pradeep Singh, Anastasia Strati (Co-Lead Member), Joshua T. Tuhumwire (Lead Member), Giorgio de la Torre, Nomikou Paraskevi

20. Amardeep Dhanju (Convenor); Bera Arsonina, Kacou Yeboue Seraphim, Alan Simcock (Co-Lead Member), Joshua T. Tuhumwire (Lead Member), Koffi Robert Dapa, Hans-Peter Damian, Giorgio de la Torre

21. Ana Širović (Convenor); Karen Evans (Lead Member), Carlos Garcia-Soto (Co-Lead Member), John A. Hildebrand, Sérgio Jesus, James H. Miller

22. Takvor Soukissian (Convenor); Joan Bondareff, Valerie Cummins, Amardeep Dhanju, Carlos Garcia-Soto (Co-Lead Member), Lars Golmen, Osman Keh Kamara (Co-Lead Member), Jimmy Murphy, Eric Mwangi Njoroge, Anastasia Strati (Lead Member), Georges Vougioukalakis

25. Thomas W. Therriault (Convenor); Qiao Bing, Marnie L. Campbell, Alan Deidun, Sarah Bella Galil, Chad L. Hewitt, Graeme Inglis, Henn Ojaveer (Lead Member), Chul Park (Co-Lead Member), Renison Ruwa (Co-Lead Member), Evangelina Schwindt

26. Robert Blasiak (Joint Convenor), Ellen Kenchington (Joint Convenor); Jesús M. Arrieta, Jorge Rafael Bermúdez-Monsalve, Hilconida Calumpong (Co-Lead Member), Sanae Chiba (Lead Member), Hebe Dionisi, Carlos Garcia-Soto (Co-Lead Member), Changwei Shao, Helena Vieira, Boris Wawrik

27. Alan Simcock (Convenor and Lead Member) Carlos Garcia-Soto (Co-Lead Member), Aninda Mazumdar, Aaron Micallef, Katherine Segarra, Joshua T. Tuhumwire (Co-Lead Member), Leonid Yurganov, Joseph Montoya

28. Karen Evans (Convenor and Lead Member); Roland Cormier, Piers Dunstan, Elizabeth Fulton, Essam Yassin Mohammed (Co-Lead Member), Alan Simcock (Co-Lead Member), Jörn Schmidt (Co-Lead Member), Vanessa Stelzenmüller, Ca Thanh Vu (Co-Lead Member), Skipton Woolley

29. Alan Simcock (Convenor and Lead Member), Jarbas Bonetti, Louis Celliers, Karen Evans (Co-Lead Member), Leandra Gonçalves, Marcus Polette, Julian Renya, Ca Thanh Vu (Co-Lead Member), Ståle Navrud

30. Piers Dunstan (Convenor); Hilconida Calumpong (Co-Lead Member), Louis Celliers, Valerie Cummins, Michael Elliott, Karen Evans (Co-Lead Member), Antony Firth, Frederic Guichard, Quentin Hanich, Ana Cristina de Jesus, Manuel Hildago, Hector Manuel Lozano-Montes, Chanda L. Meek, Essam Yassin Mohammed (Co-Lead Member), Marcus Polette, Jemma Purandare, Anita Smith, Anastasia Strati (Lead Member), Ca Thanh Vu (Co-Lead Member)

31. Luciano Hermanns (Convenor); Denis Worlnanyo Aheto, Adem Bilgin, Robert Blasiak, Cecile Brugere, Marinez Eymael Garcia Scherer, Deborah Greaves, Wenhai Lu, Iryna Makarenko, Essam Yassin Mohammed (Lead Member), Osman Keh Kamara (Co-Lead Member), Stale Navrud, Jörn Schmidt (Co-Lead Member), Anastasia Strati (Co-Lead Member), Rashid Sumaila, Kateryna Utkina, Wojciech Wawrzynski, Stale Navrud