Conservation of Arctic Flora and Fauna

CIRCUMPOLAR BIODIVERSITY MONITORING PROGRAM

State of the Arctic Marine Biodiversity Report

ARCTIC COUNCIL

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MONITORING PROGRAM

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Key Findings

Food resources are being lost for many Arctic species in Arctic marine environments. Many species have to travel further and expend more energy to feed, leading to concerns about individual health and potential effects at the population level.

- Ivory gull declines coincide with reduction in their sea ice feeding areas.
- Reduced ice cover has also led to increased polar bear predation on ground-nesting common eiders and cliff-nesting murres, potentially leading to local population declines.
- Black guillemots in Alaska feed at the ice edge and have been forced to travel greater distances to foraging areas as sea-ice retreats, leading to lower breeding success.
- Barents Sea harp seals have reduced body condition associated with reduced food availability as their travel time to the ice edge to feed and is longer.
- Some Indigenous communities have noted a change in walrus stomach contents, with more open water fishes and less clams, indicating that the distribution and availability of benthic resource species are changing in some areas.

Some Arctic species are shifting their ranges northwards to seek more favourable conditions as the Arctic warms. These movements pose unknown consequences for Arctic species and their interactions, such as predation and competition.

- The northward expansion of capelin has led to changes in seabird diet in northern Hudson Bay. It also may affect marine mammals.
- Warming can have surprising and contradictory effects on species e.g. rising temperatures in the Chukchi Sea have been associated with an increase in nutritious copepods with high fat content

Northward movement is easier for more mobile open-water species. Open water species such as polar cod, are more mobile compared to those linked to shelf regions, such as benthic species including some fishes for which suitable habitat may be unavailable if they move northward.

- Greenland halibut have the potential to expand into the Arctic Basin with climate change, but only given the availability of suitable prey and topography.

Increasing numbers and diversity of southern species are moving into Arctic waters. In some cases, they may outcompete and prey on Arctic species, or offer a less nutritious food source for Arctic species.

- The boreal copepod *Calanus finmarchicus* is expanding north from the Atlantic and replacing its more nutritious Arctic relatives *C. glacialis* and *C. hyperboreus*.
- Complex patterns of benthic biomass change in the Barents Sea are related to, amongst other pressures, warming of the Barents Sea improving conditions for boreal species to move further north.
- The distribution of Atlantic cod is expanding in the Atlantic Arctic and increasing predation pressure on the polar cod, an important nutrient-rich prey fish, important for other fishes, seabirds and marine mammals, especially seals.
- The more temperate killer whale is expanding in Arctic waters and may compete with other apex predators for nutritious seals.

Current trends indicate that species reliant on sea ice for reproduction, resting or foraging will experience range reductions as sea ice retreat occurs earlier and the open water season is prolonged.

- Since the 1980s, ice amphipod abundance has declined around Svalbard and it is possible that sea ice algal community structure has changed in the central Arctic.
- Although there are no documented cases of widespread population changes, some Arctic-breeding seabirds and some resident marine mammals have been observed shifting behaviours.
- Ducks breeding on the Siberian tundra and wintering at sea have shortened migration in response to declines in winter sea ice cover.
- Belugas in Hudson Bay varied timing of migration in response to variations in temperatures. These migrations may affect the ability of people to find and use these resources.
- Changes in sea ice conditions are probably linked to declines in the abundance of hooded seals, lower reproduction rates of Northwest Atlantic harp seals, reduced body condition of Barents Sea harp seals, and changes in prey composition of bearded seals.
- Extirpation of some stocks of ice-dependent seals are possible, but is expected to vary locally because of large regional variation in ice cover decline.
- Early spring sea ice retreat also reduces suitable breeding and pup rearing habitat for ringed seals. This affects the ability for polar bears, which feed on ringed seals, to rebuild energy stores after fasting during their own breeding period.
- Historically, walruses rested on sea ice located directly over prime feeding areas, but due to late season ice formation are increasingly using coastal haul-out sites instead of sea ice. In addition to travelling further to access foods, this also increases the risk of calf mortality due to stampede.

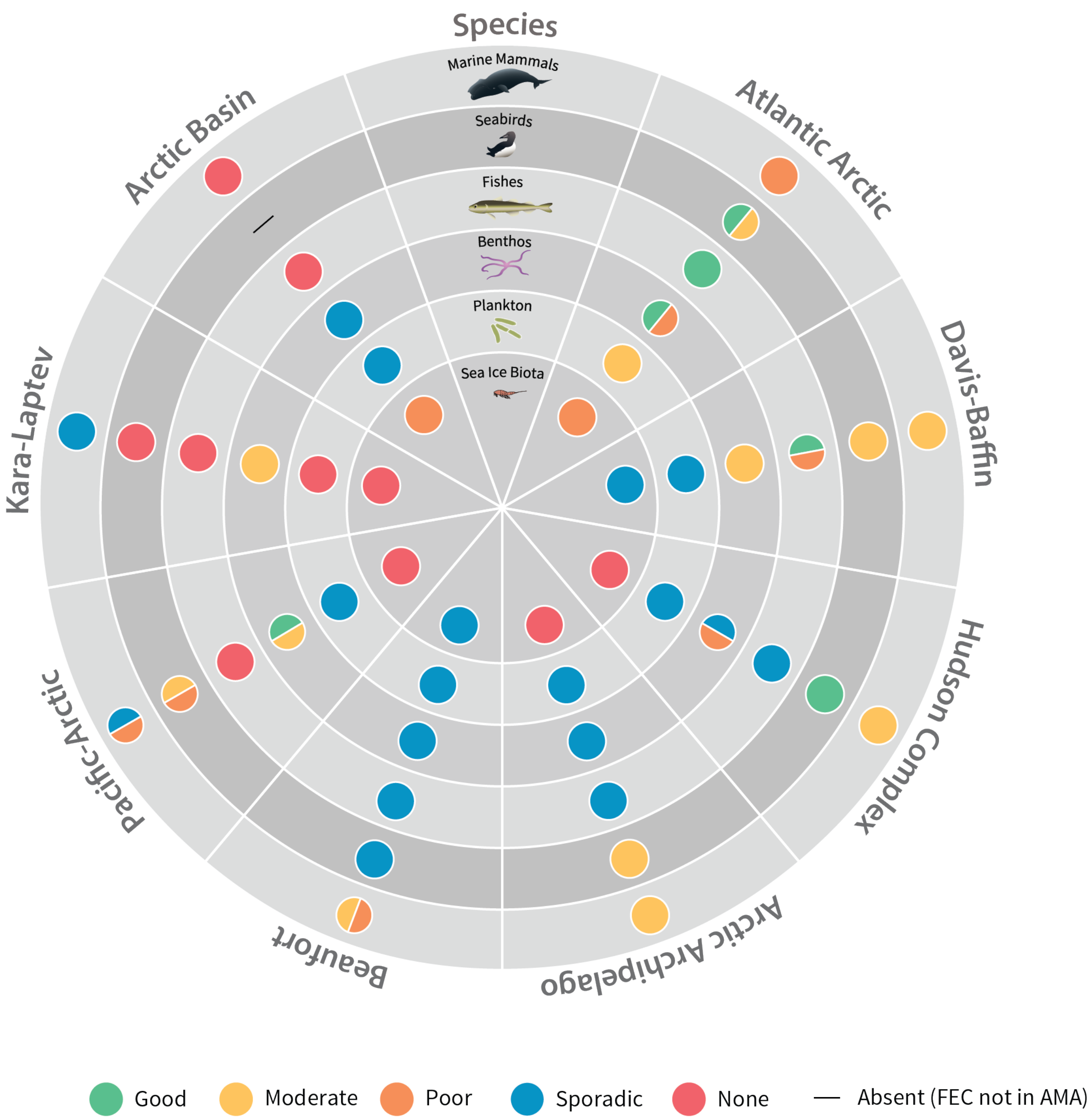


Figure 1: Status of monitoring activities for each Focal Ecosystem Component (i.e., selected species groups) across each Arctic Marine Area as included in this report.

Arctic marine species and ecosystems are undergoing pressure from cumulative changes in their physical, chemical and biological environment. Some changes may be gradual, but there may also be large and sudden shifts that can affect how the ecosystem functions. It is hard to determine where and when these "tipping points" exist because the Arctic marine environment experiences a variety of stressors and subsequent reactions that can interact in complex and surprising ways. For those charged with managing natural resources and public policy in the region, it is crucial to identify the combined effects of stressors and potential thresholds to prepare effectively for an uncertain future.

Increases in the frequency of contagious diseases are being observed.

- Incidents of avian cholera have increased in the northern Bering Sea and Arctic Archipelago.
- The first designated Unusual Mortality Event in the U.S. Arctic occurred in 2011 and involved species of seals and walrus—essential food resources—affecting coastal community health, nutrition, cultural and economic well-being in areas of Canada, U.S., and Russia.

Advice for monitoring

Monitoring the status and trends of Arctic biodiversity and attributing causes of change are challenging. Complexity, logistics, funding, international coordination, natural variability, and availability of expertise and technology combine to limit available data and knowledge. These limitations affect biotic groups unevenly.

Traditional and local knowledge (TLK) is a valuable source of information for marine areas, and the *CBMP Marine Plan* worked to address this issue by trying to engage and include Traditional Knowledge (TK) and TK holders within its design and implementation, a lack of funding, support, and capacity hindered its effect within the Marine Expert Networks and this report. With the understanding of the importance to utlize both science and TLK in order to understand the current state of the marine environment, examples are provided of the type of information that TK holders have to offer.

Coordination

Better coordination allows for increased value for investment in monitoring programs, better opportunity to compare results, and more ability to draw meaningful conclusions from data.

- Strategically locate Arctic research stations and monitoring vessels, and use all collected specimens, to allow the collection and analysis of as many CBMP FECs as possible.
- Ensure research stations operate all year to better study FECs year round.
- Combine national monitoring with collaborative approaches that allow for sufficient integration and standardization to conduct syntheses across the circumpolar region.
- Standardize how data are collected, managed and made available. This is a key component in ensuring circumpolar Arctic comparability and should be an important consideration in the implementation of monitoring plans.
- Encourage states to increase the implementation of existing internationally coordinated monitoring plans.
- Connect monitoring initiatives and report across scales so that results are meaningful for local, sub-national, national, regional and global decision-makers.
- Continue to increase coordination between CBMP and other regional and global monitoring initiatives e.g., the Group on Earth Observations Biodiversity Observation Network (GEOBON), International Council for the Exploration of the Sea (ICES) and the Intergovernmental Platform on Biodiversity and Ecosystem Service (IPBES).


Ice divers
Photo: The Hidden Ocean, NOAA

Methods

Increased attention to methodology allows for more precise and comparable results, standardized data collection, and ability to link regional monitoring to circumpolar efforts.

- Ensure that Arctic monitoring programs are ecosystem-based and include as many CBMP FECs as possible to include functionally important taxonomic groups and improve our understanding of how the ecosystem functions, and how its components are related. Such monitoring programs can serve to underpin management of human activities in the Arctic marine environment.
- Standardize methodology, including taxonomic identification in order to allow production of comparable data and results.
- Ensure training of personnel performing sampling and analyses.


Katrin Iken and Bodil Bluhm sift through deep sea mud for species samples.
Photo: Kevin Raskoff, California State University, NOAA/Flickr.com

An Inuit man observers the sea while hunting in Greenland.
Photo: Carsten Egevang/ARC-PIC.com

Traditional and Local Knowledge (TLK)

Utilizing TLK and involvement of TK holders allows for increased understanding of relationships and changes underway in Arctic ecosystems, current and historical trends, and serves to build valuable partnerships on the ground in Arctic communities.

- Use TLK within the design and implementation of monitoring plans. The TLK of people living along and off the Arctic Ocean is an invaluable resource for understanding changes in Arctic marine ecosystems and its inclusion should be supported by national governments.
- Increase engagement and partnerships with local residents and easy to access technology in monitoring programs. Indigenous communities are important 'first responders' to catastrophic events. More importantly, their knowledge systems provide a wealth of knowledge that should be involved in the analysis of collected data for increased understanding of current trends and filling historical gaps.
- There is a need for TLK on a range of FECs and to engage networks of TLK holders and Indigenous organisations.
- Use both TLK and scientific information on the analysis of harvest levels and status when evaluating overall population health and managing hunts.

Community-based monitoring networks and community relationship building

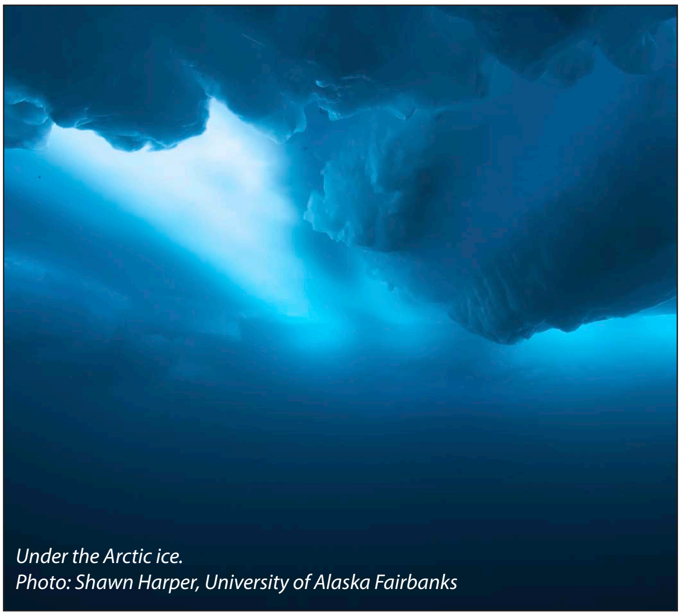
- Increase the span of networks in the CBMP to include Community-based monitoring networks.
- Communicate information on changes and the results of monitoring between scientists and the public in both directions. This is crucial to the development of effective management strategies and human activities.

Looking for marine mammals in the Pacific Arctic
Photo: Josh London,Alaska Fisheries Science Center, NOAA

Knowledge gaps

Filling gaps in knowledge helps us better understand key elements and functions of the ecosystem that can help explain change and understand the system.

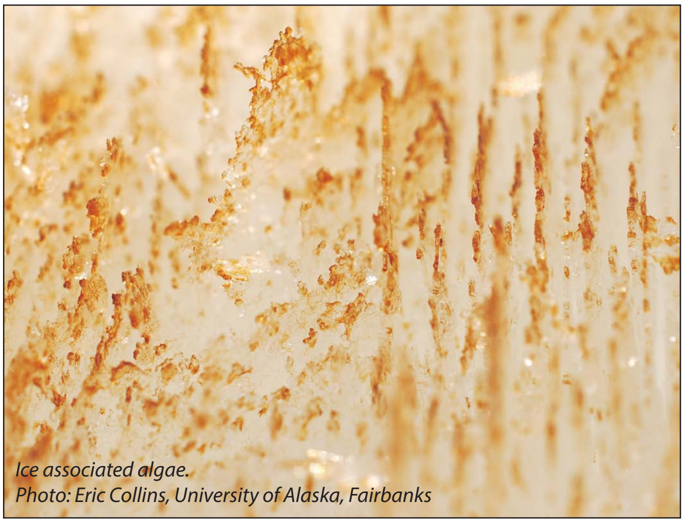
- Encourage the monitoring of relevant physical parameters alongside some FECs that are particularly sensitive to their effects, including sea ice biota and plankton.
- Expand monitoring programs to include important taxonomic groups and key ecosystem functions. These gaps are likely due to logistical challenges or lack of expertise in specific fields.
- Expand monitoring programs to include those utilizing both TK and science; involvement of Indigenous organizations and build capacity to provide a co-production of knowledge platform.



Under the Arctic ice.
Photo: Shawn Harper, University of Alaska Fairbanks

Marine Expert Networks

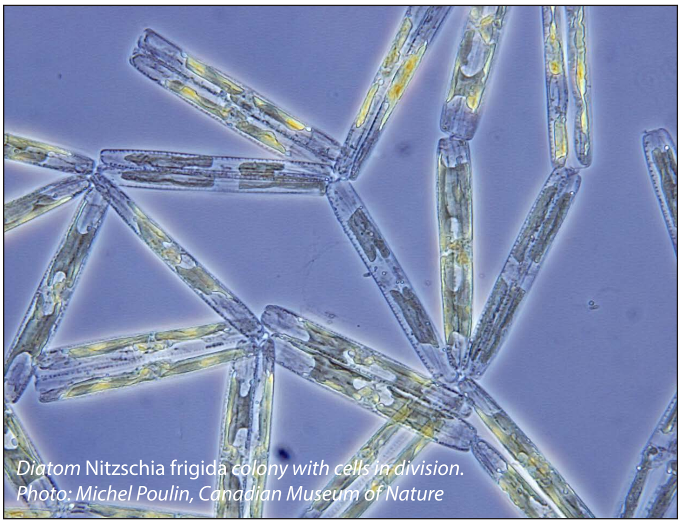
Proactive biodiversity monitoring can help anticipate and provide future knowledge needs. Each CBMP Marine Expert Network has provided advice for their area of expertise to help Arctic biodiversity monitoring programs deliver relevant information and advice for policy-makers.



Ice associated algae.
Photo: Eric Collins, University of Alaska, Fairbanks

Sea ice biota

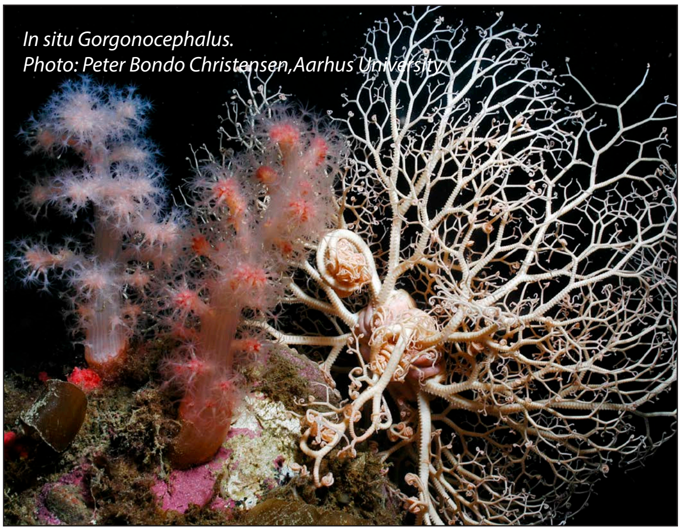
- Establish an annual monitoring programme from landfast sea ice at selected Arctic field stations in Canada (Resolute, Cambridge Bay), Greenland (Kobbefjord, Disko Bay, Zackenberg), Norway (Kongsfjorden, Billefjorden, Van Mijenfjorden), and the U.S. (Barrow).
- Establish a standardized monitoring protocol, including sample collection, preservation, microscopic and genetic analyses, taxonomic harmonization, and data sharing.
- Establish opportunistic monitoring from drifting sea ice during cruises of opportunity.
- Collect macrofauna samples in drifting sea ice via ship-based activities, scuba diving, use of electrical suction pumps, under-ice trawl nets, and remotely operated vehicles.



Diatom Nitzschia frigida colony with cells in division.
Photo: Michel Poulin, Canadian Museum of Nature

Plankton

- Follow standardized protocols for monitoring plankton, including sample collection and preservation, microscopic and genetic analyses with taxonomic harmonization.
- Ensure that full data sharing occurs between scientists, and is deposited in publicly-accessible national data centers. Continue to consolidate older data.
- Train highly qualified personnel to perform plankton sampling and species-level analyses, including the use of molecular techniques.
- Establish long-term funded annual monitoring programmes of plankton from selected Arctic field stations or Arctic campaigns/cruises in Canada, the U.S. and Russia, which together with the ongoing monitoring in Greenland, Iceland and Norway will secure a pan-Arctic coverage.
- Develop species indexes and if possible, identify indicator taxa for monitoring.



In situ Gorgonocephalus.
Photo: Peter Bondo Christensen,Aarhus University

Benthos

- Develop a time- and cost-effective, long-term and standardized monitoring of megabenthic communities in all Arctic regions using regular national groundfish assessment surveys. Expanding monitoring on micro-, meio- and macrobenthic groups is encouraged.
- Gather information from research programs in regions without regular groundfish-shellfish trawl surveys. These are usually short-term and do not guarantee spatial consistency in sampling, but provide valuable information on benthic biodiversity and community patterns.
- Generate information on benthos from little-known regions, such as the Arctic Basin and Arctic Archipelago, on cryptic or difficult taxonomic groups, and on biological "hotspots".
- Systematic studies of macrobenthos (grab investigations) and megabenthos (trawl bycatch of regular fishery surveys including both annual studies, as in the Atlantic Arctic, and periodic studies as in the Northern Bering and Chukchi Seas) are the most suitable and practical approach to long-term monitoring.
- Standardize methodology, including taxonomic

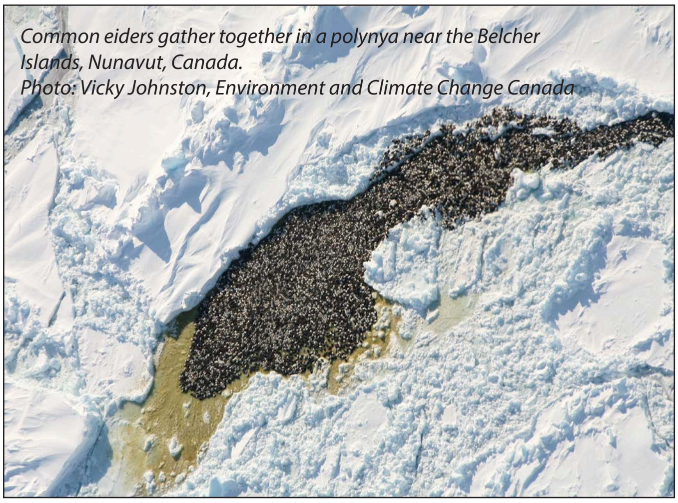
identification, across regions to assist in regional comparisons.

- Recognize and support the use of TLK as an invaluable resource for understanding of changes in Arctic benthic communities.

Polar cod hiding in ice habitat.
Photo: Peter Leopold/Norwegian Polar Institute

Marine fishes

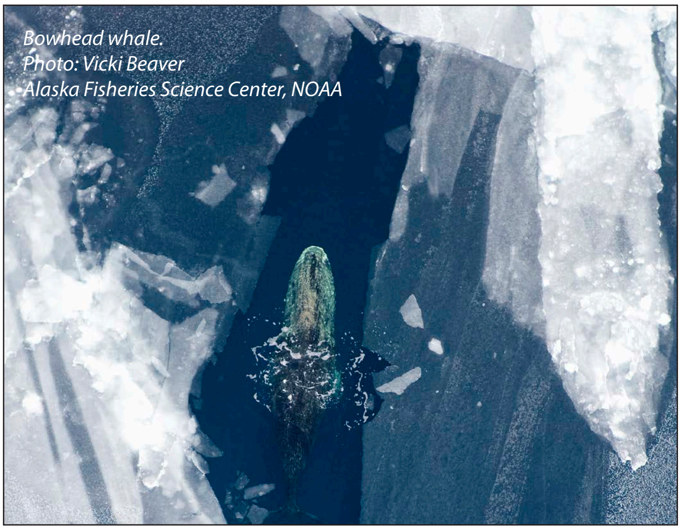
- Conduct pan-Arctic taxonomic analyses to clarify zoogeographic patterns that are important for detecting and understanding change.
- Establish and conduct a monitoring plan that is independent of fisheries-related programs to assess changes in fish abundance and distributions. Use information from non-commercial fish species caught in groundfish surveys to provide a first step in this direction.
- Use information from TK holders for monitoring marine fishes.
- Connect monitoring initiatives across scales.
- Conduct laboratory studies to examine the possible effects of abiotic and biotic changes (e.g. temperature, salinity, acidity and diseases) on fish species
- Ensure that data on fisheries (commercial as well as artisanal) are accurate and registered in catch databases (such as the Food Agriculture Organisation of the United Nations). Information from logbooks is also relevant as it can be used to estimate the bycatch and the effects of fisheries.



Common eiders gather together in a polynya near the Belcher Islands, Nunavut, Canada.
Photo: Vicky Johnston, Environment and Climate Change Canada

Seabirds

- Develop methods for assessing diet to increase our understanding of changes in the ecosystem and how they affect seabird populations.
- When selecting sites for new monitoring, consider proximity to hotspots for marine activities, access to the sea, and inclusion of plankton monitoring.
- Expand colony-based monitoring and strive to include a more complete array of parameters, in particular, diet and measures of survival.
- Consider a higher frequency of monitoring as current levels make it difficult to identify mechanisms or causes of change in populations.
- Conduct targeted surveys and individual tracking studies of seabird interactions at sea to improve our understanding of seabird interactions at sea, where seabirds spend most of their time.
- Continue to conduct at sea surveys on an opportunistic basis.



Bowhead whale.
Photo: Vicki Beaver
Alaska Fisheries Science Center, NOAA

Marine mammals

- Implement existing international monitoring plans such as those for ringed seals and polar bear, with adaptive management principles to address the eleven FEC marine mammal species.
- Expand marine mammal monitoring efforts to include parameters on health, passive acoustics, habitat changes, and telemetry tracking studies.
- Obtain more knowledge about population sizes, densities, and distributions of marine mammal populations in order to understand the relationships between sea ice loss and climate change and to manage Arctic marine mammal populations in an appropriate manner.
- Involve indigenous and local peoples in the design and implementation of monitoring programs so that scientific knowledge and TLK holders are working collaboratively.
- Pursue a multidisciplinary and multi-knowledge approach and a high degree of collaboration across borders and between researchers, local communities and Arctic governments to better understand complex spatial-temporal shifts in drivers, ecological changes and animal health.

Phytoplankton bloom in the Barents Sea.
Photo: Envirisat, European Space Agency

1. Introduction

Tom Barry[1], Tom Christensen[2], Marianne Olsen[3], and Courtney Price[1]

[1] CAFF International Secretariat, [2] Aarhus University, [3] Norwegian Environment Agency

This is the first Circumpolar Biodiversity Monitoring Program (CBMP) report to summarize status and trends in key biotic elements of the Arctic marine environment, what the CBMP refers to as Focal Ecosystem Components (FECs). The results are based on efforts to locate, gather, integrate and interpret all available existing Arctic marine biodiversity monitoring datasets to improve the detection and understanding of changes in circumpolar marine biodiversity.

The process to produce this report has identified knowledge gaps in circumpolar biodiversity monitoring and adjustments to program design are needed to achieve additional implementation of the *Arctic Marine Biodiversity Monitoring Plan* (*CBMP Marine Plan*; Gill et al. 2011). The *CBMP Marine Plan* has learned a lot from this process, which will inform additional program development, as new knowledge, improved conceptual models, new technologies and adjustment in design feed back into the adaptive integrated approach of the CBMP. This is just the beginning of a continued effort to further advance work in circumpolar biodiversity monitoring efforts and to understand the impact of changes on Arctic marine ecosystems and life in the oceans.

1.1 What is the Circumpolar Biodiversity Monitoring Program (CBMP)

The CBMP is the cornerstone program of the Conservation of Arctic Flora and Fauna (CAFF), the Arctic Council's biodiversity working group. The Arctic Council is the leading intergovernmental forum promoting cooperation, coordination and interaction among the Arctic States, Arctic Indigenous communities and other Arctic inhabitants on common Arctic issues, in particular, on issues of sustainable development and environmental protection in the Arctic.

The CBMP is an international network of scientists, governments, Indigenous organizations, and conservation groups working to harmonize and integrate efforts to monitor the Arctic's living resources and aims to incorporate Traditional Knowledge (TK) holders. Its goal is to facilitate more rapid detection, communication and response to significant biodiversity-related trends and pressures affecting the circumpolar world while also establishing international linkages to global biodiversity initiatives. The CBMP applies a question-driven and integrated ecosystem-based approach to long-term monitoring to describe ecosystem and biodiversity change, and to identify important trends (Fig. 1.1).

It does this by:

- compiling, harmonizing and enhancing Arctic biodiversity monitoring efforts, thereby improving the ability to detect and understand significant trends; and
- reporting to, and communicating with, key decision makers and stakeholders, thereby enabling effective conservation and adaptation responses to changes in Arctic biodiversity.

The CBMP facilitates monitoring through the implementation of four Arctic Biodiversity Monitoring Plans (marine, coastal, freshwater and terrestrial). A State of the Arctic Biodiversity Report will be created under each of these monitoring plans, followed by regular combined reports in the future.
The approach adopted in these plans follows the steps required for an effective and adaptive monitoring program (Lindenmayer and Likens 2009) and includes a consideration of what future priority questions and user needs the program should cover. While much work remains to integrate existing Arctic biodiversity monitoring, the continued implementation of the CBMP is a major achievement (Barry et al. 2013).

1.2 What is the State of the Arctic Marine Biodiversity Report (SAMBR)?

This *State of the Arctic Marine Biodiversity Report* (SAMBR) is the first integrated reporting outcome from the *CBMP Marine Plan*.

Where it has been possible, the SAMBR:

- describes current and/or historical baseline status of identified FECs;
- evaluates historical and contemporary trends;
- considers how changes in biodiversity may be linked to stressors;
- describes differences that have occurred within the Arctic Marine Areas (AMAs);
- describes status of Arctic biodiversity monitoring;
- identifies research priorities, knowledge gaps; and
- provides advice for monitoring and management.

The *Arctic Biodiversity Assessment* (ABA) (Meltofte 2013) provides the fundamental baseline to make trend assessments in SAMBR possible. Six Marine Expert Networks (Sea ice biota, Plankton, Benthos, Fishes, Seabirds and Marine mammals) provide the framework to implement the *CBMP Marine Plan* and generate the information required for SAMBR.

1.3 What is the Arctic Marine Biodiversity Monitoring Plan (CBMP Marine Plan)?

The *CBMP Marine Plan* (Gill et al. 2011) is an agreement across Arctic States to compile, harmonize and compare results from existing Arctic marine biodiversity and ecosystem monitoring efforts, across nations and oceans. The *CBMP Marine Plan* developed conceptual ecological models and identified recommended selected aspects of the environment to monitor at various trophic levels using specific parameters, methodologies and sampling designs.

This approach considers the integrity of ecosystems and their interactions and focuses on a series of FECs defined in the *CBMP Marine Plan*; these are subject to revisions based upon outcomes of this report. This approach aligns with other comparable initiatives, including the Essential Biodiversity Variables (Pereira et al. 2013), developed by the Group on Earth Observations Biodiversity Observation Network (GEOBON). The resulting information contributes directly to providing decision makers and other users with information to inform effective conservation, mitigation and actions in an Arctic context.

For the purposes of reporting and comparison, the *CBMP Marine Plan* identified eight physically and biogeochemically distinct AMAs (Fig. 1.2).

1.4 Traditional Knowledge (TK)

To have a thorough understanding of the state of the Arctic and how it is changing, it is necessary to consider both TK[1] and science. The *CBMP Marine Plan* endeavours to build a network based on both sources of knowledge and bring together TK holders and scientists to work collaboratively. However, a lack of funding support and capacity has hindered effective inclusion of TK holders within the *CBMP Marine Plan*. It is important for Arctic States to support the experts (both TK holders and scientists) needed to do this work.

Although it is an imperfect treatment, this report provides examples to demonstrate the wealth and value of information that may be provided by TK. These case studies are derived from information found within published literature. As the CBMP progresses in its work, there is a continued effort and willingness to meaningfully engage TK, recognize TK monitoring methodologies and include TK holders throughout the process.

1.5 Arctic Biodiversity Data Service (ABDS)

Datasets compiled for SAMBR are available on the Arctic Biodiversity Data Service (ABDS), the online interoperable system for managing data generated via CAFF projects and activities. The goal of the ABDS is to facilitate access, integration, analysis and display of biodiversity information for scientists, managers, policy makers and others working to understand, conserve and manage the Arctic's wildlife and ecosystems. It ensures that biodiversity data provided to CAFF are organised to guarantee a legacy in a manner that facilitates: data discovery; increased understanding; informed and rapid decision-making; and ongoing research.

Figure 1.1: Work flow of the Circumpolar Biodiversity Monitoring Program (CBMP).

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[1] The Indigenous organisations who are Permanent Participants to the Arctic Council have defined TK as "a systematic way of thinking and knowing that is elaborated and applied to phenomena across biological, physical, cultural and linguistic systems. TK is owned by the holders of that knowledge, often collectively, and is uniquely expressed and transmitted through indigenous languages. It is a body of knowledge generated through cultural practices, lived experiences including extensive and multigenerational observations, lessons and skills. It has been developed and verified over millennia and is still developing in a living process, including knowledge acquired today and in the future, and it is passed on from generation to generation" (Permanent Participants of the Arctic Council 2015). Indigenous peoples' organizations have been granted Permanent Participant status in the Arctic Council. The Permanent Participants have full consultation rights in connection with the Council's negotiations and decisions. The following organizations are Permanent Participants of the Arctic Council: Aleut International Association (AIA), Arctic Athabaskan Council (AAC), Gwich'in Council International (GCI), Inuit Circumpolar Council (ICC), Russian Association of Indigenous Peoples of the North (RAIPON) and the Saami Council (SC)

Box 1.1 Focal Ecosystem Components (FECs)

The CBMP uses the term FECs to describe biological elements that are considered central to the functioning of an ecosystem, of major importance to Arctic residents, and/or are likely to be good proxies of change in the environment. Marine FECs addressed in the SAMBR are:

Marine mammal	
Beluga	*Delphinapterus leucas*
Narwhal	*Monodon monoceros*
Bowhead whale	*Balaena mysticetus*
Spotted seal	*Phoca largha*
Ringed seal	*Pusa hispid*
Bearded seal	*Erignathus barbatus*
Ribbon seal	*Phoca fasciata*
Harp seal	*Phoca groenlandica*
Hooded seal	*Cystophora cristata*
Walrus	*Odobenus rosmarus*
Polar bear	*Ursus maritimus*
Seabirds	
Glaucous gull	*Larus hyperboreus*
Ivory gull	*Pagophilia eburnea*
Least auklet	*Aethia pusilla*
Little auk	*Alle alle*
Common murre	*Uria aalge*
Thick-billed murre	*Uria lomvia*
Black-legged kittiwake	*Rissa tridactyla*
Common eider	*Somateria mollissima*
Fishes	
Capelin	*Mallotus villosus spp.*
Polar cod	*Boreogadus saida*
Greenland halibut	*Reinhardtius hippoglossoides*
Benthos	
Macrobenthos	
Megabenthos	
Plankton	
Phytoplankton and larger protists	
Microbial eukaryotes	
Bacteria and Archaea	
Zooplankton	
Sea ice biota	
Prokaryotic microbes, including Archaea and Bacteria	
Ice algae and other single-celled eukaryotes	
Ice meiofauna	
Macrofauna: Under-ice amphipods	

Figure 1.2. Arctic Marine Areas (AMAs) as defined in the CBMP Marine Plan.

1.6 Global linkages

The size and nature of Arctic ecosystems make them critically important to the biological, chemical and physical balance of the globe (Meltofte 2013). CAFF makes significant efforts to develop strategic partnerships and ensure that Arctic biodiversity information contributes to other Arctic Council activities and to the attainment of global biodiversity goals, targets and commitments of biodiversity-related Multilateral Environmental Agreements (MEAs) and other relevant international biodiversity fora[2].

The CBMP has been endorsed by the Arctic Council and the United Nations Convention on Biological Diversity (CBD) (CBD 2010, 2012, Barry et al. 2013, Arctic Regional Workshop 2014, Arctic Council 1996-2015) and is the biodiversity component of the Sustaining Arctic Observing Networks (SAON). The CBMP is the official Arctic Biodiversity Observation Network (Arctic BON) of GEOBON and a partner to the Global Biodiversity Indicators Partnership (BIP).

The outputs of the SAMBR will contribute to these partnerships—for example, by helping to measure progress towards the CBD Aichi Biodiversity Targets[3] —and will ensure that relevant and reliable information on Arctic biodiversity informs regional and global processes that affect Arctic biodiversity.

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[2] CAFF has signed Resolutions of Cooperation with the Global Biodiversity Information Facility (2016), the East Asian-Australasian Flyway Partnership (2013), the Ramsar Convention on Wetlands (2012), the United Nations Convention on Migratory Species (2013), the African-Eurasian Waterbird Agreement (2012), United Nations Convention on Biological Diversity (2010) and the Association of Polar Early Career Scientists (2009).

[3] The Aichi targets were agreed at the 10th meeting of the UN CBD Conference of the Parties, October 2010. These targets are a means to evaluate progress towards halting biodiversity loss by 2020

Box 1.2 Marine sensitive and significant areas in the Arctic

Several recent initiatives have focused on the identification of marine areas of ecological importance and/or sensitive to pressures from specific activities. In 2013, the Arctic Council identified ecologically and culturally significant marine areas vulnerable to marine vessel activities changing climate conditions and increasing multiple marine uses (AMAP/CAFF/SDWG, 2013) as a follow up to the Arctic Marine Shipping Assessment (PAME 2009). This process entailed compiling existing information and identification of significant areas, which were then overlapped with existing information on Arctic marine vessel activity to assess their vulnerability. The outcomes informed consideration of "Specially Designated Marine Areas in the Arctic High Seas" (Det Norske Veritas 2014), which explored the need for internationally designated areas that might warrant protection from risks posed by international shipping activities, such as the potential application of Special Areas (SA) and Particularly Sensitive Sea Area (PSSA) measures under the International Maritime Organisation (IMO) (Barry et al. 2016).

Informed by these efforts, and as part of a global effort to identify Ecologically or Biologically Significant Marine Areas (EBSAs), in 2014 the CBD convened a workshop to identify Arctic EBSAs and focus future conservation and management efforts. This process collected a broad range of data in differing formats, scales and details relevant to identifying areas meeting the criteria to qualify as EBSAs (Arctic Regional Workshop, 2014). These data were analysed and used to identify and define Arctic EBSAs (Box. Fig. 1.1). The outcomes will be relevant in any subsequent steps of selecting conservation and management measures by states and intergovernmental organizations, for example, within the United Nations Convention on the Law of the Sea (UNCLOS) (Barry et al. 2016).

Box figure 1.1: Arctic Ecologically and Biologically Significant Areas (EBSAs) and Arctic Marine Areas of Heightened Ecological and Cultural Significance as identified in the Arctic Marine Shipping Assessment (AMSA) IIC report.

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A crane lands researchers onto the sea ice.
Photo: Caitlin Bailey, GFOE, The Hidden Ocean, NOAA

2. Setting the scene

Tom Christensen[1], Courtney Price[2], Marianne Olsen[3], Tom Barry[2], Kári Lárusson[2]

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2.1 Arctic marine ecosystems

The processes that control Arctic marine ecosystems differ from other ocean environments. The absence of light during winter months limits primary production, which then bursts into action upon the return of the spring sun. Large areas of sea ice also characterize Arctic Marine Areas (AMAs), and appear seasonally over extensive shelves and more permanently as a large central area of multi-year pack ice.

Marine areas in the Arctic are often highly stratified because freshwater flows from rivers and melting ice make the upper layer of the ocean less salty compared with other oceans. Currents from Atlantic and Pacific water masses mix elements such as nutrients, organic matter, plankton, and larvae of fish and invertebrates at different depths and in different patterns. Relatively warm and salty Atlantic water enters the Arctic through the eastern part of Fram Strait and less salty Pacific water enters through the Bering Strait, while the western Fram Strait acts as the major outflow from the Arctic Ocean (Eamer et al. 2013, Meltofte 2013; Figure 2.1). Arctic marine biodiversity is linked to these dynamic patterns of ocean conditions. Fish species associated with warm Atlantic waters thrive in the Barents and Greenland Seas, while bottom-dwelling invertebrates of Pacific origin are found in the Chukchi, Beaufort and northern East Siberian Seas (Eamer et al. 2013). Other related physical features, including polynyas, leads, marginal ice zones and upwelling zones have major impacts on Arctic marine ecosystems.

Some key elements that determine the diversity of species and ecosystems in the Arctic marine environment are the high degree of seasonality in environmental conditions, critical influence of the large continental shelves and sea ice,

Box 2.1 Some features of the sea ice environment

Marine areas seasonally or permanently covered by sea ice are a globally unique habitat. Ice edges and open water areas favour wind-driven mixing of the seawater that enhances local production and can create biological hotspots. Some key features of the sea ice environment in the Arctic include:

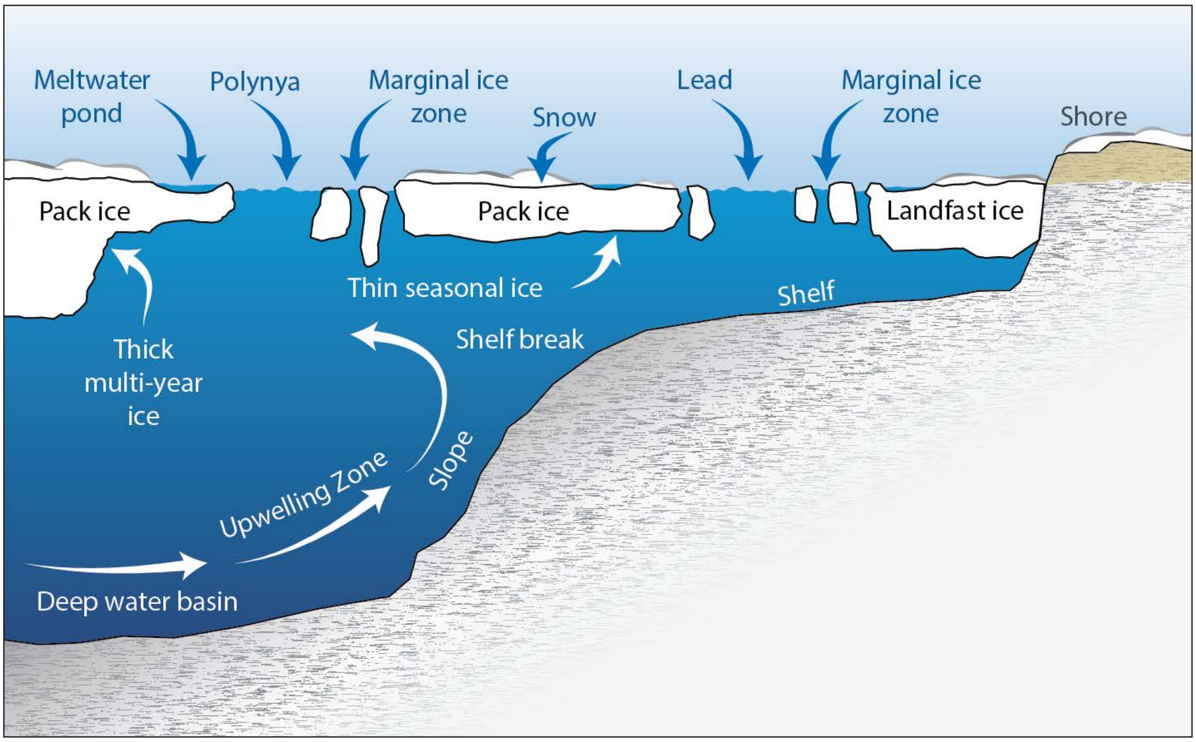
Polynyas: areas of permanently or frequently open water in winter surrounded by sea ice

Leads: linear stretches of open water in sea ice, often between landfast ice and pack ice

Marginal ice zones: transition areas from pack ice to open water

Upwelling zones: where deep, often nutrient–rich water rises to the surface due to wind or currents interacting with bathymetry

These and other features of the sea ice environment are illustrated below:



Box figure 2.1. Some features of the sea ice environment. Marine areas seasonally or permanently covered by sea ice are a globally unique habitat. Ice edges and open water areas favour wind-driven mixing of the seawater that enhances local production and can create biological hotspots. Adapted from Eamer et al. (2013).

and the connection to other oceans via 'corridors' (Meltofte 2013, Hunt et al. 2016). Despite extreme environmental conditions, Arctic marine ecosystems support a great diversity of life, including species found nowhere else on Earth. The Arctic marine environment supports over 5,000 animal species, including commercially valuable fish species, large populations of migratory birds and some of the world's largest seabird colonies, and unique and iconic Arctic species such as polar bear (*Ursus maritimus*), walrus (*Odobenus rosmarus*) and narwhal (*Monodon monoceros*) (Meltofte 2013). There are also tens of thousands of less understood, but vitally important species of bacteria, microbes, algae, single-celled organisms and parasites, with many more species to be discovered (Meltofte 2013). Zooplankton represent key links between primary producers and middle trophic levels (e.g., fish and seabirds), with *Calanus* copepods and pelagic or ice-associated amphipods as the most important groups in the Arctic for lipid production and transfer to higher trophic levels as well as to the benthos though vertical flux (Falk-Petersen et al. 2009, Søreide et al. 2013).

When sufficient light penetrates the ice pack in spring, it kick-starts the development of ice algae in early spring. A phytoplankton bloom will usually take place later in the summer in the water column. These events deliver energy and materials to zooplankton and other trophic levels, resonating throughout the food web (Eamer et al. 2013). Most Arctic marine species are highly seasonal and specialized when it comes to feeding, reproduction and migration patterns, so the timing and duration of sea ice retreat and ice-free ocean determine when, where and for how long species can accomplish activities that are vital to survival.

The food web extends well beyond just the transfer of energy to encompass diverse cultural and social benefits that humans derive from their environment. Importantly, Arctic marine ecosystems support human life. Indigenous peoples of the Arctic have lived with the polar environment for thousands of years, and many marine species are important not just for food and clothing, but hold special significance for spiritual and cultural meaning and purpose (Raymond-Yakoubian et al. 2014, ICC-Alaska 2015, Slavik 2015). Non-indigenous Arctic residents also hold a special relationship to the sea, recognizing it as a force that shapes their individual livelihoods, as well as economies and cultures (Einarsson et al. 2011, Schweitzer 2014).

2.2 Physical drivers

The Circumpolar Biodiversity Monitoring Program's (CBMP) *Arctic Biodiversity Marine Monitoring Plan* (*CBMP Marine Plan*) identifies several priority drivers that influence the chosen Focal Ecosystem Components (FECs) (Gill et al. 2011). What follows are descriptions of key physical parameters that influence Arctic marine ecosystems. This section addresses physical drivers (i.e. natural variability parameters) that result in change over time, whereas Chapter 2.3 summarizes some anthropogenic drivers. The most relevant climate system parameters are included in the physical driver's section, although climate change is also an anthropogenic driver. Physical or anthropogenic drivers that have particular effects on FECs will be revisited in Chapter 3.

Box 2.2: Key physical drivers of change

Physical drivers are identified in the CBMP *Arctic Marine Biodiversity Monitoring Plan* (*CBMP Marine Plan*; Gill et al. 2011). The physical drivers were further developed during the implementation of the *CBMP Marine Plan*, and do not strictly follow the categories used in the *CBMP Marine Plan*.

These are:

- Sea surface temperature
- Ocean currents and frontal boundaries
- Sea surface salinity
- Ocean acidification
- Nutrients
- Sea ice, including
    - ice cover
    - ice concentration
    - ice dynamics
    - marginal ice zones
    - landfast ice
    - polynyas and leads

Monitoring temperature, light, sea ice cover, storm events and other abiotic drivers, including those described in Box 2.2, are outside the scope of the CBMP, although information on key abiotic parameters is important to correctly interpret and analyse biodiversity and ecosystem information in a comprehensive way.

Most of the drivers mentioned in Box 2.2 can be linked with climate system parameters. When considering physical drivers, the CBMP distinguishes between variability and change. Variability can be regarded as the short-term, non-directional shift in parameter values, usually within some reasonably predictable range of limits, whereas change is a long-term, directional trend or shift in some aspect of the climate system (or other recipient systems) due to external forcings or internal feedback. Climate change embodies both alterations in parameter variability as well as changes in those parameters.

Arctic Ocean ***sea surface temperature*** have been recorded during many research and monitoring projects. According to the IPCC (2013) and NOAA (2015), the available data are insufficient to reliably calculate long-term trends for the vast majority of the Arctic marine environment (Fig. 2.3). However, existing monitoring in some areas suggests that the Arctic marine environment is undergoing a rapid warming trend, which follows a general documented warming trend in global ocean temperatures over the past 30 years (AMAP 2013). For example, temperatures recorded for the Barents Sea has increased since the 1970s (Johannesen et al. 2012, Smedsrud et al. 2013). As the world's oceans absorb more heat, sea surface temperatures will increase and ocean circulation patterns that transport warm and cold water around the globe will change. A rise in seawater temperature of up to 4°C is expected in the Atlantic sector of the Arctic Ocean, which is expected to have direct and indirect impacts on marine biodiversity (Müller et al. 2009, Meltofte 2013, Hunt et al. 2016). Such changes in temperature can affect any and/or all aspects of species life cycles, including breeding, rearing, feeding, predator-prey relations, population cycles, and timing and duration of migration (Meltofte 2013).

Large ***ocean currents*** encircle the world like a conveyor belt and are highly connected to the atmosphere, playing a major role in global weather patterns and affecting ocean life. The Arctic plays a key role in the global climate system through the production of North Atlantic Deep Water, which helps drive the circulation of the world's oceans. Simplified Arctic Ocean currents (Fig. 2.1) show that the main circulation patterns follow the continental shelf breaks and margins of the basins in the Arctic Ocean. Different global models predict different types of changes, which can cause changes to Arctic ecosystems (AMAP 2013, Meltofte 2013).

Ocean frontal boundaries separate two distinct water masses. With sharp gradients in parameters such as temperature and nutrient richness, ocean frontal boundaries often create hot spots for biological production (Meltofte 2013). These frontal boundaries can shift location from year to year depending on physical parameters such as river inputs and salinity, and temperature in water masses advected from other areas. The area of the Barents Sea where cold, less saline Arctic water meets warm, saline Atlantic water (i.e., the Polar Front) is known to be an area of high biological production. Arctic and more southern species tend to meet in this area because of increased food availability and because thermal barriers prevent further distribution northwards for southern species. There are similar patterns in other places in the Arctic, including in the Bering Sea (Meltofte 2013).

Changes in ***sea surface salinity*** can alter the physical and chemical environment, affecting ocean currents and potentially altering marine food webs (Carmack and Wassmann 2006). Pacific water enters the Arctic Ocean

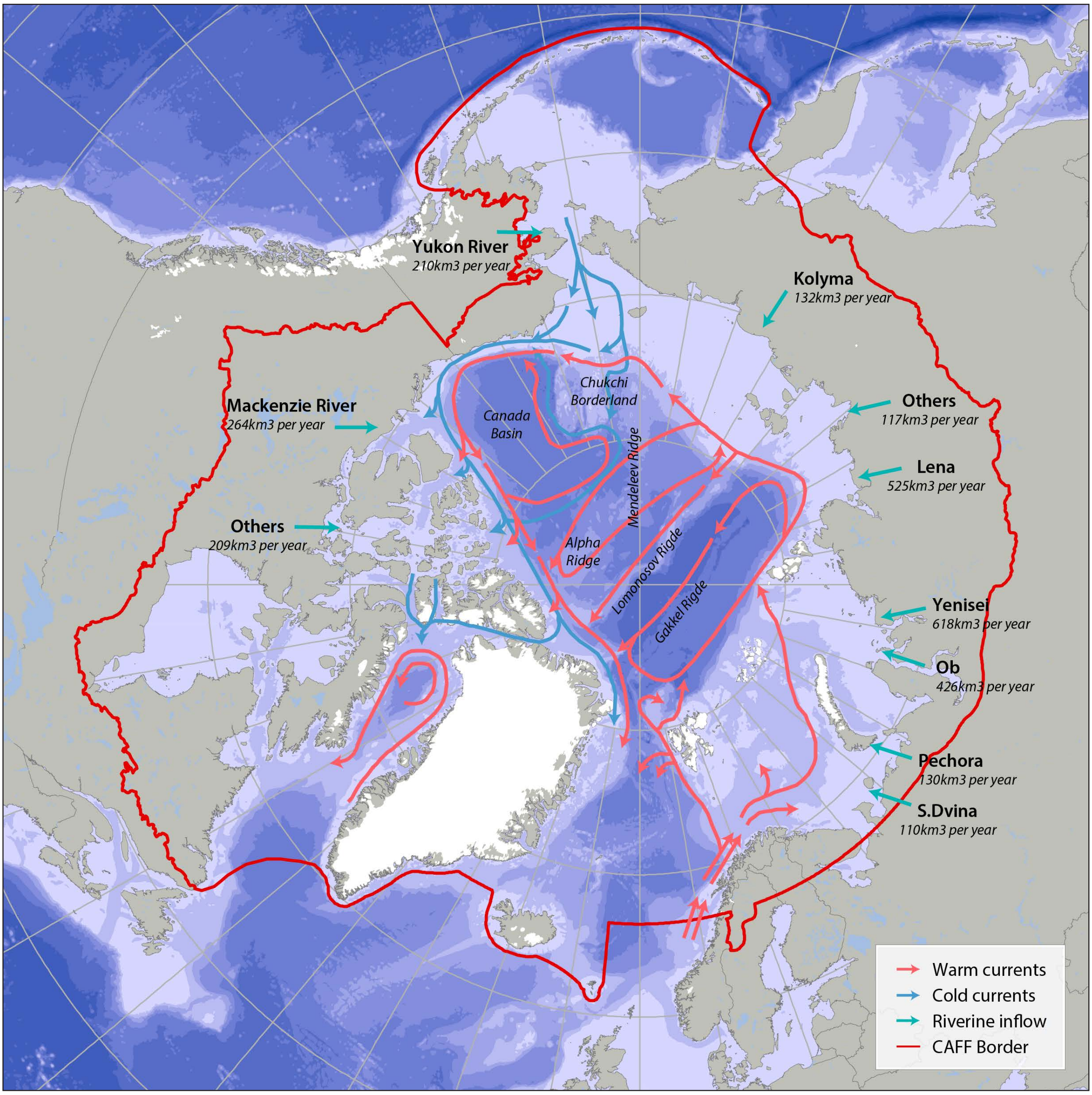


Figure 2.1. Bathymetric features, warm currents (red arrows), cold currents (blue arrows) and riverine inflow in the Arctic. Adapted from Jakobsen et al. (2012).

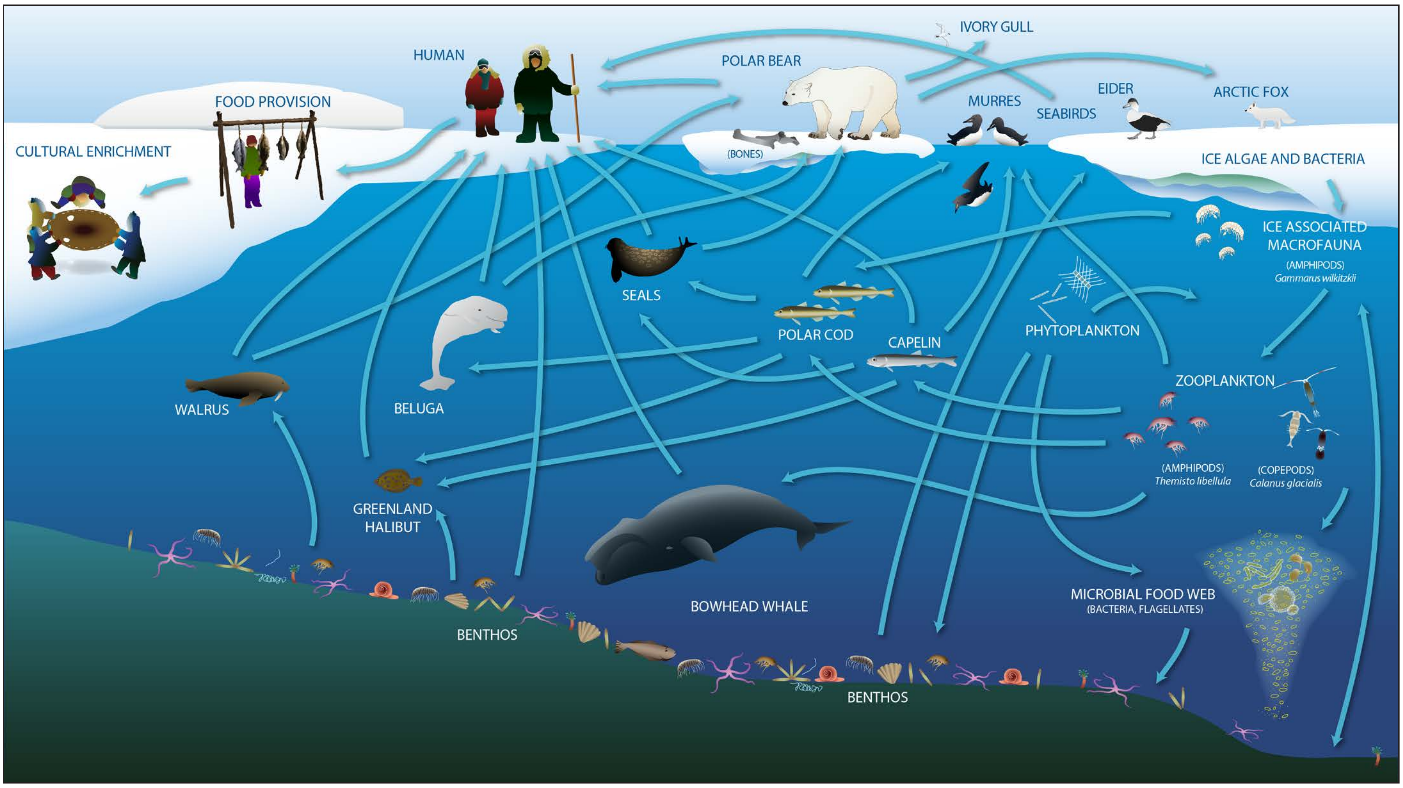


Figure 2.2a. Conventional conceptualization of energy flow in the High Arctic marine environment. The Arctic marine food web includes the exchange of energy and nutrition, and also provides cultural, social and spiritual meaning for human communities. Adapted from Darnis et al. (2012) and the Inuit Circumpolar Council-Alaska (2015).

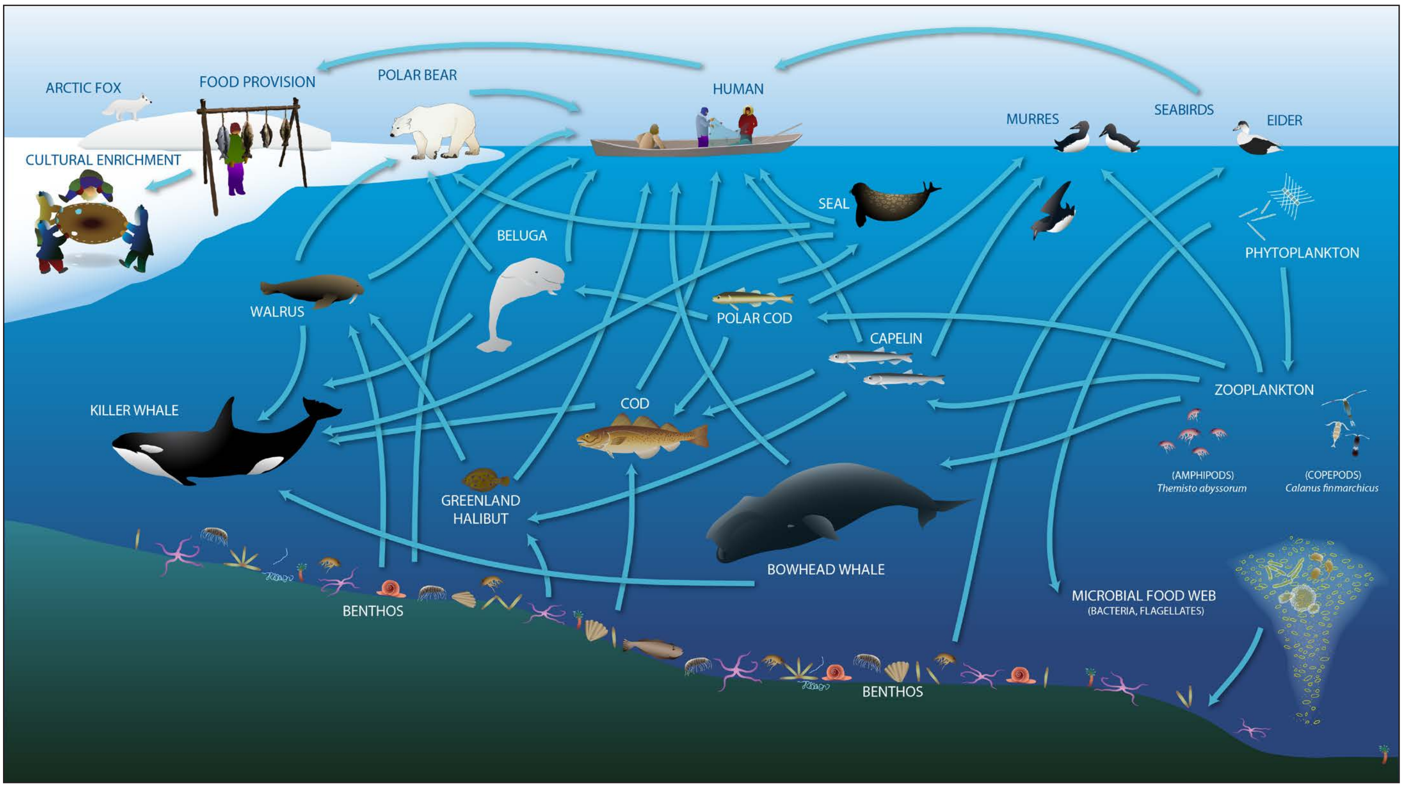


Figure 2.2b: Changes expected or underway in the energy flow in the High Arctic marine environment. The Arctic marine food web includes the exchange of energy and nutrition, and also provides cultural, social and spiritual meaning for human communities. Adapted from Darnis et al. (2012) and the Inuit Circumpolar Council- Alaska (2015).

through the shallow and narrow Bering Strait (Fig. 2.1). Pacific water is less saline and therefore less dense than Atlantic water, and forms a distinct layer on top of the Atlantic water. Furthermore, freshwater enters the Arctic Ocean from river basins and glaciers, mainly from Russia and Canada—countries that contain some of the largest freshwater systems in the world. This input of freshwater contributes to stratification, making the top 45 m or so of the Arctic Ocean less saline than the water below. Warming, combined with increased precipitation, has caused an increase in freshwater discharge into the Arctic Ocean (Dyurgerov et al. 2010), for example, increased melting from the Greenland Ice Sheet has increased freshwater inflow to areas in the North Atlantic.

Alkalinity is a fundamental chemical property of the carbonate system for seawater. Oceans have been increasingly absorbing carbon dioxide (CO_2) because of the rising levels of CO_2 in the atmosphere (Freely et al. 2004, Pelejero et al. 2010, AMAP 2013). The resulting higher concentration of CO_2 in the world's oceans causes ***ocean acidification***, a phenomenon that changes the chemical carbonate balance of the sea water, and thus the living conditions for biota. The Arctic is especially vulnerable to this acidification since CO_2 dissolves more easily in colder water.

Less alkaline waters may dissolve the materials that some organisms need to build their skeletons and shells (Orr et al. 2005, AMAP 2013), although organisms in many cases will still be able to construct their skeletons at the cost of increased energy requirements (Browman 2016). Calcium carbonate crystalizes in two forms, calcite and aragonite, which have different solubilities in relation to pH. Organisms using the more soluble form, aragonite, are most sensitive to acidification. Pelagic snails (pteropods) are an important component of zooplankton and experimental studies have shown that they are highly vulnerable to dissolution of their aragonite shells at close to current pH levels (Bednarsek et al. 2014). On the other hand, organisms incorporating the less soluble calcite, such as the abundant planktonic algae belonging to the group coccolithophores, may be better able to adapt to increasing acidity at the cost of expending more energy on constructing their skeletons (Beaufort et al. 2011). Arctic copepods, such as *Calanus glacialis*, are less affected by increased seawater pCO_2, even at the younger life stages (Bailey et al. 2017). However, lowered pH may increase metabolic cost for this species at the expense of growth performance (Thor et al. 2016).

Nutrient-rich areas stimulate growth of ice algae, phytoplankton and invertebrates and serve as important feeding grounds for larger animals such as fish, seals, whales and seabirds (Chapter 2.3). Nutrient-rich waters can be found in areas of sea-ice melt, ice edges, upwelling zones and throughout nutrient-rich currents such as the Anadyr Current, which moves northward into the Arctic Ocean via the Pacific Arctic Bering Strait region (Codispoti et al. 2005). Changes in nutrient supply related to changes in physical parameters, such as sea ice and current alteration, could dramatically alter ocean ecosystems (Meltofte 2013).

Timing, distribution and characteristics of ***sea-ice cover*** define and drive the conditions in many Arctic marine ecosystems, affecting seasonal cycles of light availability, water temperature, nutrients and the flow of energy through the food web. Some of the features of the sea ice environment are illustrated Box 2.1.

Average summer ***sea-ice extent and thickness*** is decreasing (AMAP in press a, b; Fig. 2.4), which can have major impacts on sea-ice dependent species and ice-associated ecosystems.

The presence of sea ice impedes surface water mixing, and influences freshwater and heat fluxes, which, in combination with snow cover, reduces light availability for primary producers. Therefore, snow cover and sea-ice melt/break-up appear to control the timing of ice-associated (i.e., ice algae) and pelagic (i.e., phytoplankton) blooms (Michel et al. 2006, Lavoie et al. 2009).

Most of the Arctic Ocean is projected to be virtually ice-free in summer within 30 years, with multi-year ice persisting mainly in the Arctic Archipelago, the narrow straits between Canada and Greenland, and north of Greenland (Wang and Overland 2012, Eamer et al. 2013, Meltofte 2013). Multi-year ice is very low in the straights between Greenland and Canada, with the high productivity surface water historically in Northern Baffin Bay moving north. The most obvious negative impacts of rapid changes in sea ice are on species that depend on the ice as habitat, such as polar cod (*Boreogadus saida*), ivory gull (*Pagophilia eburnea*), ice seals and polar bear (Chapter 3). Together with more extreme weather events, such as storms, changes in sea ices are also likely to have direct or indirect effects on many other species and on productivity (Meltofte 2013).

Polynyas and leads play an important role in the productivity and biodiversity of Arctic marine ecosystems. Polynyas are pockets of recurrent open water areas amidst ice-cover and are distinguished from leads by being broad openings rather than long, narrow fractures. They occur throughout the Arctic and are associated with circumpolar flaw lead systems that form along the edge of landfast ice areas (where ice is frozen to the coast and does not move with wind or currents). Polynyas can be sites of enhanced or early season productivity, making them important biological hotspots (Bursa 1963, Hirche et al. 1991, Stirling 1997, Moore and Laidre 2006). In summer, the region of the North Water Polynya in Baffin Bay supports some of the largest concentrations of seabirds anywhere in the Arctic and is a critical habitat to several populations of marine mammals (Stirling 1997, Christensen et al. 2012, Heide Jørgensen et al. 2013).

2.3 Human drivers

Many Arctic regions have seen little or no direct human-induced habitat change compared with other parts of the world. Some historical examples can be found in activities such as hunting, commercial fishing, oil spills and others where human-induced impacts have had direct effects on Arctic marine ecosystems (Meltofte 2013). The *CBMP Marine Plan* identifies several important drivers that influence the FECs (Gill et al. 2011).

Overharvest has not only caused depletion of some target populations, but in some cases, it has had cascading ecosystem effects. For example, the elimination of large whales by commercial whaling may have been followed

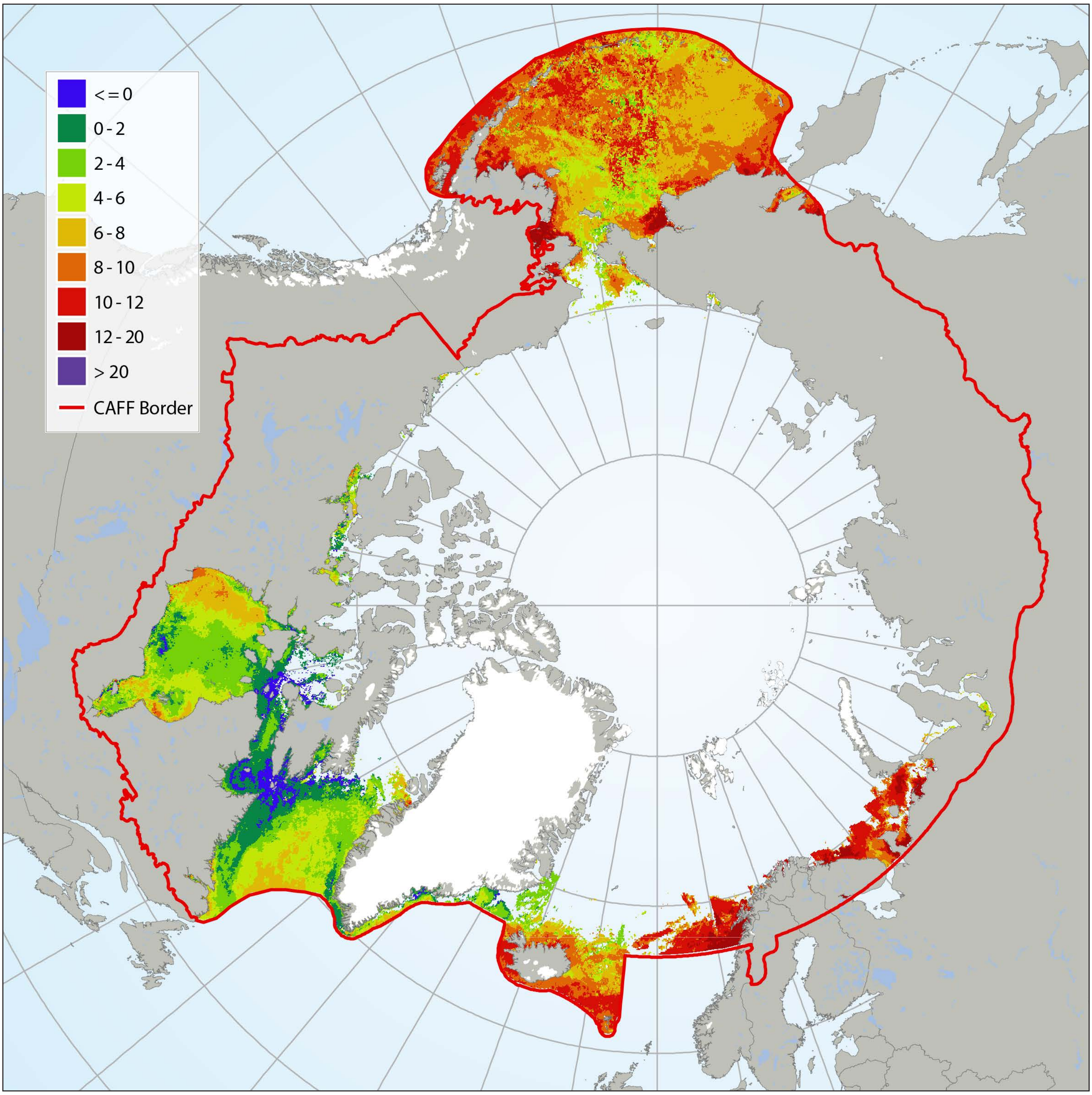


Figure 2.3: It has not been possible to identify available trend data for Arctic Ocean sea surface temperatures because there is not enough data to calculate reliable long-term trends for much of the Arctic marine environment (IPCC 2013, NOAA 2015). Here, sea surface temperature for July 2015 is shown from CAFF's Land Cover Change Index. MODIS Sea Surface Temperature (SST) provided a 4 kms spatial resolution monthly composite snapshot made from night-time measurements from the NASA Aqua Satellite. The night-time measurements are used to collect a consistent temperature measurement that is unaffected by the warming of the top layer of water by the sun.

by increasing populations of smaller marine mammals together with some seabirds (Springer et al. 2003). Another example is the depletion of large populations of predatory fish (Smetacek and Nicol 2005) that may have resulted in reduced genetic variability of some species (Meltofte 2013). The impact of historical harvest of marine mammals, fish and seabirds on current structure and function of Arctic marine ecosystems is not well documented, but the removal of such a large biomass of targeted species would have affected the flow of energy and trophic interactions. Overharvest was historically the primary human impact on many Arctic species, but sound management has successfully addressed this problem in most, but not all, cases. However, there have been management failures and high harvest pressure continues for some fish stocks and seabird populations (Meltofte 2013).

Fisheries in some Arctic regions play a significant role in the economy (AMAP in press a). For example, Greenlandic commercial fisheries produce over half of the total service and goods export value for the country, amounting to 57% in 2011 (AMAP in press a). Commercial fisheries are also rapidly expanding in the waters off Nunavut, Canada, with an increase in total value from 38 million to 86 million CAD during the period 2006-2014 (AMAP in press a). Up to 1,600 vessels may be active at times in the ice-free sections of the Barents Sea (PAME 2009).

Conventional ***bottom trawl*** fisheries for groundfishes are highly efficient, but can be damaging to the environment, as they can change the composition of benthic communities. Fishing practices such as bottom trawling may pose serious threats to benthic communities and remain an important stressor in some areas (Thurstan et al. 2010, Meltofte 2013). The most harmful effects of trawling have been demonstrated for hard-bottom habitats dominated by large sessile (immobile) fauna (Lyubin et al. 2011, Jørgensen et al. 2015, AMAP in press a).

The recent levels of ***mercury*** and ***persistent organic pollutants*** (POPs) in some areas are believed to exceed the threshold for biological effects in some species, in particular, top predators in Davis Strait-Baffin Bay, East Greenland and Svalbard (Letcher et al. 2010, AMAP 2011, Fauchald et al. 2015). It is anticipated that mercury concentration will increase in the environment and wildlife, while legacy POPs controlled by or subject to national and international regulations will likely decrease (AMAP in press a). However, new and emerging compounds (such as such as brominated and fluorinated compounds and siloxanes) with unknown effects on biodiversity will likely continue to be found in the environment.

The extraction and use of ***oil, gas and minerals*** is probably the single most important human-induced contributor to pollution, both locally in the form of release of toxic compounds and accidents (AMAP 2009, Meltofte 2013) and globally in the form of greenhouse gases, black carbon and mercury emitted when fossil fuels are combusted. This is particularly relevant for the Arctic, not only because the region potentially holds one-fifth of the world's yet undiscovered hydrocarbon resources, but also because it experiences globally disproportionate and amplified effects of warming (Bird et al. 2008, Meltofte 2013).

Box 2.3. Key anthropogenic drivers of change

- Harvest and fisheries
    - ○ direct impacts: mortality, population demographic shifts
    - ○ indirect impacts: bycatch, habitat loss, disturbance (displacement from important habitats; some hunting activities, alteration (trawling) and changes/reduction of prey availability and size.
- Persistent, bio-accumulative and toxic contaminants: impact of persistent organic pollutants (POPs) and toxic metals (e.g., methylmercury), originating primarily from non-Arctic sources.
- Industrial development: habitat loss, alteration, disturbance, seismic activity, oil spills, pollution, garbage, noise, etc.
- Shipping: oil spills, chemical discharges, waste, noise over and under the water, collisions with marine mammals, introduction of invasive alien species, etc.
- Invasive alien species

Environmental impacts from exploring and extracting raw materials may change with a changing climate, requiring a call for flexible and adaptive management actions (AMAP in press a). Overall, warming will increase access to resources and this may increasingly expose vulnerable areas to resource exploration activities.

Projected losses of Arctic sea ice are likely to influence future ***shipping activities*** as natural resource development, regional trade, transportation of goods, tourism and research activities are developing in relation to climate change. Climate change and resulting changes in sea ice extent are recognised as important drivers for future shipping in the Arctic (PAME 2009, AMAP, in press a). In relation to transit shipping, the Northeast Passage will likely be an important gateway from the Pacific to the Atlantic in the future. However, other drivers outside the Arctic such as market constraints, as well as geopolitics, including the deepening of the Panama Canal and Suez Canal will also affect the transit and destinational shipping in the Arctic, and are therefore important drivers for future Arctic shipping activities.

If not regulated properly, ***shipping and industrial development activities*** are likely to have serious consequences for the Arctic environment (Reeves et al. 2014) and for those living in the region that continue to rely on the environment for food security and livelihoods. Impacts include accidental or regular discharge of oil, noise, air emissions, garbage discharge, invasive species introduction, light disturbance, whale strikes and more. However, a large oil spill is probably the most serious hazard to the Arctic marine environment (Skjoldal et al. 2009) and is a major concern to communities, fishers and hunters, politicians, environmentalists, and the scientific community.

Figure 2.4. Average September sea ice extent in 1979 (blue) compared with 2016 (white) and the median sea ice extent (yellow line) from 1981 to 2010 (Data: NSDIC 2016).

Invasive alien species have been recognized as one of the greatest biological threats to the planet's ecological and economic well-being (McNeely et al. 2001) and the adverse impacts of invasive alien species recognised as constituting one of the most significant stressors facing Arctic biodiversity (CAFF 2017).

2.4 Cumulative effects

A single driver may put relatively little pressure on the environment, but in combination, multiple repeated drivers can create cumulative effects in the environment with surprising and hard-to-predict results. Different drivers act on different elements within the ecosystem and different pressures may have either synergistic or antagonistic effects on particular ecosystem components. Drivers may also have direct and indirect effects on the ecosystem, further complicating relationships between drivers and change. Worldwide there is an increasing awareness of cumulative effects and the need to take a holistic and integrated approach to management to ensure the sustainability of marine ecosystems (ICC-Alaska 2015, Ottersen et al. 2011, O'Boyle and Jamieson 2006). Little is known about the patterns of cumulative effects and the changes these effects may cause. There currently exists no method or standardized approach for determining the impacts of cumulative effects. However, knowledge about causalities in the ecosystem, spatial data on important areas for species and ecosystems, and data on the distribution and intensity of human activities in marine areas are all essential in establishing a more adaptive and ecosystem-based approach to marine environmental management (Halpern et al. 2008, 2015, Ottersen et al. 2011).

Figure 2.5 Circumpolar map of known polynyas. Note that polynyas are dynamic systems and some may no longer exist in the form known from their recent history. Adapted from Meltofte (2013) and based on Barber and Massom (2007).

Inuit understanding of the environment also places strong recognition and consideration on the need to monitor connections between components of the ecosystem and how systems interlink (ICC-Alaska 2015). This approach is important to contribute towards a better understanding of cumulative effects (ICC-Alaska 2015). For example, Inuit walrus hunters consider not just the walrus, but also the connections between the animal and sea ice thickness, benthic food supply, ocean currents and more, as these drivers shape the appearance, location and health of the walrus (ICC-Alaska 2015). Collaboration and co-production of knowledge between scientists and Traditional Knowledge (TK) holders can foster important relationships, meaningful engagement and understanding, thus increasing collective knowledge about cumulative effects and points of resilience and vulnerability (ICC-Alaska 2015).

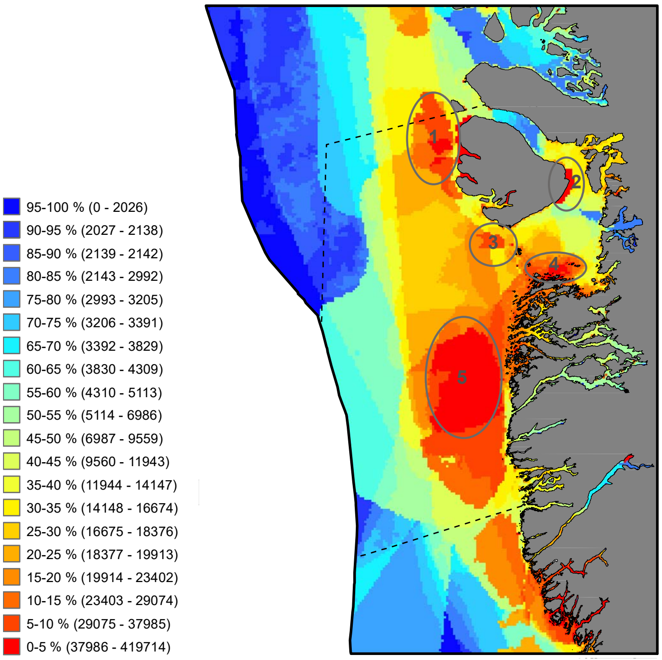
Ecosystem-based management (EBM) has been identified by Arctic States as key to an adaptive way to sustainably manage Arctic ecosystems. Its interdisciplinary approach considers the political, regional and cultural contexts of an area and provides a flexible means to manage the effects of multiple pressures on Arctic ecosystems (Arctic Council 2013). An important goal of EBM is to consider the cumulative environmental effects of important pressures and impacts on the environment.

Box 2.4 Looking at cumulative effects and ecosystem-based management

Critical to the successful implementation of ecosystem-based mangement (EBM) in the Arctic is the existence of a cohesive circumpolar approach to the collection and management of data and the application of compatible frameworks, standards and protocols that this entails.

Many examples demonstrate how more intensive use of spatial data has been applied in a national context to implement a marine spatial planning exercise in support of marine EBM. For instance, EBM regimes are introduced for Norwegian Sea areas. These can be regarded as large-scale spatial management tools and are coordinated by a management forum led by the Norwegian Environment Agency, and an advisory forum for monitoring, led by the Institute of Marine Research. EBM also requires an ecosystem-based approach to the monitoring of effects. One example is the plan for the Barents Sea (Olsen et al. 2007). In the Barents Sea example, monitoring effects is a stepwise process. Firstly, information on environmental conditions, commercial activities in the sea areas and value creation are compiled to provide a common factual basis for impact assessments. Secondly, impact assessments are carried out for all main activities that may affect the environment and relevant indicators to monitor are identified. An inter-ministerial steering committee carries out the environmental targets, based on the scientific advice. The monitoring program is regularly updated according to new knowledge and research (Ottersen et al. 2011).

Another recent example from Greenland demonstrates how different parameters, including species and ecosystem distribution, and human induced effects, were compared spatially to identify areas in need of special management attention. In response to the potential impacts from shipping and other activities in Disko Bay and Store Hellefiskebanke, the Danish Ministry of Environment conducted an extensive spatial analysis and modelling exercise to inform the development of appropriate management initiatives (Christensen et al. 2015). Abundance, occurrence and migration routes for over 65 species in the region were mapped focusing on the spatial distribution of important marine species and ecosystem components. These map layers were then combined to identify the most biologically important areas according to a set of criteria informed by the Convention on Biological Diversity to identify Ecologically and Biological Sensitive Areas (EBSAs) and by the International Maritime Organization (IMO) to identify Particular Sensitive Sea Areas (PSSA). This method was inspired by impact-mapping approaches used in marine regions outside the Arctic, as described by Halpern et al. (2008). Each of the biological features was assessed and ranked according to its specific sensitivity to potential environmental effects caused by shipping. This analysis found that several smaller areas around Disko Bay and Store Hellefiskebanke are sensitive or very sensitive to the environmental impacts that shipping may cause. Five sub-areas were identified (Box Fig. 2.2) where heightened awareness is needed in relation to impacts from shipping.



Box figure 2.2. Relative environmental sensitivity of areas in Disko Bay and Store Hellefiskebanke, western Greenland including five sub-areas (1 – 5) where there may be need for heightened awareness in relation to shipping. The colours indicate sensitivity in 2.5 x 2.5 km^2 grids, based on an assessment of existing species and ecosystem-component sensitivity to environmental impacts from shipping (oil, noise/ disturbance, organic garbage). Grids are divided into 5% fractiles with the relatively most sensitive in red. Adapted from Christensen et al. (2015).

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Ice associated algae.
Photo: Eric Collins, University of Alaska, Fairbanks

3.1 Sea ice biota

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Snapshot

- Multi-year sea ice is disappearing and will be replaced by first-year sea ice, which will cause shifts in ice algal communities with cascading effects on the ice-associated ecosystem.
- Seasonal duration of first-year sea ice is expected to become shorter, with more snow on the ice, which may decrease the growth season for ice algae, with unknown consequences for biodiversity.
- Sea ice is an important Arctic habitat that supports a rich diversity of species—many of which we know little about.
- It is possible that sea ice algal community structure has changed in the central Arctic between the 1980s and 2010s. This change probably occurred when sea ice extent and thickness declined, but also when sampling efforts and regions shifted, so it is difficult to attribute change.
- Ice amphipod abundance has declined around Svalbard since the 1980s, coinciding with declining sea ice conditions.
- Changes in sea ice biota are very challenging to detect because sea ice is a dynamic system that has large natural variability, and there has been a lack of consistent sea ice biota monitoring.
- Sea ice biota are affected by temperature and salinity, nutrient and space limitations and the ephemeral nature of the ice habitat, therefore making them very susceptible to climate change.
- Sea ice biota monitoring has occurred most frequently in the central Arctic, Svalbard, Barrow (Alaska) and the Canadian Arctic, with new sites developing in Greenland. Consistent monitoring protocols, equipment and methodology are required.

3.1.1 Introduction

The sea-ice related food web and biodiversity are critical components of the Arctic marine ecosystem. Higher trophic levels are directly or indirectly supported by over 2,000 species of small algae and animals that are associated with sea ice, but are often inconspicuous to the naked eye. These species inhabit a wide range of microhabitats inside the brine channel system, on top of the ice in melt ponds, immediately underneath the ice at the ice-water boundary and including extensive pressure ridges (Figure 3.1.1). The spatial distribution of sea ice biota (hereafter referred to as sympagic or ice biota, cf. Legendre et al. 1992) is shaped by dynamic properties of the sea ice. Spatial scales range from the micrometre dimension of the brine channel network to the metre scale that defines ice thickness and horizontal floe extent, to the hundreds of kilometre scale of ice drift patterns across the entire Arctic Ocean. The origin and age of sea ice are important factors which impact the resulting community composition of sea ice biota, with pronounced differences among biota and living conditions in annual landfast sea ice, offshore annual pack ice and multi-year pack ice (also called drift ice).

The hallmark of climate change is the drastic decline in the sea ice cover over at least the past 40 years since the satellite record has allowed accurate observation and interannual comparisons (e.g., Perovich et al. 2015). The Arctic ice cover has declined during all seasons of the year and, concomitantly, the proportion of multi-year sea ice has decreased while the share of first-year sea ice has increased (Nghiem et al. 2007, Barber et al. 2015). Shifts are expected in ice-associated biota composition, abundance, biomass and the timing of the seasonal development (referred to as phenology) (Gradinger et al. 2010, Leu et al. 2011). Without sufficient monitoring, such changes will be impossible, or at best difficult to detect until effects are dramatic or until they are detected in other parts of the ecosystem due to the coupled processes between sea ice, water column and benthic biota. Higher trophic levels, including seabirds and marine mammals, can also function as indicators of changes in the lower part of marine food webs because their diets, conditions and survival depend on availability of suitable prey (e.g., Mehlum and Gabrielsen 1993, Bluhm and Gradinger 2008).

Close association of living organisms with Arctic sea ice has already been reported ~160 years ago by Ehrenberg (1853) and related knowledge has expanded extensively since then by several authors including, for example, Grunow (1884), Nansen (1906), Hsiao (1983), Horner (1985), Melnikov (1997) and others. As a result of international research in largely independent projects, a total of several thousand species of auto-, mixo- and heterotrophs encompassing viruses, bacteria, fungi, microalgae, and other protists and multicellular animals have been recorded (overviews in Poulin et al. 2011, Daniëls et al. 2013, Josefson and Mokievsky 2013, Lovejoy 2013, Bluhm et al. 2017). These include a combination of ice-endemic species, and taxa of pelagic or benthic origin as well as larval (meroplanktonic) stages of benthic fauna. The inventory of ice biota is still incomplete as new species of bacteria, microalgae, fungi and animals continue to be described from the sea ice environment, partly due to the advances of molecular methods during the last decade (Brinkmeyer et al. 2003, Piraino et al. 2008, Collins et al. 2010, Collins 2015). In addition to studies focusing on diversity and phenology in taxonomic composition, the ecology and physiology of selected ice-related organisms have also received increased focus (Arndt and Swadling 2006, Werner 2007, Fuhrmann et al. 2011, Leu et al. 2015).
Data on sea ice biota diversity have been collected as part of scientific expeditions over many years, and we present

these here in a pan-Arctic context based on a comprehensive approach of data assimilation and integration. The choice of Focal Ecosystem Components (FECs) considered is based on the *Arctic Marine Biodiversity Monitoring Plan* (Gill et al. 2011; *CBMP Marine Plan*), with some modifications. The CBMP Sea Ice Biota Expert Network has included here: (1) Bacteria and Archaea, assessed by molecular methods; (2) ice algae and other protists, referring to photosynthesizing single-celled eukaryotes, and hetero- and mixotrophic protists, assessed by morphological characters through optical and electron microscopy; (3) ice meiofauna, referring to multicellular organisms larger than ~20 µm to ~500 µm living inside the ice brine channel network and primarily assessed by morphological characters; and (4) under-ice macrofauna, typically larger than ~500 µm, here exclusively represented by ice amphipod crustaceans. Sea ice associated fish, specifically polar cod (*Boreogadus saida*; referred to as Arctic cod in North America) and ice cod (*Arctogadus glacialis*; referred to as polar cod in North America), are included in the Fish chapter (Chapter 3.4). Viruses and fungi are excluded in this report, although they may occur in very high abundances in sea ice (Maranger et al. 1994, Hassett et al. 2016a). Virus occurrence exhibits strong seasonal variability, but their hosts (eukaryotes or bacteria) have not yet been identified. Fungi are dominated by Chytridiomycota and Dikarya, and those chytrids parasitizing on diatoms are most abundant during the ice algal spring bloom (Hassett et al. 2016b).

In this report, we consider some aspects of the diversity (here defined as taxon richness and taxonomic composition), abundance, biomass and distribution of these FECs in different ice types, seasons and years, on pan-Arctic distribution scales. In compiling the relevant information, however, it became apparent that such data were not consistently available for all targeted ice biota FECs. Thus, attention is given to the following four topics. First, the CBMP Sea Ice Biota Expert Network presents the *taxonomic composition and species richness* of organism groups for which at least moderate to high taxonomic resolution is available; these include Bacteria and Archaea, ice algae and ice amphipods. Second, the CBMP Sea Ice Biota Expert Network summarizes the *composition and abundance of sympagic meiofauna* at the pan-Arctic scale, but at coarser taxonomic resolution. Third, the CBMP Sea Ice Biota Expert Network gives two examples of the sparse data sets available on seasonal trends in ice biota, here on the abundance of sympagic meiofauna. Finally, *interannual trends* – for which data are even sparser – in community structure of ice algae (and other protists) and densities of ice amphipods are shown, with interpretations reflecting that these are composite data sets rather than monitoring data. Other, more advanced indicators mentioned in Gill et al. (2011), such as ratios between certain taxa, are not included.

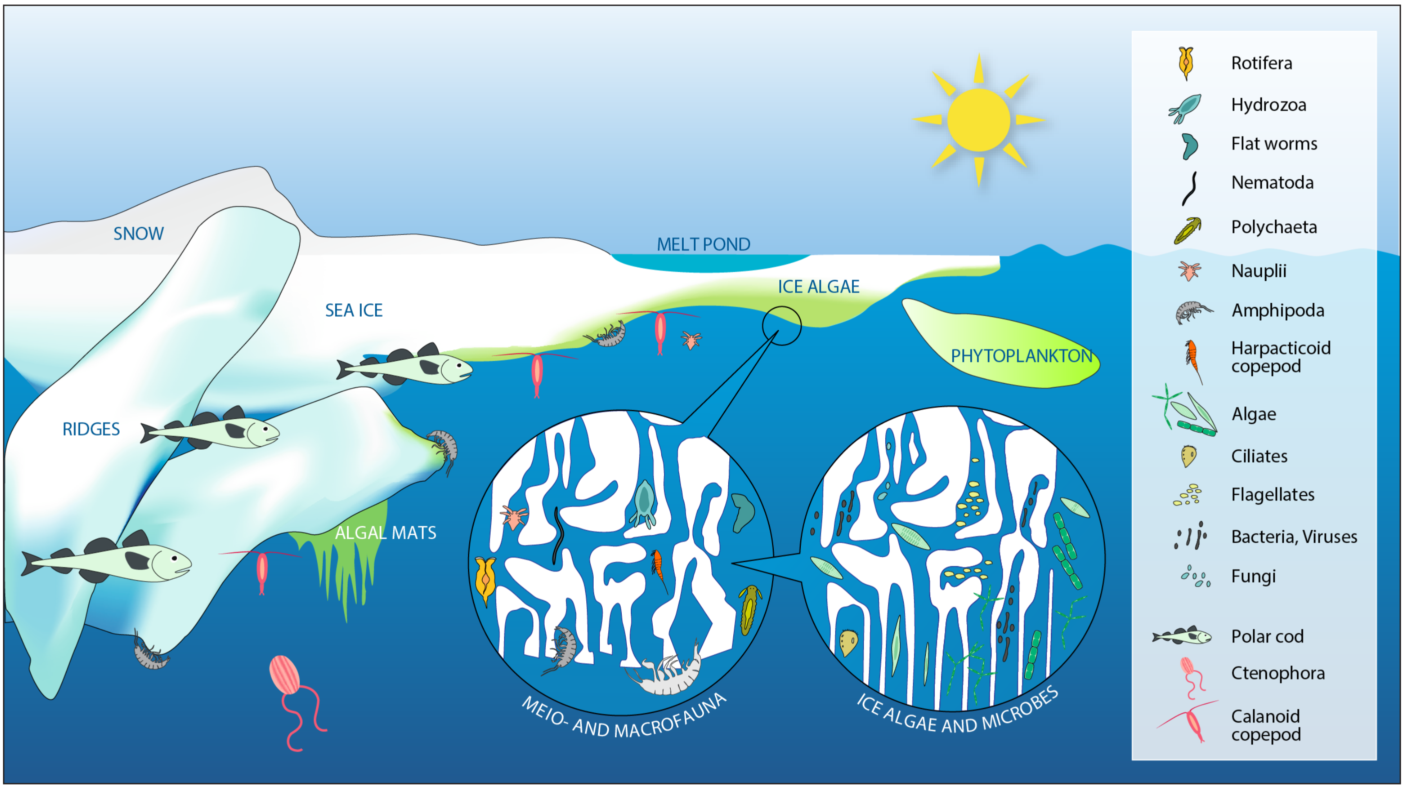


Figure 3.1.1 The Focal Ecosystem Components (FECs) (circles) in sea ice. Sea ice provides a wide range of microhabitats for diverse biota including microbes, single-celled eukaryotes (labelled algae), multicellular meiofauna, larger under-ice fauna (represented by amphipods), as well as polar cod (Boreogadus saida). Modified from Bluhm et al. (2017).

Box 3.1.1: Technical terms related to sea ice biota and plankton communities

Algae: phototrophic eukaryotes, especially those associated with surfaces ('ice algae')

Autotrophs: organisms that produce energy-rich organic compounds from inorganic molecules using an external energy source, either sunlight (phototrophy) or additional inorganic molecules (chemotrophy)

Bacteria and Archaea: the largest taxonomic groups of single-celled microbes lacking a nucleus.

Biological Carbon Pump: the mechanism by which carbon dioxide (CO_2) is sequestered to the deep sea. Phototrophs fix CO_2 into biomass and contribute to the biological carbon pump when they sink out of the surface ocean or are consumed by zooplankton that produce fecal pellets that sink out of the surface ocean. The effectiveness of the biological carbon pump is uncertain and relies on a dominance of microalgae.

Copiotrophs: heterotrophs that prefer environments rich in organic matter

Eukaryotes: organisms with a nucleus and other organelles (mitochondria, chloroplasts etc.), including plants, animals, fungi and protists

Flagellates: microbial eukaryotes that have whip-like tails called flagella. Most are either photosynthetic or predators of bacteria

Heterotrophs: organisms that use organic compounds as their energy source, including predators.

Macrofauna: animals visible to the naked eye, generally larger than 500 µm

Marine Alveolates (MALVs): diverse groups of mostly uncultured protists. MALVs mostly occur as parasites or parasitoids of other marine protists and zooplankton

Meiofauna: microscopic animals, between 62 µm and 500 µm in size

Meroplankton: animals that are planktonic for only part of their life cycle (usually larvae)

Microbes: microscopic organisms

Micro- (plankton, phytoplankton, flagellate, algae): microbes between 20 µm and 200 µm in size.

Mixotrophs: microbes that are both autotrophic and heterotrophic, including some Bacteria and Archaea, and eukaryotic microbes that can both photosynthesize and consume organic matter or other microbes

Nano- (plankton, phytoplankton, flagellate): microbes between 2 µm and 20 µm in size

Oligotrophs: microbes that prefer environments with low nutrient concentrations

Phytoplankton: phototrophic microbes that live in the water column

Photosynthesis: the process of producing energy-rich organic compounds from inorganic molecules using sunlight as an energy source

Phototrophs: organisms that photosynthesize

Pico- (plankton, phytoplankton, flagellate): organisms between 0.2 µm and 2 µm in size

Plankton: free-floating organisms that cannot swim against currents

Protists: single-celled microbial eukaryotes

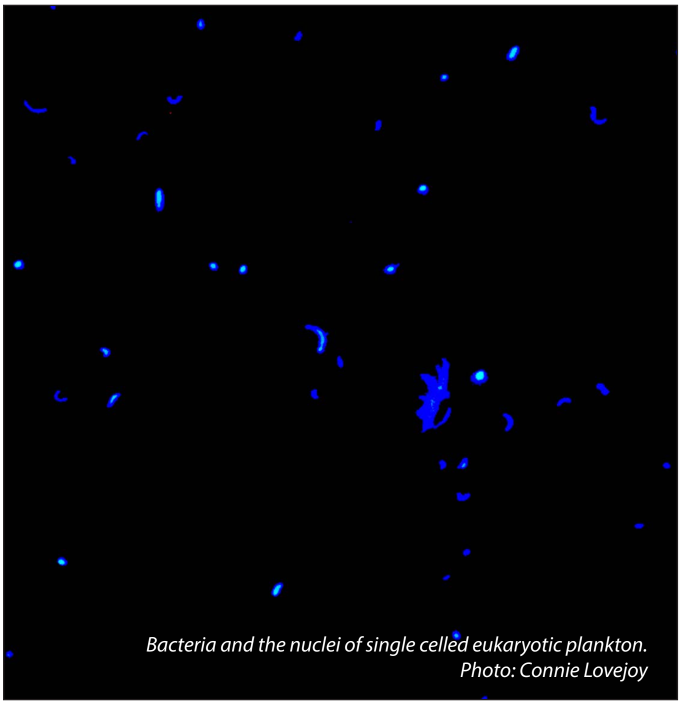
Sympagic: ice-associated biota

Ice sampling in the Canadian Beaufort Sea.
Photo: Michel Poulin, Canadian Museum of Nature

Bottom of ice core with algae.
Photo: Michel Poulin, Canadian Museum of Nature

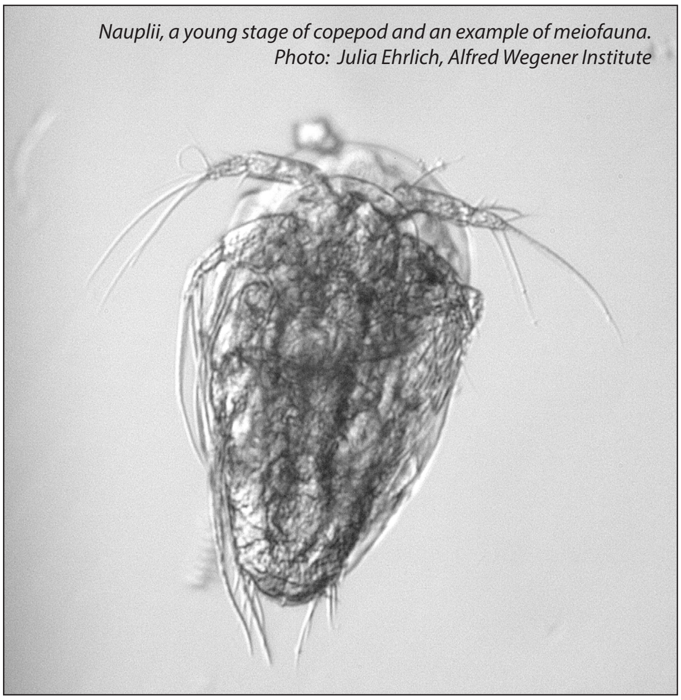
Table 3.1.1. Current estimates of species richness and peak abundances of the four FECs reviewed in this chapter. OTU – operational taxonomic unit (approximately at the "genus" level in this analysis). Relative to the Arctic Marine Biodiversity Monitoring Plan *(Gill et al. 2011), Bacteria and Archaea were included for consistency with the plankton FECs, while ice-associated fishes are covered in Chapter 3.4.*

Taxon group (FEC)	Estimated number of species/OTUs	Bloom (peak) abundance	Key references
Bacteria and Archaea	> 120 at 95% similarity	> 210 cells m^{-2}	This chapter
Microalgae and other protists	1,276	< 109 cells m^{-2}	Philippe 2013; this chapter
Sympagic multicellular meiofauna	> 60	> 400,000 ind. m^{-2}	Bluhm et al. 2017; this chapter
Under-ice macrofauna	> 40 (amphipods: 6-17)	< 5,590 ind. m^{-3} (I.A. Melnikov unpubl. data)	Arndt and Swadling 2006; this chapter



Bacteria and the nuclei of single celled eukaryotic plankton.
Photo: Connie Lovejoy

Algal lumps.
Photo: Peter Leopold, Norwegian Polar Institute



Nauplii, a young stage of copepod and an example of meiofauna.
Photo: Julia Ehrlich, Alfred Wegener Institute

The amphipod Gammarus wilkitzkii*, an under ice macrofauna.*
Photo: Shawn Harper, University of Alaska Fairbanks

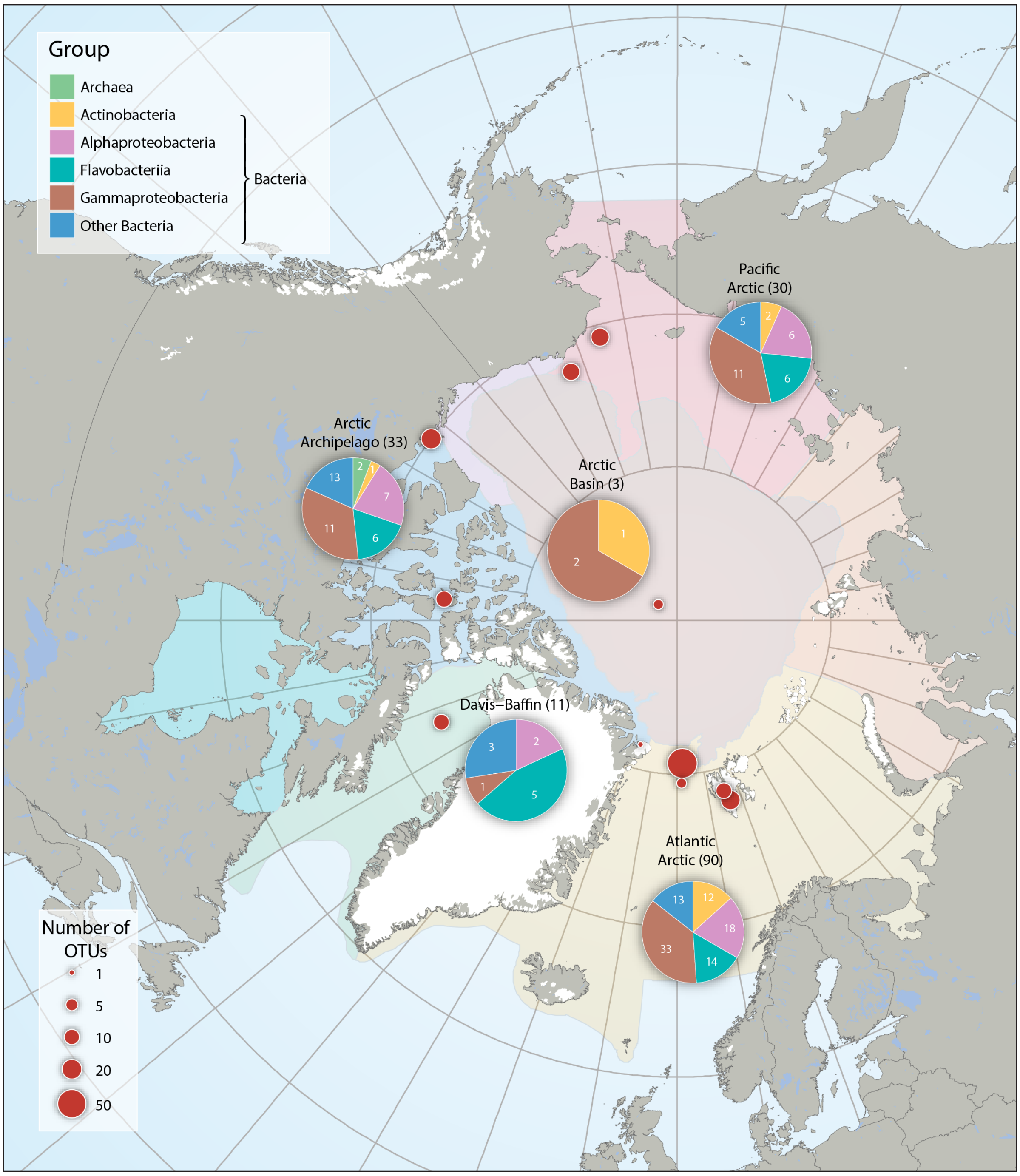


Figure 3.1.2 Bacteria and Archaea across five Arctic Marine Areas (AMAs) based on number of operational taxonomic units (OTUs), or molecular species. Composition of microbial groups, with respective numbers of OTUs (pie charts) and number of OTUs at sampling locations (red dots). Data aggregated by the CBMP Sea Ice Biota Expert Network. Data source: National Center for Biotechnology Information's (NCBI 2017) Nucleotide and PubMed databases.

3.1.2 Current monitoring

Sea ice biota is not monitored regularly at any location and our description is, therefore, based on synthesis of available data from a series of research projects. For each FEC, a brief background and description of data sources and analysis approach is provided. Note that the available historical data sources go back much further in time for morphologically identifiable taxa than for microbial diversity due to morphological studies preceding the development of DNA (or protein) sequencing methodology.

Bacteria and Archaea

Single-celled microorganisms belonging to the domains Bacteria and Archaea are highly diverse and make up a large fraction of the biomass in the global ocean, including the sea ice habitat. These microbes are principal actors in carbon and nitrogen cycling, making nutrients available to other organisms. DNA (or protein) sequence similarity is the only reliable way to measure the taxonomic diversity of these communities. The most widely used marker for this purpose is found in the ribosome (the cellular structure used for protein synthesis), specifically the small subunit ribosomal RNA gene (16S rRNA gene for Bacteria and Archaea, 18S rRNA gene for Eukarya). Modern phylogenetics highlighting evolutionary relationships of microbes have mostly been developed during the last two decades (e.g., Junge et al. 2002, Collins et al. 2010, Deming 2010, Collins 2015). The relatively few studies available indicate that sea ice harbours an active microbial food web, which comprises high abundances of cold-adapted, halophile (thriving at high

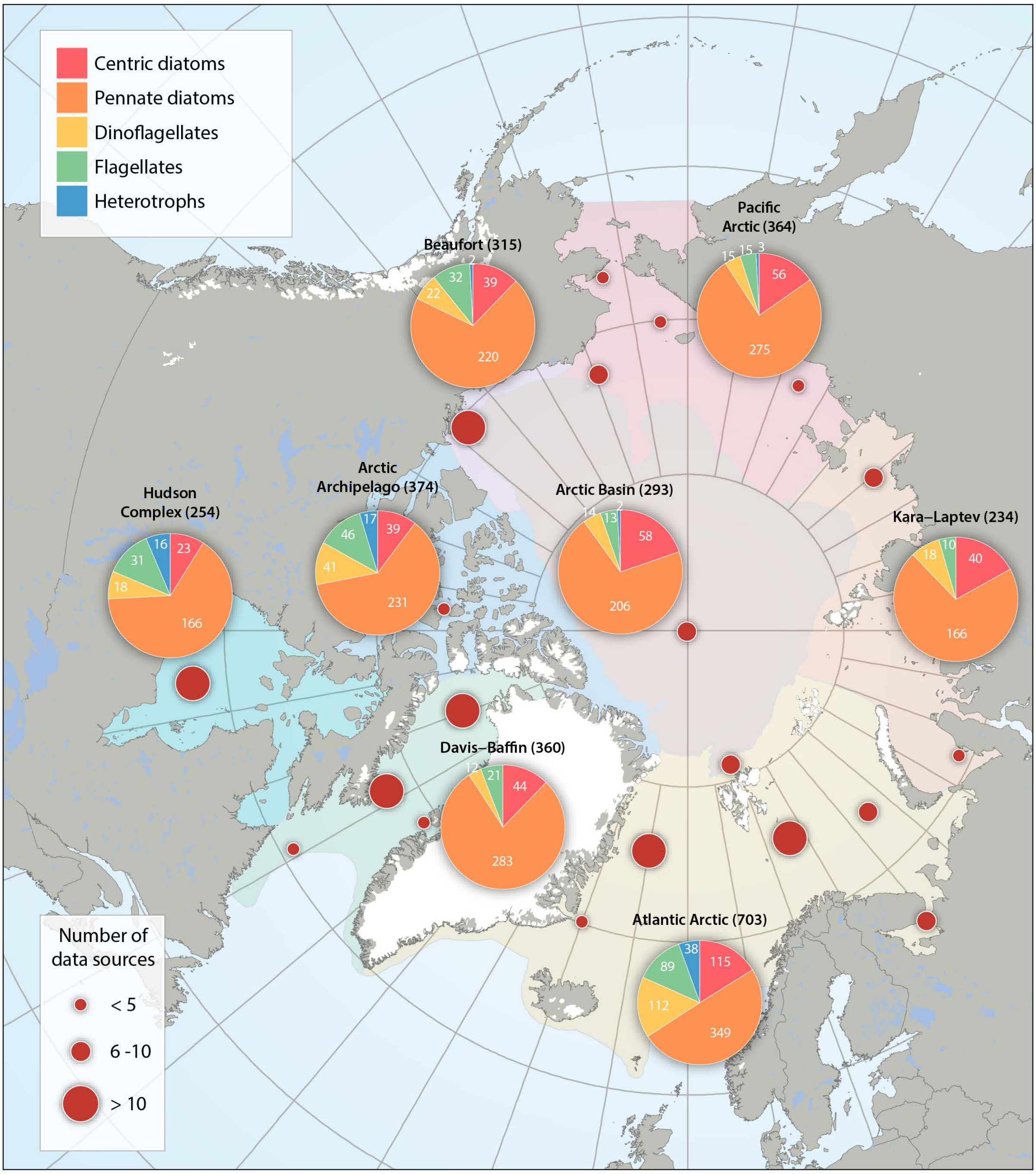


Figure 3.1.3 Numbers and taxonomic composition of five single-celled eukaryote groups for the regional divisions of the Arctic Marine Areas (AMAs, pie charts), as well as the number of data sources reviewed across the Arctic (red circles). Total number of taxa is given in parenthesis after each region. Flagellates include: chlorophytes, chrysophytes, cryptophytes, dictyochophytes, euglenids, prasinophytes, prymnesiophytes, raphidophytes, synurales, and xanthophytes, and- for practical purposes though not flagellates - cyanophytes. Heterotrophs include: choanoflagellates, kinetoplastea, incertae sedis. Updated from Poulin et al. (2011).

salt concentrations) bacteria that typically are most abundant in high concentrations of organic matter. Most of these sea ice-associated bacteria are heterotrophs utilizing organic substances released from the primary producers (autotrophic taxa) at the base of the food web. Patterns in bacterial community composition in Arctic sea ice differ from those of the underlying water column for both first-year (Collins et al. 2010) and multi-year ice (Bowman et al. 2012). Species richness in Bacteria and Archaea is often indicated by the number of operational taxonomic units (OTUs, or molecular species). Typical values of the number of OTUs in sea ice are about half of that in the underlying water column (Bowman et al. 2012). Bacterial abundances in sea ice, however, vary with season and at times exceed those of the water column by three orders of magnitude, when scaled to the brine channels they inhabit within the ice. Ice bacterial biomass contributes substantially (a third or more) to particulate organic matter produced in sea ice (Gradinger et al. 1999). The ratio between bacterial and primary production in sea ice varies between 10 and 38% (Nguyen et al. 2011).

Synthesis of available data was performed by using searches conducted in the National Center for Biotechnology Information's (NCBI) Nucleotide and PubMed databases. Aligned DNA sequences were clustered into OTUs by maximum likelihood phylogenetic placement, a method that uses the most probable assignment to a reference phylogenetic tree showing the relationship among genetically identified units. The genetic resolution of OTUs in this analysis is approximately at the genus level.

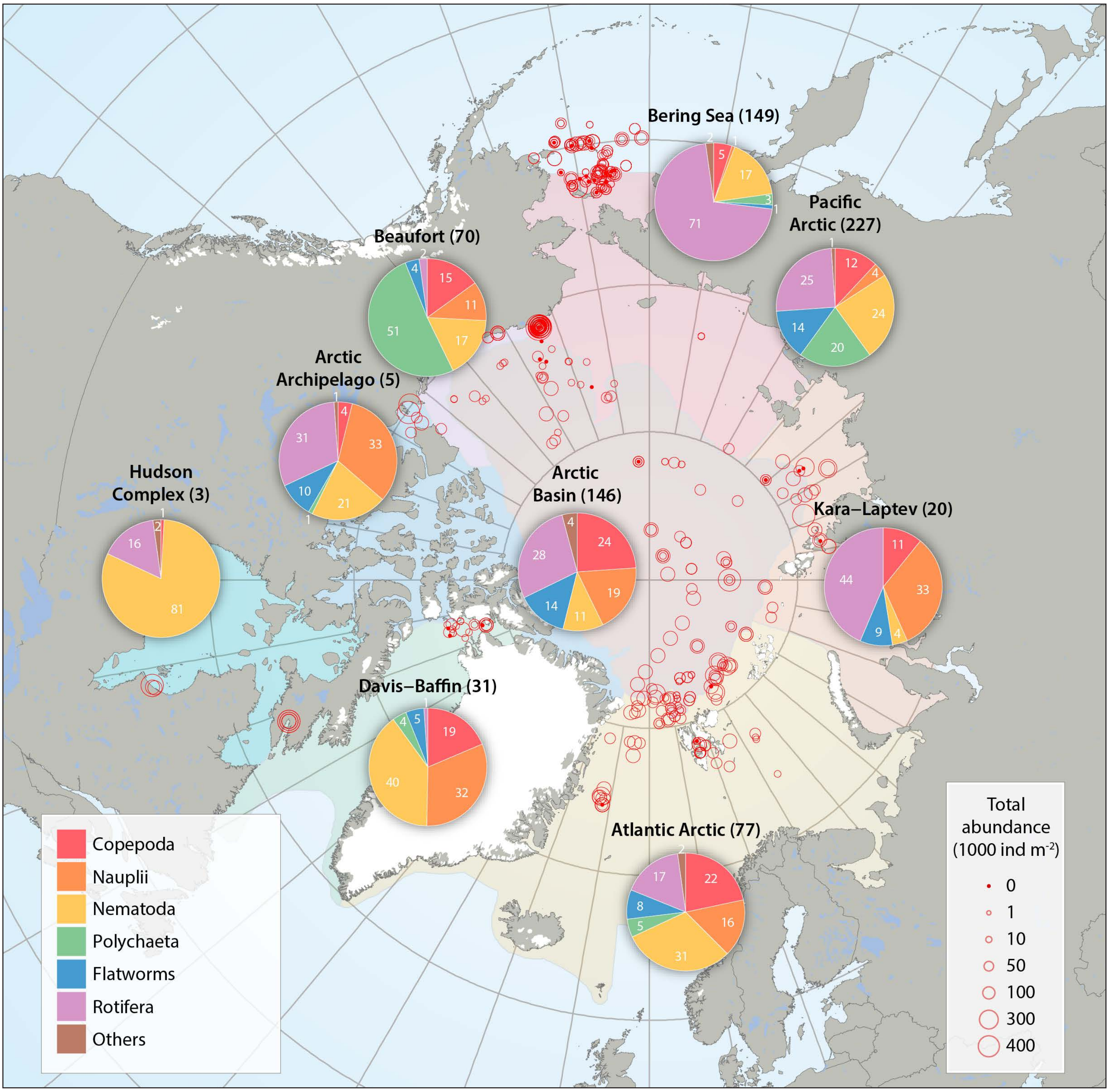


Figure 3.1.4 Sea ice meiofauna composition (pie charts) and total abundance (red circles) across the Arctic, compiled by the CBMP Sea Ice Biota Expert Network from 27 studies between 1979 and 2015. Scaled circles show total abundance per individual ice core while pie charts show average relative contribution by taxon per Arctic Marine Area (AMA). Number of ice cores for each AMA is given in parenthesis after region name. Note that studies were conducted at different times of the year, with the majority between March and August (see 3.1 Appendix). The category 'other' includes young stages of bristle worms (Polychaeta), mussel shrimps (Ostracoda), forams (Foraminifera), hydroid polyps (Cnidaria), comb jellies (Ctenophora), sea butterflies (Pteropoda), marine mites (Acari) and unidentified organisms.

Ice algae and other single-celled eukaryotes

Different types of biotic communities, namely surface, interior, bottom and sub-ice, have been described for Arctic sea ice based on their vertical occurrence and dominance in the ice matrix (Syvertsen 1991, Horner et al. 1992). However, the bulk of the standing stock and taxonomic diversity is mainly found in the bottom 10 cm of the ice matrix, generally in the lowermost 3-4 cm of the ice during springtime (Różańska et al. 2009, Duarte et al. 2015, Leu et al. 2015). Often, ice algae and other protists are entrapped in newly formed sea ice during autumn and remain dormant over the winter (Gradinger and Ikävalko 1998, Różańska et al. 2008). In the spring, increasing light levels trigger the first sign of growth, which is often followed by rapid ice-algal growth in the dense network of brine pockets and channels in the bottom section of the ice matrix, sustained by nutrient-rich underlying water (von Quillfeldt et al. 2003, Różańska et al. 2009). These ice algal communities provide early food for sympagic and pelagic herbivorous grazers such as copepod and amphipod crustaceans and contribute to carbon cycling (Michel et al. 2002, 2006, Tamelander et al. 2009, Søreide et al. 2010). The colonial centric diatom, *Melosira arctica*, can form 2 m long strands attached to the underside of the sea ice matrix in densely packed filamentous rows of cells hanging in the water column like curtains (Melnikov 1997, Boetius et al. 2013). This sub-ice community may serve as host substrate for epiphytic algae, such as the diatoms *Attheya* *septentrionalis*, *Synedropsis hyperborea*, *Pseudogomphonema arcticum* (von Quillfeldt 1997, von Quillfeldt et al. 2003, Poulin et al. 2014). Ice algae can also form aggregates, which had already been observed during the Norwegian Fram Expedition in 1894 (Gran 1900, Nansen 1906) and the Russian North Pole drift ice station NP-23 in 1977 (Melnikov 1997). Such aggregates of ice-associated pennate diatoms have been found floating below the ice (Assmy et al. 2013) or in melt ponds (Lee et al. 2015). Aggregation of organic material from the ice may also promote the vertical export of material towards the benthos, thus strengthening ice-pelagic-benthic coupling (Tamelander et al. 2006, Renaud et al. 2007, Juul-Pedersen et al. 2008, Morata et al. 2011).

For a pan-Arctic assessment of biodiversity (here as species richness based on presence/absence), the first comprehensive assessments of this FEC from a few years ago (Poulin et al. 2011, Daniëls et al. 2013) have been updated with 134 documents and databases screened and mapped following the eight regional divisions of the Arctic Marine Areas (AMAs) (Gill et al. 2011; Fig. 3.1.4), including standardization of taxonomic names and nomenclature based on original literature. For the analysis of possible interannual trends in the ice algal community, we used a data set from the Arctic Basin, the area most consistently and frequently sampled (Melnikov et al. 2002, I.A. Melnikov unpubl. data). Multivariate community structure was analysed based on a presence-absence matrix of ice protists (autotrophs) from sections of ice cores taken from 1980 to 2013 and mostly identified to species level. The analysis is biased by the varying number of analysed cores taken annually ranging from 1 to 24, with ice thickness varying between 0.6 and 4.2 m, and including both first-year as well as multi-year sea ice. Sampling locations were confined within 74.9 to 90.0°N and 179.9°W to 176.6°E and exact locations varied among years, depending on the drift patterns of the ice stations.

Ice meiofauna

Arctic ice meiofauna is comprised of multi-cellular taxa including flatworms (of the phyla Acoelomorpha and Platyhelminthes), round worms (Nematoda), copepods (Crustacea), wheel animals (Rotifera), and less frequent taxa such as polyps (hydrozoan Cnidaria) and ribbon worms (Nemertea) (e.g., Marquardt et al. 2011, Bluhm et al. 2017). Single-celled ciliates are included in some studies, but are in others referred to as microfauna (< 62 µm; Carey 1985), and are not included in this synthesis. In addition to ice endemic species, both pelagic and benthic meiofauna species occur in sea ice and are included here. Ice meiofauna settle in sea ice through active migration, are scavenged during ice formation, disperse from multi-year ice, or are recruited from resting stages (Carey and Montagna 1982). Many ice meiofauna taxa graze on the abundant and highly concentrated ice algae early in the season (Grainger and Hsiao 1990), allowing for higher growth rates than under concurrent phytoplankton bloom concentrations (McConnell et al. 2012). Yet, meiofauna grazing does not appear to limit ice algal growth despite their seasonally high abundance: estimated ingestion rates by multicellular meiofauna are generally < 10% of ice algal biomass (Gradinger 1999, Michel et al. 2002). The small size of the brine channel system, mostly <1 mm in a given channel, may restrict some meiofauna from exploiting niches with high ice algal growth (Krembs et al. 2000). This limitation rapidly changes during the onset of melting when brine channels become connected (Gradinger et al. 2010). Direct ingestion of ice-produced dissolved organic matter is an alternative feeding mode suggested for ice meiofaunal nematodes (Tchesunov and Riemann 1995). Meiofaunal predators, however, appear to be rare (Bluhm et al. 2007, Siebert et al. 2009).

Here, the CBMP Sea Ice Biota Expert Network synthesized 27 studies across the Arctic conducted between 1979 and 2015. This extensive effort includes several unpublished sources (see Appendix 3.1.1 and 3.1.2). These studies sampled landfast sea ice and offshore pack ice, both first-year and multi-year ice, using ice cores. Meiofauna abundances from ice cores were converted to individuals m^{-2} of sea ice. Due to the generally low taxonomic resolution in the reviewed studies, ice meiofauna were grouped into: copepods (Copepoda), nauplii (i.e., young stages of copepods as well as other taxa with naupliar stages), round worms (Nematoda), bristle worms (Polychaeta) (mostly juveniles, but also the larval stage, trochophores), flatworms (Acoelomorpha and Platyhelminthes; these phyla have mostly been reported as one category), Rotifera and others. The category 'others' includes typically rare groups such as meroplanktonic larvae other than Polychaeta, mussel shrimps (Ostracoda), forams (Foraminifera), hydroid polyps (Cnidaria), comb jellies (Ctenophora), sea butterflies (Pteropoda), marine mites (Acari) and unidentified organisms. Percentage of total abundance for each group was calculated for each ice core, and these percentages were used for regional averages. Maximum available ice-core length was used in data analysis, but 50% of these cores included only the bottom 10 cm of the ice profile, 12% the bottom 5 cm, 10% the bottom 2 cm and 11% the entire ice profile. Data from 728 cores were used. In addition to showing composition and peak abundance ranges, the phenology of ice meiofauna is illustrated over the ice-covered season in data sets from landfast ice near Barrow, Alaska, and in drifting pack ice north of Svalbard.

Under-ice macrofauna

The most prominent members of the under-ice community typically include the gammarid amphipods *Apherusa glacialis*, *Gammarus wilkitzkii*, *Onisimus glacialis* and *O. nanseni*, as well as the polar cod and ice cod (Lønne and Gulliksen 1989, Gradinger and Bluhm 2004, Mecklenburg et al. 2011, Hop and Gjøsæter 2013). All inhabit the under-ice realm for at least part of their lives (Gulliksen and Lønne 1991, Melnikov 1997, Poltermann et al. 2001). The amphipods have different feeding preferences and longevities, with *G. wilkitzkii* being the most predatory and long-lived, at six to seven years (Poltermann 2000, Beuchel and Lønne 2002). The ice-associated fishes primarily eat crustaceans including under-ice amphipods, copepods, hyperiid amphipods and mysids with proportions varying regionally (Lønne and Gulliksen 1989, Christiansen et al. 2012, Dalpadado et al. 2016). Dozens of other taxa, such as copepods, ctenophores and pteropods, also inhabit the under-ice realm (Arndt and Swadling 2006, Bluhm et al. 2017), but are not included here. Gelatinous zooplankton (ctenophores and jellyfish) have been observed at high densities just below the ice by remotely operated vehicles and scuba divers (Raskoff et al. 2005, 2010, Purcell et al. 2010, H. Hop unpubl. data), where they congregate in turbulence areas created by ridges.

This summary includes 47 data sources of under-ice amphipods published between 1977 and 2012. When available, the CBMP Sea Ice Biota Expert Network collected information on their abundance (individuals m^{-2}, or individuals m-3 that were converted to individuals m^{-2}) and biomass (g m^{-2}, wet weight). If abundance or biomass data were not available, presence/relative abundance information was included. Frequency of occurrence was calculated for regions across the Arctic using integrated data for all available years. Due to large variability, medians and median absolute deviations (MAD) were used to present abundance and biomass data.

The only available time-series of sympagic fauna is based on composite data of ice-amphipod abundance and biomass estimates from 1981 to 2012 for the Svalbard and Fram Strait region (Hop et al. 2013). Samples were obtained by scuba divers that collected amphipods quantitatively with electrical suction pumps under the sea ice (Lønne 1988, Lønne and Gulliksen 1991a, b, Hop and Pavlova 2008).

3.1.3 Status and trends of FECs

Bacteria and Archaea

Forty-five data sets in the NCBI Nucleotide database were analysed for the present synthesis. They included a total of 1,146 sequences of the target gene (small subunit ribosomal RNA) from Arctic sea ice. On average, these sequences consisted of 1,256 base pairs (i.e., the building blocks) and the mean number of sequences per study was 25 (median= 3). These sequences represented 120 bacterial and two archaeal OTUs, of which 95 (81% of sequences) were at the genus level and the remainders were not represented in the database or at higher taxonomic levels. The analysed data sets revealed different groups of species, with an overlap of only one third of the 43 OTUs found to occur in two or more studies.

The total diversity of Bacteria and Archaea found in sea ice spans the phylogenetic tree, but the dominant taxa are concentrated within the Gram-negative bacterial groups Gammaproteobacteria, Bacteroidetes, and to a lesser extent the Alphaproteobacteria (Fig. 3.1.2). Biodiversity was highly dominated by a few taxa: the five most common taxa represented 50% of all sequences in the dataset (*Pseudoalteromonas*, *Colwellia*, *Shewanella*, *Marinomonas* and *Pelagibacter*). There are no known bacterial or archaeal genera unique to sea ice, and at more refined taxonomic levels there is not enough information to determine to what extent microbes found in sea ice are endemic to the ice (Collins 2015).

Ice algae and other single-celled eukaryotes

The species richness of microalgae and other protists in sea ice is high. As with ice microbes, the inventory of these single-celled eukaryotes is incomplete, which makes assessment of temporal changes challenging. A few years ago, a first inventory found 1,027 single-celled eukaryotes inhabiting Arctic sea ice (Poulin et al. 2011, Daniëls et al. 2013). The present synthesis by the CBMP Sea Ice Biota Expert Network documented that increased effort still increases the inventory, which now includes more than 200 additional taxa for a total of 1,276 sympagic algae and other protists (Figure 3.1.3) Cyanobacteria (phototrophic Bacteria) and five supergroups of eukaryotes (cf. Adl et al. 2012) are present in Arctic sea ice (Poulin et al. 2011). Most of this sea ice biota inventory, however, consists of large diatom and dinoflagellate cells (>20 µm) that are relatively easily identified through light microscopy (von Quillfeldt et al. 2003, Różańska et al. 2009, Poulin et al. 2011). Large cells contributed 82% of the known pan-Arctic species numbers, with 82% for the Hudson Bay Complex and Atlantic Arctic, 83% for the Arctic Archipelago, 89% for the Beaufort Sea, 94% for Davis Strait-Baffin Bay, 95% for both the Pacific Arctic and Arctic Basin, and 96% for the Kara-Laptev. The highest inventory, and reporting effort, of sea ice microalgae and other protists has been recorded for the Atlantic Arctic, with an almost two-fold higher number of taxa (700) compared to the other seven regional divisions of the AMAs (Figure 3.1.3).

The Arctic Archipelago and Pacific Arctic had intermediate species richness (>350), whereas the lowest (< 300) was reported for the Kara-Laptev Seas, the Hudson Bay Complex and the Arctic Basin. High research effort in the Atlantic Arctic also resulted in the identification of a significant contribution of 18% small-sized cells (<20 µm), an otherwise morphologically poorly documented size group. During the algal bloom, the bottom ice communities are predominantly represented by colonial diatoms, e.g., *Nitzschia frigida* and *Fragilariopsis cylindrus*, while some solitary cells are also frequently encountered, e.g., *Cylindrotheca closterium* and *Navicula directa*. Pennate diatoms are the most abundant single-celled eukaryotes across the Arctic, contributing a low 50% in Atlantic Arctic to a high 79% in Davis Strait-Baffin Bay of the eukaryote community in sea ice (Figure 3.1.3).

Standard microcopy counts do not take into account the diversity of smaller mixotrophic and heterotrophic microbial eukaryotes in ice. Molecular techniques indicate these groups in ice may be as diverse as in the water column (Comeau et al., 2013).

Ice meiofauna

On a coarse taxonomic level, most meiofauna taxa occur rather consistently across the Arctic, although their proportions vary with region and season of sampling (Figure 3.1.4). Total abundance of meiofauna can be higher close to land compared to offshore locations. This is partly explained by the contribution of meroplankton, the frequently abundant larval stages of benthic organisms, and the fact that most studies there were conducted during spring. In offshore drift ice, the proportion of species of pelagic origin within the ice meiofauna is higher than in shallow areas where adults of taxa of benthic origin are also found (e.g., Friedrich and De Smet 2000). Regional comparisons are limited by differences in seasonal and taxonomic coverage, but available data indicate that rotifers, for example, dominate in some areas such as the Bering Sea in the Pacific Arctic and the Kara-Laptev. Rotifers can be abundant in these areas, although they are small and therefore contribute much less to the total in-ice meiofauna biomass than other taxa (Friedrich 1997). By comparison, nematodes dominate in Davis Strait-Baffin Bay, Hudson Bay Complex and the Greenland Sea—part of the Atlantic Arctic (Fig. 3.1.4). Copepods are reported in all regions (although their composition may vary which we do not show here) and their nauplii cause large seasonal fluctuations in meiofauna abundance (Figure 3.1.5). Separating seasonal fluctuations from geographical differences is difficult due to the low number of studies, and because most studies take place during the spring when copepod nauplii are the most abundant. Nauplii, however, appear to be particularly common in the Atlantic-advective inflow area. In coastal fast ice of the Beaufort Sea, in turn, the positive influence of meroplanktonic stages of primarily Polychaeta and Mollusca on diversity and abundance during spring months has been documented (Nozais et al. 2001, Gradinger et al. 2009).

The few studies that provide identification of ice meiofauna taxa beyond the order level suggest nearly pan-Arctic distribution ranges for those taxa (examples shown in Bluhm et al. 2017). A few ice meiofauna species appear to be endemic to the ice, such as the hydroid polyp *Sympagohydra tuuli* and the nematode *Theristus melnikovi* (Riemann and Sime-Ngando 1997, Bluhm et al. 2007), although these taxa may have been overlooked in benthic habitats so far.

Macrofauna: under-ice amphipods

A handful of gammarid amphipod species are found in the under-ice habitat across the Arctic (Figure 3.1.6). *Apherusa glacialis* is the most frequent ice amphipod, which is likely related to its herbivorous feeding style and short, two-year life cycle in drift ice (Beuchel and Lønne 2002, Arndt et al. 2005). Though most abundant, this ice amphipod contributes little to the total under-ice amphipod biomass due to its small size (Figure 3.1.7). *Gammarus wilkitzkii* is also a frequently occurring ice-amphipod with circumpolar distribution. Due to its large size (5 cm as adults), *G. wilkitzkii* dominates the ice-amphipod biomass, but tends to occur in lower frequencies than *A. glacialis* (e.g., Hop and Pavlova 2008; Figure 3.1.7). This predatory and omnivorous crustacean preys on smaller ice amphipods, such as *A. glacialis* and *Onisimus glacialis*, as well as zooplankton and detritus (Poltermann 2001). *Gammarus wilkitzkii* is often associated with structurally complex multi-year sea ice, where it can frequently be found hiding in large brine channels and crevices (Hop et al. 2000). This synthesis, however, indicates that *G. wilkitzkii* also frequently inhabits

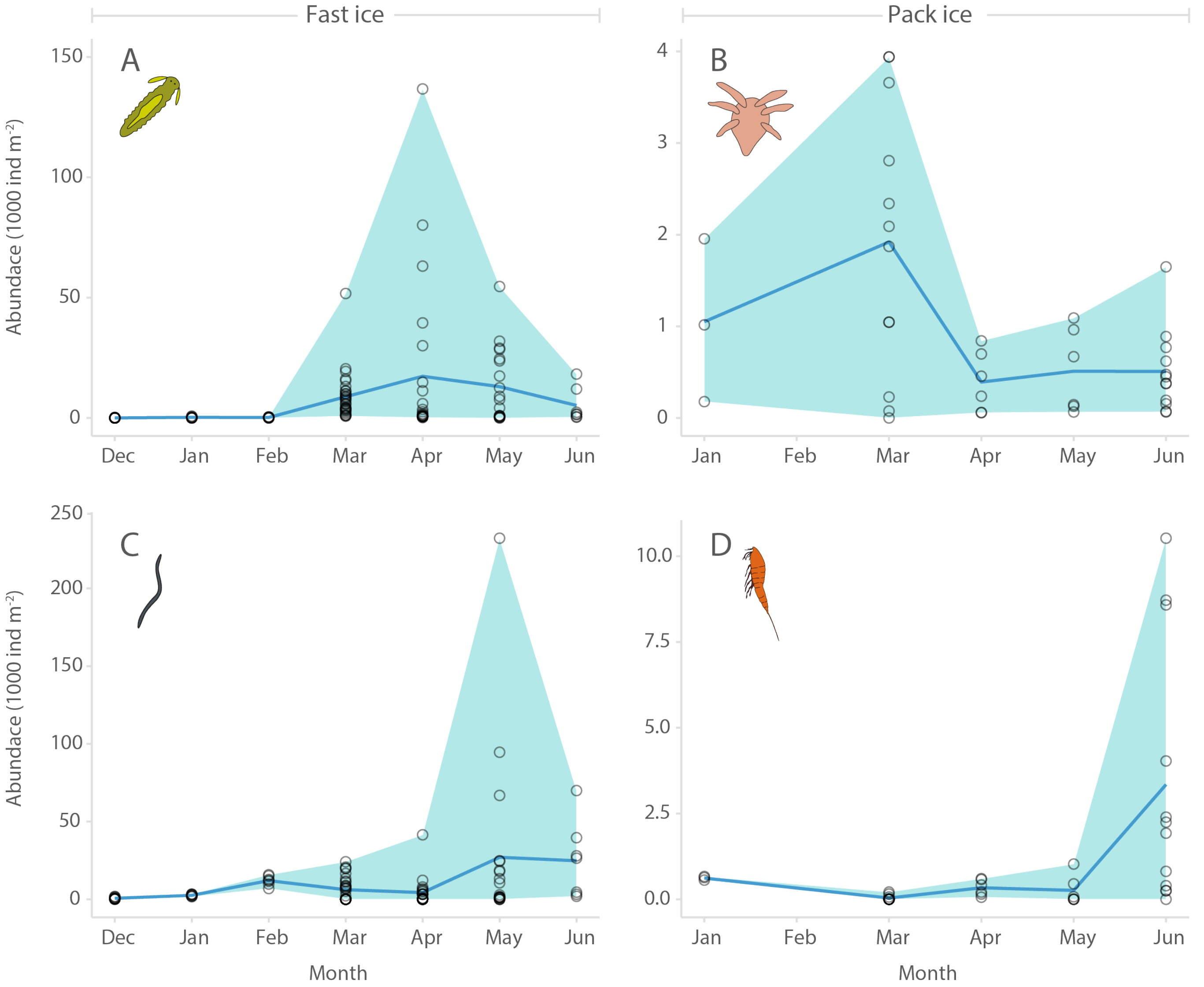


Figure 3.1.5 Seasonal abundance (1000 individuals m-²) of sea ice meiofauna at landfast sea ice (Barrow, 2005-2006, A and C) and pack ice (North of Svalbard, 2015, B and D). A and B show larval stages (polychaete juveniles and nauplii, respectively), while C and D show nematodes and harpacticoid copepods, respectively. Circles represent individual cores (n = 107 for A and C, and 39 for B and D), shading the extent of minimum as well as maximum values, and blue line indicates mean values.

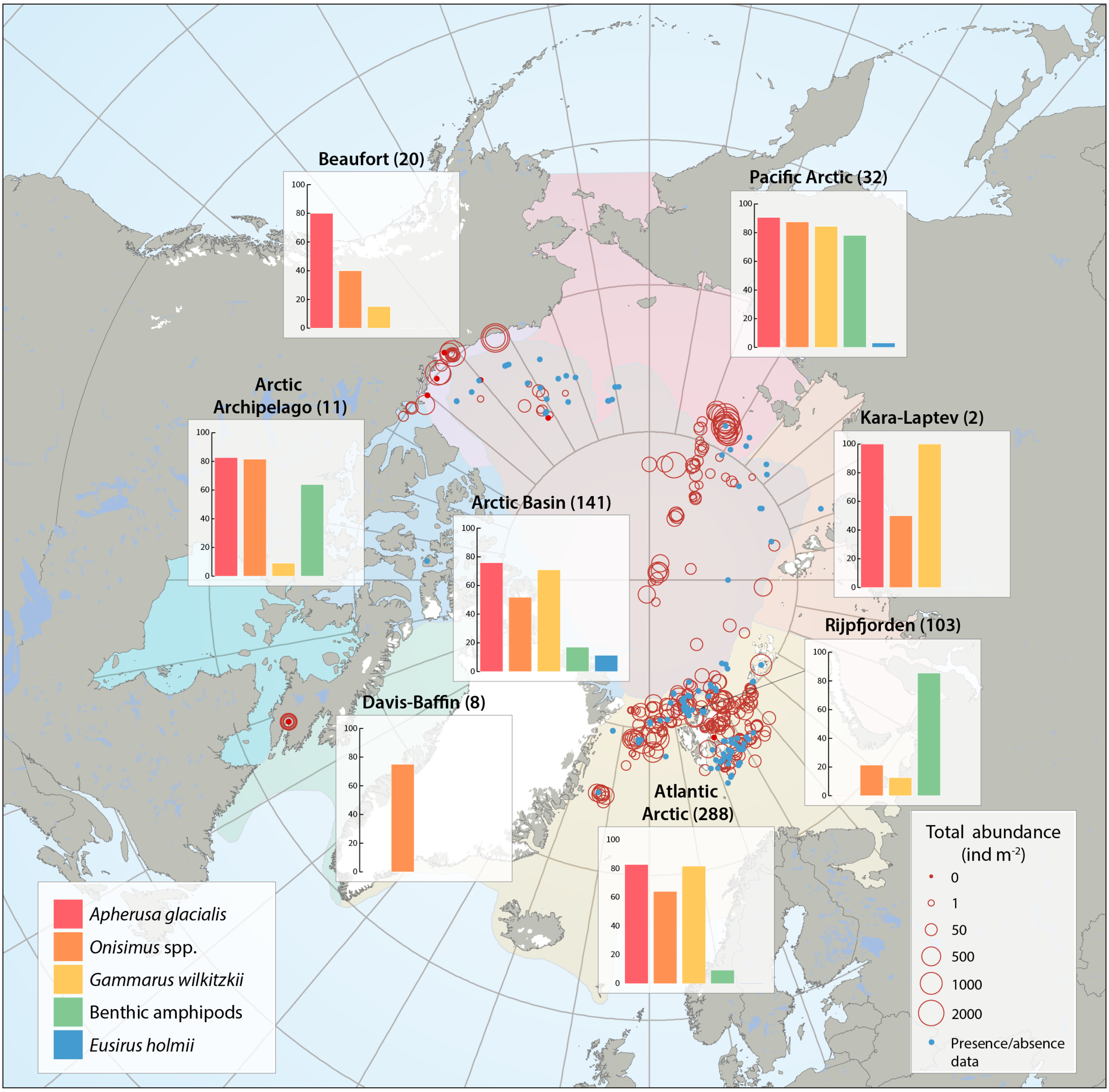


Figure 3.1.6 Sea ice amphipod (macrofauna) distribution and abundance across the Arctic aggregated from 47 sources between 1977 and 2012 by the CBMP Sea Ice Biota Expert Network. Bar graphs illustrate the frequency of occurrence (%) of amphipods in samples that contained at least one ice-associated amphipod. Red circles illustrate the total abundances of all ice-associated amphipods in quantitative samples (individuals m^{-2}) at locations of sampling for each Arctic Marine Area (AMA). Number of sampling efforts for each region is given in parenthesis after region name. Blue dots represent samples where only presence/absence data were available and where amphipods were present.

annual landfast and drift ice, although at lower frequencies than it occurs in the Arctic Basin and the East Siberian Shelf break of the Pacific Arctic (Figure 3.1.6). *Onisimus nanseni* and *O. glacialis* are difficult to distinguish from samples preserved in alcohol and therefore were not separated in most reviewed studies. Genetically, these species are also difficult to separate because of low genetic divergence (Ki et al. 2011). They occur frequently below sea ice but are generally much less abundant than *A. glacialis* and *G. wilkitzkii* (Hop and Pavlova 2008; Fig. 3.1.7). It is noteworthy that no under-ice amphipods were encountered on the Bering and Chukchi Seas and adjacent shelves of the Pacific Arctic, where some of the authors have done extensive sea ice work (R. Gradinger, K. Iken, B.A. Bluhm unpubl.). However, high amphipod abundances have been recorded on the shelf of the East Siberian Sea as well as in the Beaufort Sea, with values an order of magnitude higher than those recorded in the Atlantic Arctic (Figs. 3.1.6, 3.1.7). High abundance values likely reflect large contributions of newly hatched juveniles and benthic amphipods.

Benthic amphipods are also occasionally encountered under sea ice, particularly over shallow water (e.g., Pike and Welch 1990, Gradinger and Bluhm 2010). Even though their distributions are related to distance to land and water depth, some benthic amphipods drift with sea ice across the Arctic Basin and are present in sea ice far from its origin (Figure 3.1.6). In Rijpfjorden, Northern Svalbard, the benthic amphipods Anonyx spp. utilize sea ice as a reproductive habitat during spring (Werner et al. 2004, Nygård et al. 2012).

Most frequently occurring benthic amphipods were *Anonyx* spp. (8% of all samples), *Metopa* spp. (8%), *Gammaracanthus loricatus* (4%), *Weyprechtia pinguis* (2%) and *Gammarus setosus* (2%).

Seasonality in the meiofauna community

Biological communities in the sea ice system exhibit strong seasonality linked to the annual cycle in both sea ice formation and light. Few studies, however, actually cover full seasonal cycles; here two examples of meiofaunal communities are given. Seasonal increase in meiofaunal abundances occurs during spring (Figure 3.1.5), linked to the increase in day light that facilitates the onset of the ice algal bloom, which consequently progresses temporally with increasing latitude (Leu et al. 2015). Nearshore fast ice typically harbours the highest densities of meiofauna during spring peaks in ice algal production (up to 250,000 ind. m^{-2}; Nozais et al. 2001, Gradinger et al. 2009; Figure 3.1.5a, c), followed by density peaks observed in shelf pack ice (Gradinger 2009, Marquardt et al. 2011), with the lowest abundances in offshore drift ice and ice pressure ridges (<10,000 ind. m^{-2}; Friedrich 1997, Gradinger et al. 2005, 2010, Schünemann and Werner 2005; Figure 3.1.5b, d). Different taxonomic groups show abundance peaks at different times. For example, meroplanktonic polychaetes and copepod nauplii peak earlier during ice algal blooms (Figure 3.1.5a, b) than nematodes, which spend their entire life cycle in sea ice, and harpacticoid copepods peak even later (Figure 3.1.5c, d). Large variability in abundance indicates patchiness in the spatial distribution of meiofauna, which is related to ice properties, snow depth and sediment load in the ice, known as dirty sea ice (Nürnberg et al. 1994, Gradinger et al. 2009).

Interannual trends in ice algal community structure in the central Arctic Basin

Assessment of interannual changes of the ice-algal community in the central Arctic Basin is challenging, because of introduced biases due to variations in ice types, ice thickness, sampling date, region and number of ice cores collected. Keeping in mind this bias, species numbers recorded and community composition appear to have changed during three periods: early 1980s, late 1990s and the recent period of 2005-2013 (Fig. 3.1.8). This involved a major decrease from 50-70 species in 1980-2006 to <30 in recent years. However, the sampling effort was much greater in the earlier decades, which likely resulted in detection of more species. Community structure also

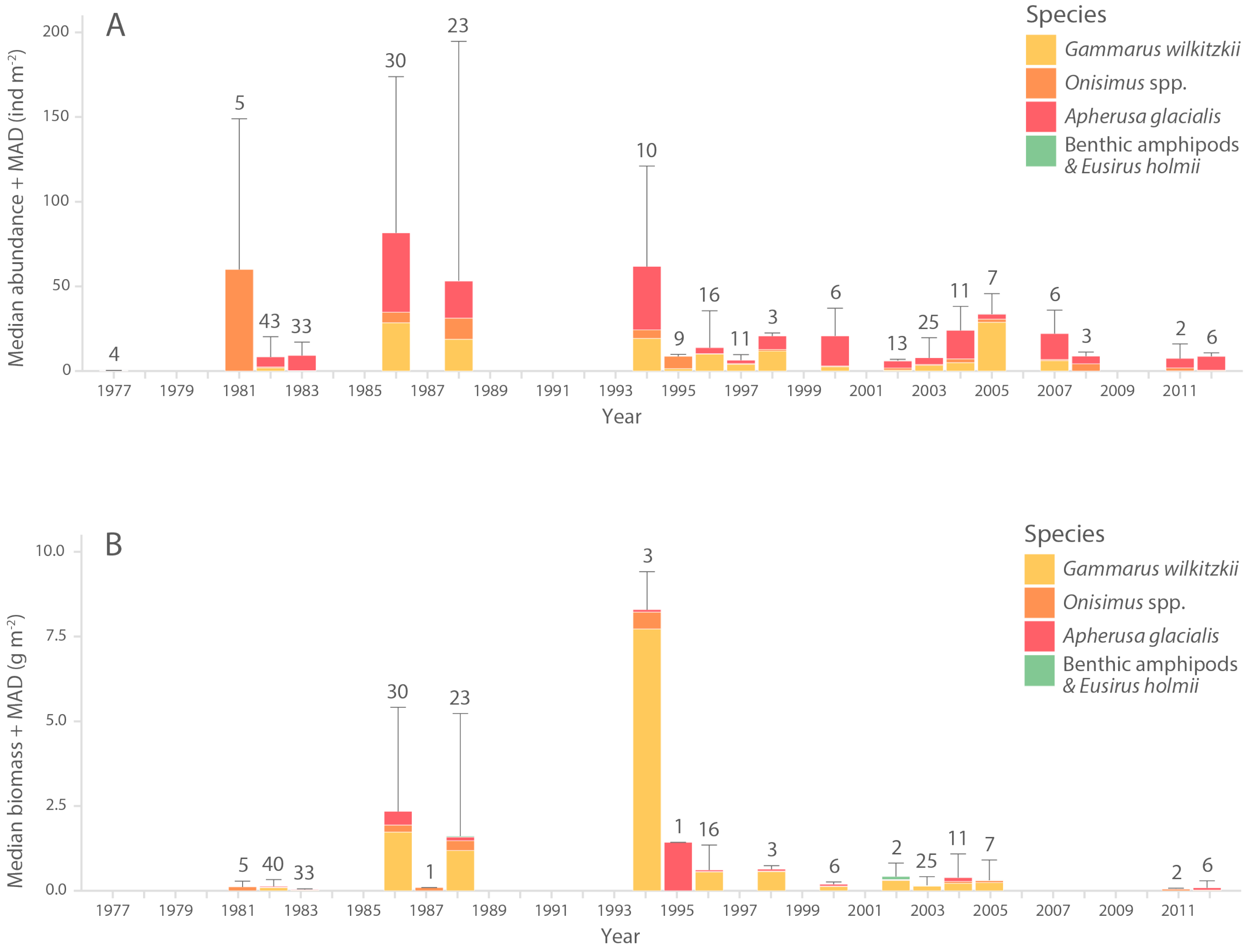


Figure 3.1.7 Multi-decadal time series of A) abundance (individuals m^{-2}) and B) biomass (g wet weight m^{-2}) of ice amphipods from 1977 to 2012 across the Arctic. Bars and error bars indicate median and median absolute deviation (MAD) values for each year, respectively. Numbers above bars represent number of sampling efforts (n). Modified from Hop et al. (2013).

appears to have shifted from the 1980s to the 2010s (Figure 3.1.8), although it, too, is somewhat influenced by sampling effort. Analysis of similarity[1] suggests that the sampling period had the strongest influence on the similarity of algal community structure followed by ice type, which was moderately influential, with less effect of region or month of sampling. The top characteristic sympagic species in the 1980s, the period where multi-year ice was more abundant than in later decades, included *Thalassiosira nordenskioeldii*, *Fragilariopsis oceanica*, *Chlamydomonas nivalis*, *Trochiscia cryophila* and *Nitzschia* spp. The cores from the 1990s were characterized by *Groenlandiella brevispina*, *Cylindrotheca closterium*, *Fragilariopsis cylindrus* and *Navicula vanhoeffenii*. After the year 2000 when perennial ice declined strongly, mostly *Nitzschia frigida*, *N. polaris*, *F. cylindrus*, *F. oceanica* and *Navicula transitans* characterized the community. For decades, the dominant multi-year ice in the central Arctic Ocean was a relatively stable ecological system with a rather consistent species composition of flora and fauna (Melnikov 1997). The ice thickness of the multi-year pack ice was maintained in equilibrium, with summer melt of the upper layers of ice from above and compensating winter ice growth from below. During the early period of observation (1975-1981), pennate diatoms dominated (56 species) in multi-year ice, while centric diatoms and dinoflagellates were species poor. Dinoflagellate species increased after the mid-1990s despite lower sampling effort, while diatom species numbers (in particular pennate form) declined. In conclusion, the results are not unequivocal, but provide some evidence that ice algal communities have undergone some changes in taxonomic composition in multi-year sea ice.

Ice amphipods around Svalbard: decadal trends

Under-ice amphipod abundance demonstrates large seasonal and interannual variability, partly due to the patchiness of their habitats and heterogeneous distribution below ice floes (Lønne and Gulliksen 1991a, b, Werner and Gradinger 2002; Figure 3.1.7). Despite the variability, a decline in ice-amphipod abundance and biomass is apparent, from high values until mid-1990s and to lower values during recent years, and very low values after 2010 (Figure 3.1.7). This trend is equally evident from regional observations: in the 1990s, the area north of Svalbard was dominated by multi-year sea ice and quantitative ice-amphipod sampling was possible to conduct at most ice stations. After mid-2000, the amount of multi-year ice in the Arctic Ocean including the area north of Svalbard declined dramatically (Polyakov et al. 2012, Perovich et al. 2015), and quantitative collections of ice amphipods are no longer possible at many ice stations in that area because of extremely low abundances of these crustaceans, with typical catches of < 1 ind. m^{-2} (H. Hop pers. obs.).

Ice-amphipod abundance seems to be connected to the amount of ice structures and the age of the ice. As shown, with decreasing extent of multi-year sea ice, abundance and biomass of ice amphipods have declined in the Eurasian Arctic. The same trend has been independently observed in the central Arctic (I.A. Melnikov pers. comm.). Multi-year sea ice is described as preferred habitat of the long-lived *G. wilkitzkii* (Lønne and Gulliksen 1991b), although this species also occurs in other ice types, as well as planktonic or benthic habitats for some parts of the summer season (Poltermann 1998, Werner et al. 1999; Fig. 3.1.6). Interestingly, some researchers have reported *A. glacialis* deep (100-2000 m) in the Arctic Basin (Berge et al. 2012), indicating that these organisms are capable of inhabiting the water column in absence of sea ice, at least for part of the year. Future projections for the under-ice associated fauna are uncertain. The multi-year ice ecosystem is capable of supporting a relatively constant species composition of permanent ice biota, while the species composition of the biota of the seasonal sea ice ecosystem largely depends on the biota of the water column for recruitment. In the current sea ice cover situation in the Arctic, these two situations co-exist.

3.1.4 Drivers of observed trends

Abundance and biomass, diversity and distribution of sea ice biota are highly variable in space and time. This variability can largely be attributed to the physical and chemical conditions in and under the sea ice. Light availability, ice and snow conditions, ice temperature, brine salinity, nutrient concentrations (for primary producers), carbon sources (for heterotrophic Bacteria and Archaea) or general food availability (for heterotrophic eukaryotes) are among the main drivers that explain the horizontal and vertical patchiness of sympagic biota. Biodiversity studies should therefore provide auxiliary information for at least the aforementioned variables. At a minimum, ice temperature as well as bulk salinity of melted samples should be determined. On larger spatial scales, ice (extent, thickness, type) and snow cover data are desirable. Below we describe briefly the influences of critical environmental factors on ice biota under the current conditions.

Light conditions under the ice are modulated by day length (i.e., seasonally) as well as by snow depth, ice thickness and particle content in the ice (Leu et al. 2015). During the melt season, ponds develop on top of the ice and increase light transmission from 5-15% to 40-70% (Ehn et al. 2011). A continuation of the observed decline in sea ice extent and thickness will increase the amount of light penetrating into the Arctic Ocean, which will further enhance melting and alter the upper ocean ecosystem (Nicolaus et al. 2012). Thinner ice may facilitate higher production and biomass of ice algae in the Arctic Ocean, but because some areas will have less ice and stratification of the upper water column may increase, the net effect for the Arctic is uncertain (Barber et al. 2015, Leu et al. 2015).

Ice properties, such as thickness, structure, drift, age and stage of freezing/melting, largely influence the seasonal occurrence of sea ice biota (Barber et al. 2015). ***Ice and snow properties*** as well as seasonal development of melt ponds on the ice are important for the energy budget of sea ice (Hudson et al. 2013). On larger scales, the ice extent, ice type (first-year versus multi-year ice, landfast ice versus. drift ice) and ridging influence the abundance and distribution of sea ice biota. Snow layer thickness and duration on top of the ice are important for light transmission and onset of the primary production of ice algae, since snow blocks out to > 80% of the radiation whereas bare ice reflects < 70% and ponded ice < 40% (Gerland et al. 2007).

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[1] Analysis of similarity (ANOSIM) was done in the software package PRIMER (Clarke, K.R., Gorley RN (2006) PRIMER v6: user manual/tutorial PRIMER-E Ltd., Plymouth)

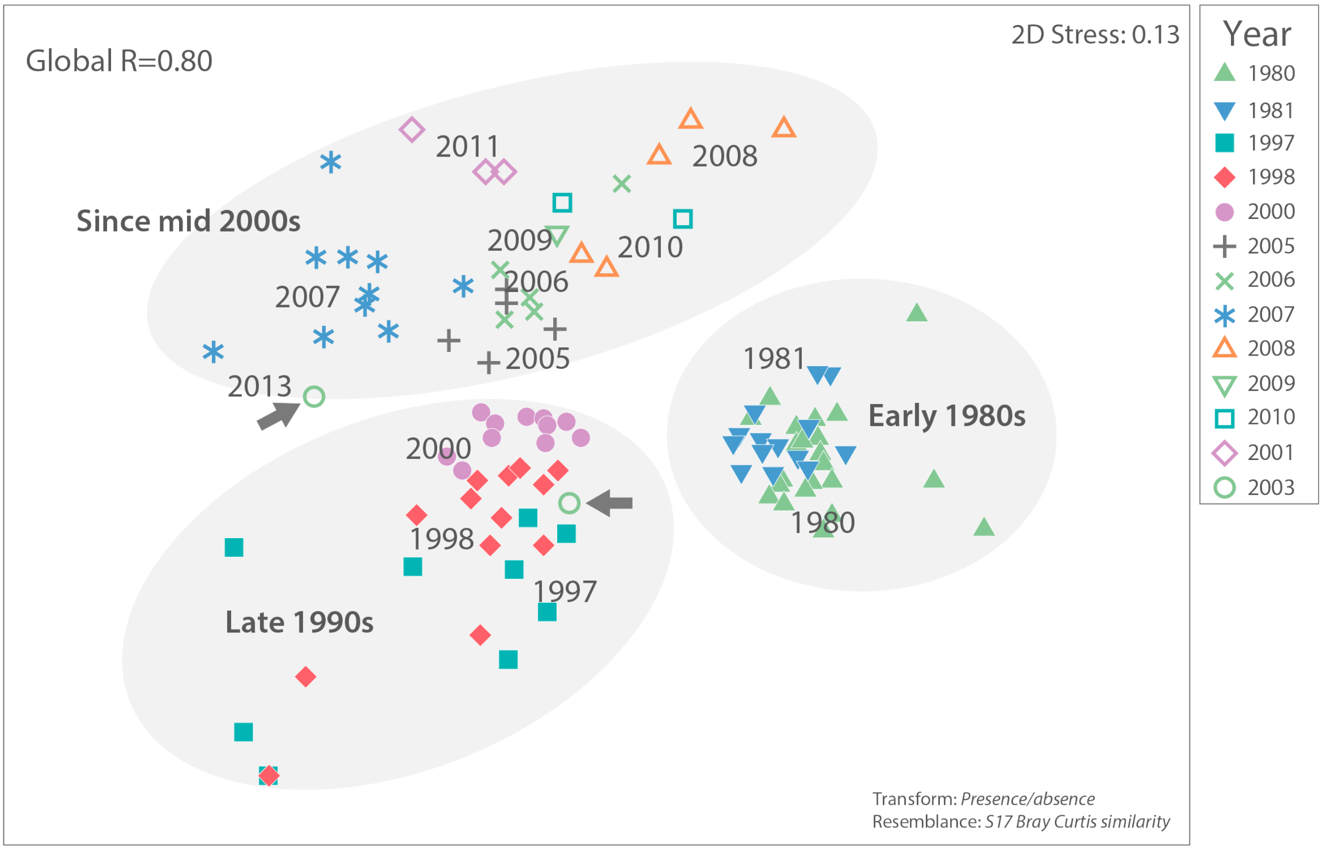


Figure 3.1.8 Ice algal community similarity of central Russian Arctic drifting stations from the 1980s to 2010s based on unpublished data by I.A. Melnikov, Shirshov Institute of Oceanology. The closer two samples (symbols) are to each other in this multi-dimensional scaling plot, the more similar their algal communities were, based on presence/absence of algal species. Samples from the same year tend to be similar and group together on the plot, with some exceptions. Dispersion across the plot suggests that community structure has changed over the decades, although sampling locations in the central Arctic have also shifted, thus introducing bias. An analysis of similarity (PRIMER version 6) with a high Global R=0.80 indicates strong community difference among decades (global R=0 indicates no difference, R=1 indicates complete dissimilarity). Regional differences were low (global R=0.26) and difference by ice type moderate (global R=0.38). Grey arrows point to the very different and only two samples from 2013.

Spatial scales in the ***ice structure*** relevant for ice biota range from the size of a brine channel to the extent of the pan-Arctic ice cover. At small scales, the sea ice brine channel network with dimensions < 1 µm to several mm, depending on temperature, influences biotic distributions (Krembs et al. 2000; Figure 3.1.1). Sea-ice pressure ridges provide niches where larger biota, including fishes, find refuge from predatory vertebrates (Hop et al. 2000, Gradinger and Bluhm 2004). In areas with multi-year ice floes, sea ice fauna can complete their life cycles in the ice habitat, allowing for the evolution of sea-ice endemic taxa (Arndt and Swadling 2006). In coastal Arctic fast ice, however, ice-endemic fauna appears to be sparser due to the habitat loss during the ice-free period.

Temperature, salinity and inhabitable space within sea ice are closely related (Mundy et al. 2011). Temperatures in the sea ice decrease from the ice-water towards the ice-snow interface, with concurrent decrease in brine volume and increase in brine salinity (Ehn et al. 2011). Temperature and brine salinity are similar to open water conditions near the sea water-ice interface. The coldest ice (<-10°C) and highest brine salinities (> 100 psu) occur near the snow-ice interface of Arctic multi-year ice floes; this ice type with extreme salinity conditions has been decreasing during the last decades. Very low salinities (1 to 2 psu, near freshwater conditions) are found in melt ponds and the upper part of melting ice floes, and a thin meltwater layer of 30 to 50 cm brackish water (salinity 5 to 25 psu) typically develops below the ice during early summer (Hop et al. 2011). Melt ponds with variable salinity conditions have become more common and may occur for a longer time during the year. They harbour characteristic biota depending on their salinity (Lee et al. 2011). Adaptations to low temperatures and high and variable brine salinities are already prerequisites for the survival of sympagic organisms in sea ice and influence their biodiversity (Gradinger and Schnack-Schiel 1998). Very low salinities are only tolerated by few marine taxa, but ice amphipods show low osmotic response to hyposmotic stress indicating that they are tolerant to salinity fluctuations in melting sea ice environment (e.g., Aarset and Aunaas 1987). Riverine influence also reduces the salinity so that typical brackish-water (rather than marine) species thrive in some coastal ice areas when the ice is formed (von Quillfeldt et al. 2003).

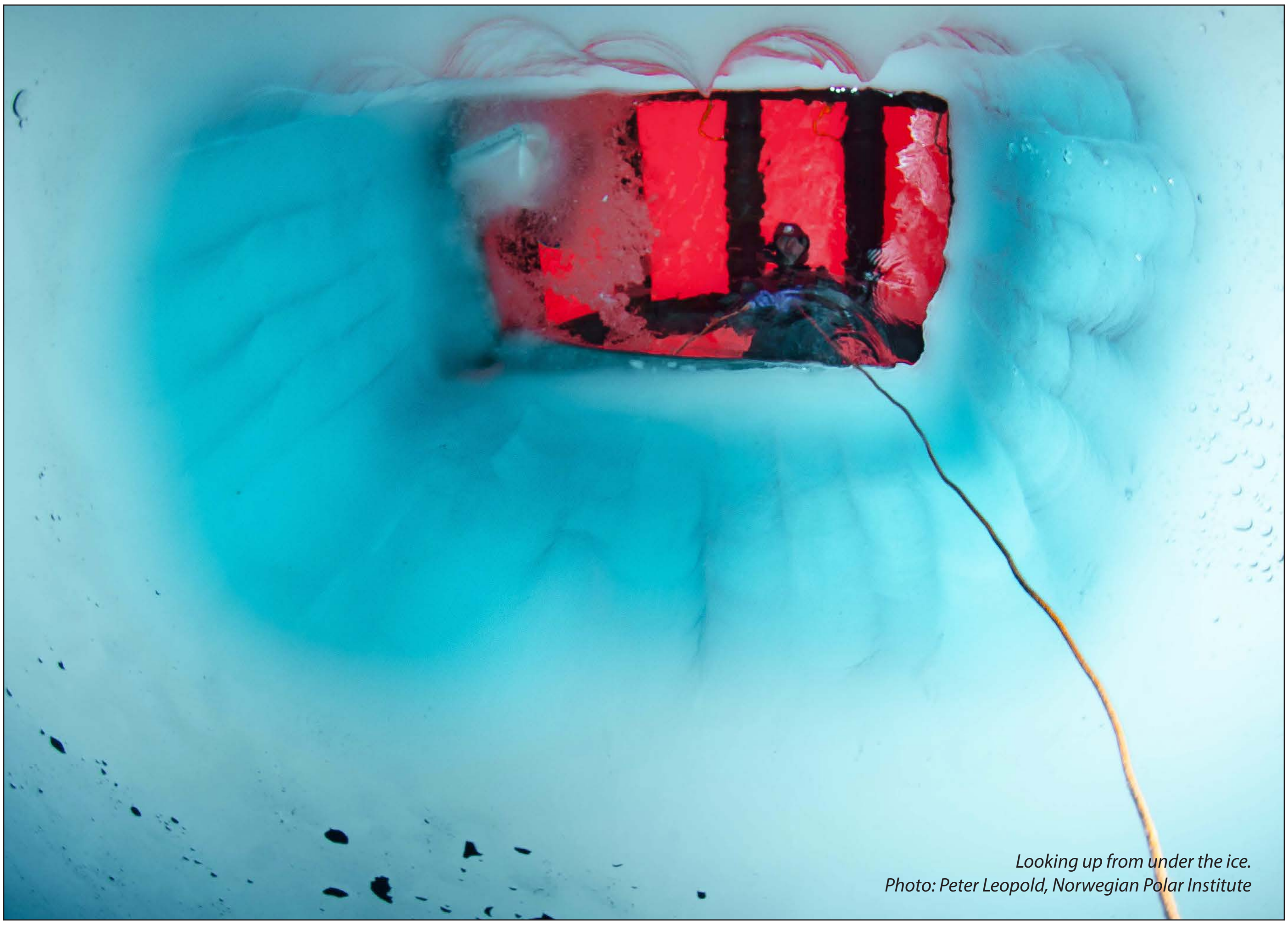
Water depth and distance from land affect the community types recorded in sea ice. The presence of a large number of typically neritic (shallow water) species and freshwater species (e.g., *Asterionella formosa* and *Tabellaria flocculosa*) indicates a coastal formation of the ice (von Quillfeldt et al. 2003). Comeau et al. (2013) also found differences in the microbial flagellates in landfast versus drift ice. Water depth and distance from land also affect the contribution of benthic taxa to the under-ice habitat (von Quillfeldt et al. 2003, Nygård et al. 2012, Bluhm et al. 2017; Figure 3.1.4, 3.1.6). Some of the fauna associated with drifting sea ice may also stay in shallow benthic areas during the ice-free season (Poltermann 1998). The temporary ice fauna, which may include larvae and juveniles of benthic taxa, can drift with sea ice far from shallow regions and increase the diversity and biomass of sea ice biota, although such organisms are most frequently found nearshore.

Nutrient concentrations available to sea ice biota are primarily a function of three factors: (1) nutrient concentrations in the ice and underlying water masses after the winter; (2) nutrients supplied by advection; and (3) biological uptake and remineralization processes (Gradinger 2009). Nutrient concentrations in surface water of a given region thus constitute a reservoir for ice algal growth (Tremblay et al. 2011). Accumulation of high ice-algal biomass (measured as chlorophyll *a*) within sea ice cannot be explained by the initial nutrient concentrations during ice formation alone, which are typically ~30% of surface water concentrations (Gradinger and Ikävalko 1998). Rather, advection of underlying, nutrient-rich water or upwelling is required to achieve high accumulation of ice algae. Upwelling of nutrient-rich water along the shelf break towards surface water layers has become more common in parts of the Arctic as ice retreats and can result in increased nutrient supplies supporting algal blooms (Carmack and Chapman 2003, Tremblay et al. 2011). Autumn blooms have also become more common through this process (Ardyna et al. 2014). Continued supply of nutrients can result in a thick layer of bottom ice algae, particularly in the shallow region of the Laptev Sea and the shelf break in the western sector of the Canadian Arctic Archipelago (Boetius et al. 2013).

Several of the above described environmental variables are currently changing in the Arctic. Sea ice extent and thickness have declined, and, with this change, the light regime is changing. Thinner ice, or more leads in the ice, result in more light available for ice algae and under-ice blooms, and therefore the potential for higher production (Arrigo et al. 2011, 2012), provided that nutrients are available and snow thickness does not increase substantially. Other processes may counteract increased algal production including the shorter ice-covered period, less extensive ice extent as well as increased stratification through increased freshwater content resulting in diminished vertical mixing, as for example in the Canada Basin (Tremblay et al. 2015).

3.1.5 Knowledge and monitoring gaps

No monitoring program currently exists for sea ice biota, and the figures presented here are based on amalgamated data collected by many different researchers. Various research groups around the Arctic, however, have regular field activities involving select sampling of one or several FECs as part of short-term funded projects. The accumulated knowledge base in this chapter can serve as a baseline for monitoring of sea ice biota. However, monitoring requires coordinated plans for sampling at set locations, with consistent sampling and analyses to ensure comparability



Looking up from under the ice.
Photo: Peter Leopold, Norwegian Polar Institute

(Gill et al. 2011). For sea ice, standardized sampling techniques have for example been summarized by Eicken et al. (2009, 2014) and Miller et al. (2015). Proper monitoring requires seasonal and annual field campaigns as well as sufficient, long-term financial support.

Most (but not all) sea ice sampling for ice biota living *within* the brine channels has been done using ice cores (methods described for example in Gradinger and Bluhm 2009). The thickness of the ice sections studied in this synthesis, however, showed high variation, depending on the goals of each study, time constraints and ambient ice thickness to name a few, resulting in different thickness horizons sampled. Often the bottom 0-4 cm or 0-10 cm were sampled (with 0 cm representing the ice-water interface), sometimes the bottom 20-30 cm and occasionally whole cores. Here, a recommendation is given to sample (at least) the bottom 10 cm of ice cores (which can be split into the lowermost 3-4 cm bottom ice and the next 6-7 cm of the core), because the bottom 10 cm often includes the majority of the biomass and abundance of ice biota (~65 % of ice meiofauna, up to 95% for algae based on the here compiled data sets). The CBMP Sea Ice Biota Expert Network also recommends the 10-30 cm section be included (separately) where feasible, as an average 12% of the meiofauna have been observed in this ice section. Microbes, particularly bacteria, are distributed ubiquitously throughout the ice column and are generally sampled in 10 -cm increments using sterile procedures to avoid contaminating the ice cores (e.g., Collins et al. 2010). Ice algal communities and biomass (chlorophyll *a*) are concentrated in the bottom few centimeters, but have in some studies been determined in 20 cm sections up to the surface of the ice (e.g., Mundy et al. 2011). The need for sampling the entire ice column will depend on project goals, which may also include modelling aspects of biota in sea ice (Duarte et al. 2015).

Under-ice sampling has been more variable in approach. Regularly used tools have included (1) SCUBA-operated suction pumps (Lønne 1988), (2) under-ice *in situ* or surface-operated still photos (Mundy et al. 2007), (3) video in a fixed location or video transects (SCUBA diver or ROV operated) (Gradinger and Bluhm 2004), (4) under-ice traps (Nygård et al. 2012) and (5) under-ice trawl nets (David et al. 2016; approaches summarized by Gradinger and Bluhm 2009). The most quantitative samples appear to be based on SCUBA-operated sampling of squares with electrical suction pump (Hop et al. 2000) and the under-ice trawl net SUIT (van Franeker et al. 2009), as well as imagery with sufficient resolution.

In terms of seasonal and annual sampling at selected stations, the most frequently sampled locations (and ice types) in the past have included: (1) Central Arctic pack ice during Russian ice drifting stations, historically in multi-year sea ice and more recently increasingly in first-year ice; (2) Barrow area, landfast ice; (3) Resolute Bay area, landfast ice, and; (4) Svalbard fjords and offshore pack ice (Figure 3.1.3, 3.1.4, 3.1.6). Not all of these locations, however, may be the most promising locations to implement monitoring at, because both the ice cover and research arenas are changing rapidly. The central Arctic Russian ice-drift stations are no longer regular events because ice conditions have become less stable. The ice camp Barneo near the North Pole, however, is still active, though partly used as a tourist location. The use of Resolute Bay facility may be shifting towards the newly constructed Canadian High Arctic Research Station (CHARS) in Cambridge Bay planned to open in 2017. However, Resolute Bay offers better conditions for sampling of Arctic ice biota based on the higher diversity of sea ice organisms at this more northern location, combined with access to a laboratory run by the Canadian Polar Continental Shelf Program. Thus, the Resolute station should be maintained as a Canadian monitoring site for sea ice biota. In Greenland, new research activities and facilities may provide opportunities to monitor ice biota in the future at Station Nord (north Greenland), Zackenberg Station (northeast Greenland) or Arctic Station (west Greenland). At Svalbard, much recent sampling has focused on fast ice in fjords, with seasonal sampling in e.g., Billefjorden. Norwegian research cruises will likely continue in the areas north of Svalbard and in the Arctic Ocean, with possibilities to incorporate monitoring elements in their sampling programs.


Dive photographer.
Photo: Peter Leopold, Norwegian Polar Institute

Regarding the choice of taxa, communities or habitats to monitor, the studies reviewed have usually focused either on a sub-habitat (e.g., ice biota inside brine channels) or on a taxonomic group (e.g., ice meiofauna), a particular method (e.g., morphological taxonomy or genetic analysis), or a combination of the three. Ice biota has rarely been studied as a whole at a given location and time period. The Russian ice-drift studies have likely been the most extensive and comprehensive studies (Melnikov 1997), and there has also been coordinated sampling of ice biota and sea ice physics at some locations in Arctic Canada and Alaska (e.g., Ehn et al.

2011, Hop et al. 2011, Mundy et al. 2011), and more recently during the N-ICE2015 campaign by the Norwegian Polar Institute to the Arctic Ocean. Indicator taxa are sometimes useful and the following could be suitable for monitoring: (1) the arborescent colonial endemic *Nitzschia frigida*, which regularly occurs in bottom sea ice and has been recorded all across the Arctic (Różańska et al. 2009, Poulin et al. 2011); (2) the diatom *Melosira arctica* based on its ability to grow to long curtains under the ice under favourable conditions; (3) the under-ice amphipod *Gammarus wilkitzkii* due to its association with multi-year ice (although certainly not exclusively, as this synthesis demonstrates). This species may be gradually replaced by the more pelagic, but also ice-associated amphipod *Eusirus holmi*, which is of similar large size as adult. Both amphipod species should therefore be monitored, since changes in their relative abundance may reflect changes in sea ice conditions.

Main challenges for monitoring include the relatively low number of people working on sea ice biota and the loss of taxonomic expertise for groups such as ice algae and other protists, but also ice-associated fauna (e.g., meiofauna and ice-associated zooplankton). Another great challenge in attempting to monitor sea ice biota is the large variability of the dynamic sea ice habitat. Ice biota composition and abundance are, as detailed above, highly dependent upon light availability (modulated by day length, ice and snow thickness, sediments in ice, etc.), nutrient availability, temperature, salinity and location. These factors modify the habitat seasonally, even in the same place or the same ice floe. This variability, in combination with historic variability in sampling approach and timing, obscure potential temporal trends. Thus, actual changes in ice biota diversity and community structure need to be substantial enough to rise beyond the existing variability in order to be detected.


Eusirus homi.
Photo: Peter Leopold, Norwegian Polar Institute

3.1.6 Conclusions and key findings

Temporal trends in sea ice biota diversity and/or abundance/biomass are very challenging to detect for two main reasons: the large natural variability within the sea ice system and the lack of systematic and consistent sea ice biota monitoring. The data sets aggregated in this synthesis suggest that changes in community structure of ice algae have occurred in the central Arctic since the 1980s, although this suspected change is coincident with a shift in the region sampled and decreased sampling effort. Over a similar period, ice amphipod abundance and biomass appear to have declined in at least the Svalbard region and perhaps elsewhere in the Arctic. Sea ice biota in general, however, is able to cope with extreme environmental conditions inherent to their habitat in terms of large variations in temperature and salinity, nutrient and space limitations and the ephemeral nature of the habitat. Regular ice biota sampling of the four FECs analysed here should be conducted in the future.

Key findings are:

- Sea ice is a species-rich habitat.
- Inventories of sea ice biota are incomplete.
- Many sea ice biota taxa are widespread across the Arctic ice cover.
- Sea ice houses some species endemic to the Arctic and species endemic to sea ice. Other taxa occur more widely.
- The ice biota generally copes with extreme conditions, although little is known about the tolerance limits and preferences of individual species in this habitat.
- Sea ice algal community structure has possibly changed in the central Arctic between the 1980s and 2010s. Identified shifts in community structure in decadal time series are confounded by shifts in sampling region and effort. Simultaneously, this shift occurred when ice conditions changed, i.e. both multi-year sea ice and ice extent declined.
- Ice amphipod abundance and biomass have declined in the Svalbard area since the 1980s. Amphipods appear to have been more abundant in the late 1970s to mid-1990s than afterwards.
- The occurrence and distribution of ice biota is highly variable in time and space related to a suite of environmental conditions. Consequently, monitoring the biota in this variable habitat is challenging.
- Regions with most frequent or consistent sampling over time (though for different FECs) include the central Arctic, Svalbard, the Barrow, Alaska area and the Canadian Arctic. New sites are evolving in Greenland. These locations are recommended for monitoring ice biota in the future.
- Consistent methodology is required for monitoring of ice biota. Available protocols need to be more widely implemented for monitoring. Monitoring should be standardized with regard to gear, collections, timing, sample preservation and processing, storage, and data management. A central receiving place as well as long-term funding for monitoring should be considered. Data should be deposited in existing databases and made available to researchers and beyond.

Appendix 3.1.1: Meiofauna References

Reference	Title	Authors	Journal	Pub. year	Volume	Pages	Place	url	doi	Temporal coverage
BEST 2008	Bering Sea Ecosystem survey 2008	Bluhm B.A. & Gradinger R.R	unpub.							2008
BEST 2009	Bering Sea Ecosystem survey 2009	Bluhm B.A. & Gradinger R.R	unpub.							2009
BEST 2010	Bering Sea Ecosystem survey 2010	Bluhm B.A. & Gradinger R.R	unpub.							2010
Bluhm & Gradinger unpubl. 2005	Barrow seasonal meiofauna study 2005	Bluhm B.A. & Gradinger R.R	unpub.							2005-2006
Bluhm & Gradinger unpubl. 2007	Barrow seasonal meiofauna study 2007	Bluhm B.A. & Gradinger R.R	unpub.							2007
Carey & Montagna 1982	Arctic sea ice fauna assemblage: first approach to description and source of the underice meiofauna	Carey, A. G. & Montagna, P. A.	Mar. Ecol. Prog. Ser.	1982	8	1-8		www.int-res.com/articles/meps/8/m008p001.pdf		1979
Friedrich 1997	Ökologische Untersuchungen zur Fauna des arktischen Meereises = Ecological investigations on the fauna of the Arctic sea-ice	Friedrich, C.	Berichte zur Polarforschung (Reports on Polar Research)	1997		211	Bremerhaven, Alfred Wegener Institute for Polar and Marine Research	http://epic.awi.de/26424/		1993-1994
Friedrich & De Smet 2000	The rotifer fauna of arctic sea ice from the Barents Sea, Laptev Sea and Greenland Sea	Friedrich, C. & De Smet, W.H.	Hydrobiologia	2000	432	73-89			10.1023/A:1004069903507	1993-1994
Gradinger et al. 2005	Abundance and composition of the sea-ice meiofauna in off-shore pack ice of the Beaufort Gyre in summer 2002 and 2003	Gradinger, R.R, Meiners, K., Plumley, G., Zhang, G. & Bluhm, B.A.	Polar Biol.	2005	28	171-181			10.1007/s00300-004-0674-5	2002-2003
Gradinger & Bluhm 2005	Susceptibility of sea ice biota to disturbance in the shallow Beaufort Sea. Phase 1: Biological coupling of sea ice with the pelagic and benthic realms	Gradinger R.R & Bluhm B.A.	OCS Study MMS 2005-062 Final Report			87				2002-2003
Gradinger et al. 2009	Pivotal role of sea ice sediments in the seasonal development of near-shore Arctic fast ice biota	Gradinger, R.R., Kaufman, M.R. & Bluhm, B.A.	Mar. Ecol. Prog. Ser.	2009	394	49-63			10.3354/meps08320	2002-2003
Gradinger et al. 2010	Arctic sea-ice ridges—Safe heavens for sea-ice fauna during periods of extreme ice melt?	Gradinger, R.R., Bluhm, B.A. & Iken, K.	Deep-Sea Res. Pt. II	2010	57	86-95			10.1016/j.dsr2.2009.08.008	2005
Grainger 1985	The sea ice fauna of Frobisher Bay, Arctic Canada	Grainger, E.H., Mohammed, A.A. & Lovrity, J.E.	Arctic	1985	38	23-30			10.14430/arctic2103	1981-1982
Grainger 1988	The Influence of a River Plume on the Sea-ice Meiofauna in South-eastern Hudson Bay	Grainger, E.H.	Estuar. Coast. Shelf S.	1988	27	131-141			10.1016/0272-7714(88)90086-8	1983
Kern & Carey 1983	The faunal assemblage inhabiting seasonal sea ice in the nearshore Arctic Ocean with emphasis on copepods	Kern, J.C. & Andrew Jr., C.G.	Mar. Ecol. Prog. Ser.	1983	10	159-167		www.int-res.com/articles/meps/10/m010p159.pdf		1980
Kramer & Kiko 2011	Brackish meltponds on Arctic sea ice—a new habitat for marine metazoans	Kramer, M. & Kiko, R.	Polar Biol.	2011	34	603-608			10.1007/s00300-010-0911-z	2007
Marquardt et al. 2011	Vertical distribution of sympagic meiofauna in sea ice in the Canadian Beaufort Sea	Marquardt, M., Kramer, M., Carnat, G. & Werner, I.		2011	34	1887-1900			10.1007/s00300-011-1078-y	2008

Reference	**Title**	**Authors**	**Journal**	**Pub. year**	**Volume**	**Pages**	**Place**	**url**	**doi**	**Temporal coverage**
N-ICE 2015	N-ICE 2015 meiofauna data	Hop, H.	unpublished							2015
Nozais et al. 2001	Abundance, biomass, composition and grazing impact of the sea-ice meiofauna in the North Water, northern Baffin Bay	Nozais, C., Gosselin, M., Michel, M. & Tita, G.	Mar. Ecol. Prog. Ser.	2001	217	235-250		www.int-res.com/abstracts/meps/v217/p235-250/		1998-1999
PSEA 2009	Beaufort Sea cruise meiofauna data	Bluhm B.A. & Gradinger R.R	unpublished							2009
Schünemann & Werner 2005	Seasonal variations in distribution patterns of sympagic meiofauna in Arctic pack ice	Schünemann, H. & Werner, I.	Mar. Biol.	2005	146	1091-1102			10.1007/s00227-004-1511-7	2002-2003

Appendix 3.1.2: Macrofauna References

Reference	Title	Authors	Journal	Pub. year	Volume	Issue	Pages	Place	url	doi	Data type	Temporal coverage
Aarset 1987	Osmotic Responses to Hyposomotic Sress in the Amphipods *Gammarus wilkitzkii*, *Onisimus glacialis* and *Parathemisto libellula* from Arctic waters	Aarset, A.V.; Aunaas, T.	Polar Biology	1987	7	4	189-193			10.1007/ BF00287415	p	1984
Aarset 1990	Effects of osmotic stress on oxygen consumption and ammonia excretion of the Arctic sympagic amphipod *Gammarus wilkitzkii*	Aarset, A.V.; Aunaas, T.	Marine Ecology Progress Series	1990	58		217-224			10.3354/ meps058217	p	1986, 1988
Arctic Ocean 1967	Arctic non-copepod Zooplankton T3 Ice Island 1966-1967	ArcOD/AOOS	IOBIS database	2012					http://www.iobis.org/		p, am3	1967
Arndt 2005a	Moutpart-atlas of Arctic sympagic amphipds--trophic niche separation based on mouthpart morphology and feeding ecology	Arndt, C., Berge, J., Brandt, A.	Journal of Crustacean Biology	2005	25	3	401-412				p	1998, 2000, 2002
Arndt 2005b	Origin and fate of ice fauna in the Fram Strait and Svalbard area	Arndt, C.; Pavlova, O.	Marine Ecology Progress Series	2005	301		55-66			10.3354/ meps301055	p, am2	2002
AWI 1997	ARK13/1a cruise 14 May -29 Sept 1997	Werner, I.	unpublished								am2	1997
AWI 2007	ARK22/2 28 July-10 October 2007	Werner, I.; Siebert, S.; Kramer, M.; Kiko, R.	unpublished								p, am2	2007
Beaufort Sea 1971	An analysis of the zooplankton community structure of the Western Beaufort Sea. WEBSEC 1971	ArcOD/AOOS	IOBIS database	2012					http://www.iobis.org/		p, am3	1971
Beuchel 2002	Population dynamics of the sympagic amphipods *Gammarus wilkitzii* and *Apherusa glacialis* in the sea ice north of Svalbard	Beuchel, F.; Lonne, O.J.	Polar Biology	2002	25		241-250			10.1007/ s00300-001-0329-8	p	1998
Canada Basin 2002	Ice amphipods Canada Basin	ArcOD/AOOS	IOBIS database	2012					http://www.iobis.org/		p	2002
Canadian Arctic 2007	The pre-winter 2007 vertical distribution of zooplankton in the Cape Bathurst and North Water polynyas, and Lancaster Sound, Canadian Arctic	ArcOD/AOOS	IOBIS database	2012					http://www.iobis.org/		p, am3	2007
Fram Strait 1997	Seasonal dynamics of sub-ice fauna below pack ice in the Arctic (Fram Strait)	ArcOD/AOOS	IOBIS database	2012					http://www.iobis.org/		p, am3	1997
Franz Josef Land 1994	Biology and Ecology of Cryopelagic Amphipods from Arctic Sea Ice Collected near Franz Josef Land in the summer of 1994	ArcOD/AOOS	IOBIS database	1994					http://www.iobis.org/		p	1994
Gradinger 2004	In-situ observations on the distribution and behavior of amphipods and Arctic cod (*Boreogadus saida*) under the sea ice of the High Arctic Canada Basin	Gradinger, R.; Bluhm, B.	Polar Biology	2004	27		595-603			10.1007/ s00300-004-0630-4	p, am2	2002

Reference	Title	Authors	Journal	Pub. year	Volume	Issue	Pages	Place	url	doi	Data type	Temporal coverage
Grainger 1985	The sea ice fauna of Frobisher Bay, Arctic Canada	Grainger, E.H.; Mohammed, A.A.; Lovrity, J.E.	Arctic	1985	38	1	23-30			10.14430/ arctic2103	p, am2, ww	1981, 1982
Grainger 2011	FRB Eastern Arctic Investigations: The *Calanus* Series (OBIS Canada)	Grainger, E.H.; Dunbar, M.J.	IOBIS database	2011					http://www.iobis.org/		p	1947-1951
Gulliksen 1984	Under-ice fauna from Svalbard waters	Gulliksen, B.	Sarsia	1984	69		17-23			10.1080/ 00364827.1984. 10420585	p, am2, ww	1982
Honer 1985	Species Composition and Abundance of Zooplankton in the Nearshore Beaufort Sea in Winter-Spring 1978-1980	Honer, R.; Murphy, D.	IOBIS database	1985					http://www.iobis.org/		p, am3	1978, 1980
Hop 2000	Ice amphipod distribution relative to ice density and under-ice topography in the northern Barents Sea	Hop, H.; Poltermann, M., Lonne, O. J., Falk-Peterson, S., Korsnes, R., Budgell, W.	Polar Biology	2000	23		357-367			10.1007/ s003000050456	p, am2, ww	1996
Hop 2008	Distribution and biomass transport of ice amphipods in drifting sea ice around Svalbard	Hop, H., Pavlova, O.	Deep Sea Research II	2008	55		2292-2307			10.1016/ j.dsr2.2008. 05.023	p, am2, ww	2003-2005
Hop 2011	Zooplankton boom and ice amphipod bust below melting sea ice in the Amundsen Gulf, Arctic Canada	Hop, H.; Mundy, C.J.; Gosselin, M.; Rossnagel, A.L; Barber, D.G.	Polar Biology	2011	34		1947-1958			10.1007/ s00300-011-0991-4	p, am2	2008
Hopky 1994a	Zooplankton data from the Canadian Beaufort Sea Shelf 1984 and 1985, Zooplankton Beaufort Sea NOGAP1	Hopky, G.E.;, Lawrence, M.J.; Chiperzak, D.B.	Can Data Report Fish Aquat Sci, Central and Arctic Region Dept Fish & Oceans	1994	922			Winnipeg, Canada	http://www.iobis.org/		p, am3	1984, 1985
Hopky 1994b	Zooplankton Data from the Canadian Beaufort Sea Shelf 1986, ZooplanktonBeaufortSeaNOGAP2	Hopky, G.E.;, Lawrence, M.J.; Chiperzak, D.B.	Can Data Report Fish Aquat Sci, Central and Arctic Region Dept Fish & Oceans	1994	923			Winnipeg, Canada	http://www.iobis.org/		p, am3	1987
Hopky 2004b	Zooplankton Data from the Canadian Beaufort Sea Shelf 1986, ZooplanktonNOGAP32b1986	Hopky, G.E.;, Lawrence, M.J.; Chiperzak, D.B.	Can Data Report Fish Aquat Sci, Central and Arctic Region Dept Fish & Oceans	2004	923			Winnipeg, Canada	http://www.iobis.org/		p	1986
Horner 1985	Species composition and abundance of zooplankton in the nearshore Beaufort Sea in winter-spring	Horner, R.; Murphy, D.	Arctic	1985	38	3	201-209				p, am3	1980
Lonne 1991a	On the distribution of sympagic macro-fauna in the seasonally ice covered Barents Sea	Lonne, O.J.; Gulliksen, B.	Polar Biology	1991	11		457-469			10.1007/ BF00233081	p, am2, ww	1983, 1985, 1986, 1988
Lonne 1991b	Sympagic macro-fauna from multiyear sea-ice near Svalbard	Lonne, O.J.; Gulliksen, B.	Polar Biology	1991	11		471-477			10.1007/ BF00233082	p, am2, ww	1986, 1988

Reference	Title	Authors	Journal	Pub. year	Volume	Issue	Pages	Place	url	doi	Data type	Temporal coverage
Markhaseva 1985	Archives of the Arctic Seas Zooplankton 1	Markhaseva, E.L.; Golikova, A.A.; Agapova, T.A.; Beig, A.A.	IOBIS database	1985					http://www.iobis.org/		p, am3	1970-1973
Melnikov 1980	Cryopelagic Fauna of the Central Arctic Basin	Melnikov, I.A.; Kulikov, A. S	In: Biology of the Central Arctic Basin (Vinogradov, M. E.; Melnikov, I. A.; eds.)	1980			97-111	Nauka, Moscow, USSR			p, am2	1977
Melnikov 2002	Sea ice biological communities and nutrient dynamics in the Canada Basin of the Arctic Ocean	Melnikov, I.A.; Kolosova, E.G.; Welch, H.E.; Zhitina, L.S.	Deep Sea Research Part I: Oceanographic Research Papers	2002	49	9	1623-1649			10.1016/S0967-0637(02)00042-0	p	1997, 1998
Melnikov 2014	Sea Ice Biota data from drift stations and research ship cruises in the Arctic Ocean from 1970s to 2011	Melnikov, I.A.	Norwegian Polar Data	2014					https://data.npolar.no/dataset/36140bc5-e8b4-40fe-b50c-a569141dd694		p, am3	1977-1981, 1997, 1998, 2000, 2007-2011
NP ICE 2011	Norwegian Polar institute ICE 2011 cruise unpublished data	Hop, H.	unpublished								p, am2, ww	2011
NP ICE 2012	Norwegian Polar institute ICE 2012 cruise unpublished data	Hop, H.	unpublished								p, am2, ww	2012
NP MOSJ 2012	Norwegian Polar institute MOSJ 2012 cruise unpublished data	Hop, H.	unpublished								p, am2, ww	2012
Nygard 2012	The amphipod scavenging guild in two Arctic fjords: seasonal variations, abundance and trophic interactions	Nygård, H.; Berge, J.; Søreide, J.E.; Vihtakari, M.; Falk-Petersen, S.	Aquatic Biology	2012	14		247-264			10.3354/ab00394	p	2007, 2008
Pike 1990	Spatial and temporal distribution of sub-ice macrofauna in the Barrow Strait Area, Northwest Territories	Pike, D.; Welch H.E.	Canadian Journal of Fisheries and Aquatic Science	1990	47	1	81-91			10.1139/ f90-008	p, ww	1985-1987
Poltermann 1998	Abundance, biomass and small-scale distribution of cryopelagic amphipods in the Franz Josef Land area (Arctic)	Poltermann, M.	Polar Biology	1998	20		134-138			10.1007/s003000050287	p, am2, ww	1994
Poltermann 2000a	Growth, production and productivity of the Arctic sympagis amphipod *Gammarus wilkitzkii*	Poltermann, M.	Marine Ecology Progress Series	2000	193		109-116			10.3354/meps193109	p	1994
Poltermann 2000b	Life under Arctic sea ice - reproduction strategies of two sympagic (ice-associated) amphipod species, *Gammarus wilkitzkii* and *Apherusa glacialis*	Poltermann, M.; Hop, H.; Falk-Petersen, S.	Marine Biology	2000	136		913-920			10.1007/s002270000307	p	1994
Poltermann 2001	Arctic sea ice as feeding ground for amphipods--food sources and strategies	Poltermann, M.	Polar Biology	2001	24		89-96			10.1007/s003000000177	p	1993, 1994
PSEA 2009	Beaufort Sea 2009 cruise unpublished data	Bluhm B.A. & Gradinger R.R	unpublished									

Reference	Title	Authors	Journal	Pub. year	Volume	Issue	Pages	Place	url	doi	Data type	Temporal coverage
Sameoto 2013	Zooplankton datasets collected using the BIONESS sampler ring and an Icelandic high speed sample 1967-2006	Sameoto, D.D.; Kennedy, M.; Spry, J.S.; Spry, J.M.	OBIS Canada Digital Collections. Biochem: Sameoto zoo-plankton collection	2013					http://www.iobis.org/		p, am3	1980, 1983
Svalbard 2000	Ice Amphipods Svalbard, 2000	ArcOD/AOOS	IOBIS database	2000					http://www.iobis.org/		p	2000
UNIS 1998a	Distribution and abundance of zooplankton and sympagic fauna in Svalbard waters	Hoem, T.; Dahl T.; König S.M.	In "Report of AB-202 Course at UNIS"	1998			21-38	Longyearbyen, Norway			p	1998
UNIS 1998b	Distribution of the sympagic fauna at three different locations north of Svalbard	Beuchel, F.; Borgå, K.; Karlsson, S.; Lilleøkdal, G.	In "Report of AB-310 course at UNIS"	1998			1-31	Longyearbyen, Norway			p, am2, ww	1998
UNIS 1999	Vertical and horizontal distribution of zooplankton and sympagic fauna in north-western Svalbard waters	Daase, M.; Martinsson, P.; Siwertson, A.M.C.; Skoglund, H.; Verreault, J.C.N.	In "Report of AB-202 Course at UNIS"	1999			79-101	Longyearbyen, Norway			p	1999
UNIS 2000	Abundance of sympagic amphipods north of Svalbard considering the ice conditions	Arndt, C.E; Kanapathippillai, P.; Kluge, R.; Krapp, R.	In "Report of AB-320 Course at UNIS"	2000			14	Longyearbyen, Norway			p, am2, ww	2000
UNIS 2002	Sympagic fauna in Fram Strait and Svalbard waters	Backman, J.; Klette, M.; Krey, A.; Luodekari, K.; Vestheim, H.	In "Report of AB-310 Course at UNIS"	2002			5-22	Longyearbyen, Norway			p, am2, ww	2002
UNIS 2004	AB320 UNIS report 2004		In "Report of AB-320 Course at UNIS"	2004				Longyearbyen, Norway			p	2004
UNIS 2006	AB320 UNIS report 2006		In "Report of AB-320 Course at UNIS"	2006				Longyearbyen, Norway			p	2006
UNIS 2008	Zooplankton and sympagic fauna in Svalbard fjords and adjacent waters focussing on taxonomy, distribution and basic ecology	Rabindranath, A.; Baczewska, A.; Loshamn, E.K.; Nielsen, D.L.	In "Report of AB-320 Course at UNIS"	2008			46	Longyearbyen, Norway			p	2008
UNIS 2012	Amphipods and their interactions in the sympagic food web in the Arctic Ocean	Berthold, M.; Kallevik, I.H.F.; Marquardt, M.; Rekdal, S.	In "Report of AB-330 Course at UNIS"	2012			39	Longyearbyen, Norway			p	2012
Werner 1999	The sub-ice fauna of the Laptev Sea and the adjacent Arctic Ocean in summer 1995	Werner, I.; Arbizu, P.M.	Polar Biology	1999	21		71-79			10.1007/s003000050336	p, am2, ww	1995
Werner 2002	Carnivorous feeding and respiration of the Arctic under-ice amphipod *Gammarus wilkitzkii*	Werner, I.; Auel, H.; Friedrich, C.	Polar Biology	2002	25		523-530			10.1007/s00300-002-0376-9	p, am2	1994, 1995, 1997, 2000
Werner 2005	Living conditions, abundance and biomass of under-ice fauna in the Storfjord area (western Barents Sea, Arctic) in late winter (March 2003)	Werner, I.	Polar Biology	2005	28	4	311-318			10.1007/ s00300-004-0678-1	p	2003
Werner unpubl.	AKR11/1 cruise 7.juli-20.Sept 1995	Werner, I.	unpublished								p, am2	1995

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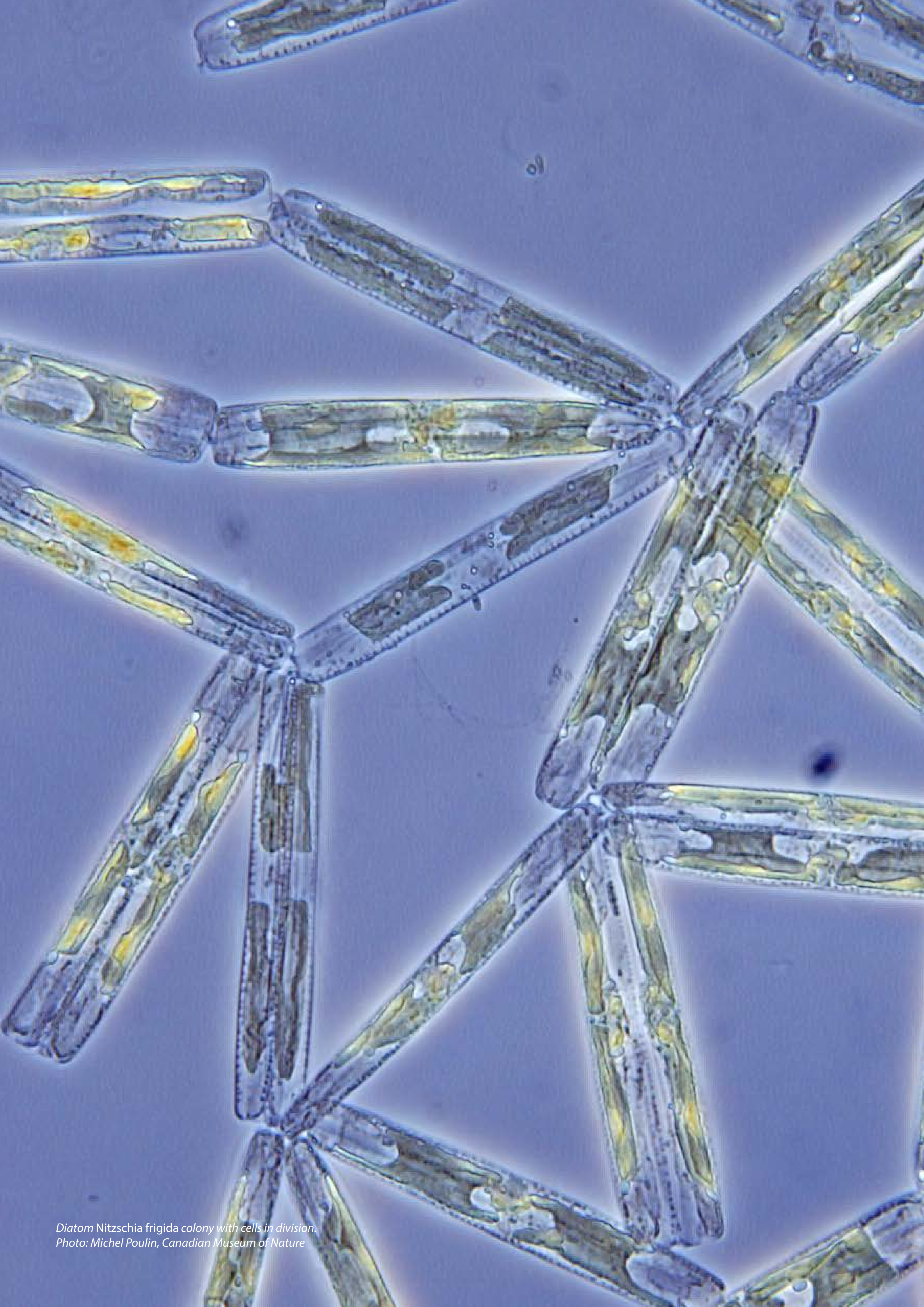

Diatom Nitzschia frigida *colony with cells in division.*
Photo: Michel Poulin, Canadian Museum of Nature

3.2 Plankton

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Snapshot

- Microbial plankton (Bacteria, Archaea, phytoplankton and heterotrophic protists) and zooplankton are the base of the pelagic Arctic marine food web, feeding large-sized zooplankton, fishes, seabirds and marine mammals. Changes in these species can have cascading effects throughout the ecosystem and can represent the first sign of overall ecosystem shifts. Despite their importance, elements of this taxonomic group are scientifically underappreciated and inadequately known.
- Particularly unknown elements include the diversity of microbes, and plankton distribution over time and space in the Arctic. This impedes better understanding of Arctic marine ecosystem structure and processes, and thus the ability to apply ecosystem based management.
- Warming can have contradictory and surprising effects on plankton. Increased temperature in the Barents Sea and around Svalbard has led to the presence of more southern species of generally less nutritional value to Arctic feeders. However, rising temperatures in the Chukchi Sea are associated with an increase in the presence of large copepods.
- Plankton are strongly affected by climate and differ between open water and ice-cover conditions, current patterns and salinity. Increased open water and less saline surface water could lead to range shifts so that Arctic species are replaced by non-Arctic species, again with unknown consequences for the Arctic marine food web.
- There is a potential risk of harmful/toxic phytoplankton causing public health threats through shellfish consumption, fish and aquatic bird kills, and decreased fitness in marine mammals.
- Systematic monitoring has most frequently occurred around Svalbard and Jan Mayen, the Barents Sea, Iceland, Greenland and the southern Bering Sea.

3.2.1 Introduction

Plankton refers to taxonomically and functionally diverse aquatic organisms that range in size from submicron (<1 µm) to centimetres (cm). For technical terms, see Box 3.1.1. They share a limited ability to control their location against oceanic currents. Phytoplankton are responsible for all primary production in the open ocean and are the base of the pelagic food chain supporting higher trophic levels. Arctic phytoplankton and other protists, which include single-celled micro zooplankton, are the main food for copepods that are the principal food for larger macrozooplankton, and some species of fish and seabirds. Bacterioplankton are essential for degrading organic carbon in the ecosystem, and in the open ocean, including the Arctic, Bacteria and Archaea are responsible for remineralization of nutrients. Heterotrophic and mixotrophic microbial eukaryotes graze on Bacteria and Archaea as well as smaller phytoplankton. All of these single-celled plankton are subject to strong environmental selection. This selectivity is profoundly evident for picophytoplankton (<2 µm), which are exclusively eukaryotic in Arctic waters in contrast to in temperate and tropical regions where picocyanobacteria are ubiquitous (Lovejoy et al. 2007, Li et al. 2009, Balzano et al. 2012). However, picocyanobacteria in the genus Synechococcus are detected by flow cytometry in the Pacific (Bering and Chukchi Seas; Li et al. 2009) and Atlantic gateways, Fram Strait and around Svalbard (Paulsen et al. 2016). Freshwater cyanobacteria phylotypes can also persist in coastal regions, where rivers enter the Arctic (Waleron et al. 2007).

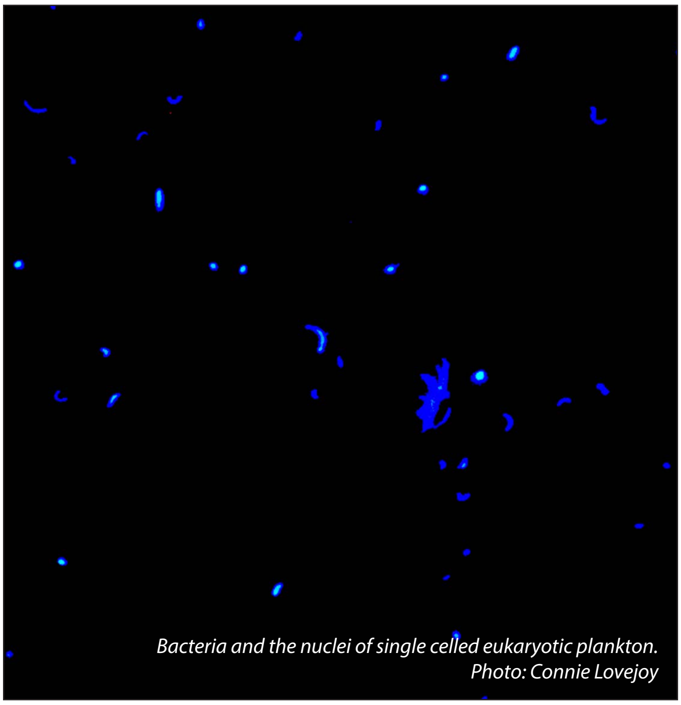
In the Arctic as elsewhere, currents, water column stratification and seasonality are recurring processes in any given region and predictable seasonal community patterns can be distinguished, with excursions indicative of change. Microbial communities are sensitive indicators of food web complexity, and the fate of photosynthetic production can be inferred from dominant species or species complexes, where a species complex consists of closely related taxa that may or may not described as species. Some plankton assemblages with their representative species are consumed in the water column, while others have a tendency to sink, either feeding the benthos along shelves or into deep basins, contributing to the biological carbon pump (see Box 3.1.2.1; Morata et al. 2011). Smaller sized (1-20 µm) phytoplankton and their associated heterotrophic assemblages drive pelagic food webs that keep carbon and energy in the upper water column. Grazing activities by metazoan zooplankton moves this carbon up the pelagic food web, and can also enhance organic carbon export to the benthos through rapidly sinking fecal pellets (see Chapter 3.3 and 3.4).

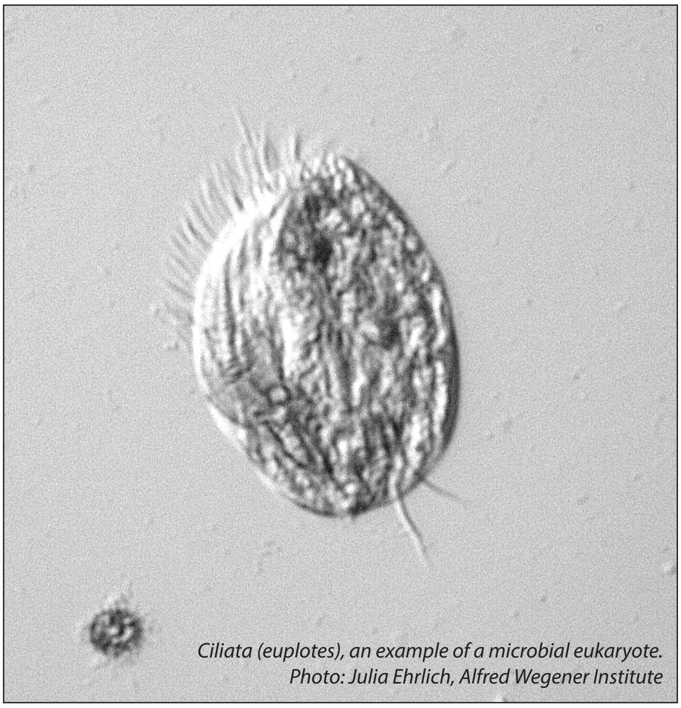
The biodiversity of Bacteria and Archaea has only been appreciated since the advent of the molecular era, as the majority of free-living pelagic microbes resist cultivation. In this sense, the 'historic' records for these organism's date from around 2000 (Huse 2008, Galand et al. 2009). More recently, the distributions of major Bacteria clades have been reviewed in Pedrós-Alió et al. (2015), who found that in the open ocean at the level of classes, Arctic bacterioplankton were similar to that of other open oceans, but with an indication that higher proportions of *beta* and *gamma* proteobacteria compared to *alpha* proteobacteria may be indicative of recent ice cover.

Molecular techniques have also been at the forefront in the discovery of endemic Arctic microbial eukaryotes (Lovejoy et al. 2007, Terrado et al. 2013). Importantly, the most widespread and abundant phytoplankton species in the summer Arctic Ocean is the Arctic picophytoplankton

Micromonas with a pan-Arctic distribution (Lovejoy et al. 2007, Vader et al. 2015). While *Micromonas* is common year round in Svalbard waters (Marquardt et al. 2016), *Phaeocystis pouchetii* can be abundant in summer (Kilias et al. 2014). Overall molecular surveys focusing on specific taxonomic groups have confirmed microscopy records reporting a mix of Arctic and Boreal-Arctic species among phytoplankton (Percopo et al. 2016), as well as heterotrophic protists (Thaler and Lovejoy 2015). Understanding the occurrence patterns of the two types of communities (strictly Arctic versus Boreal-Arctic) promises to be a powerful tool in interpreting the effects of climate change versus seasonality on marine food webs (Luddington et al. 2016).

Most Arctic phytoplankton species have pan-Arctic distributions, which are consistent with long-range transport by Arctic currents (Abelmann 1992, von Quillfeldt 2000, Poulin et al. 2011) that retain populations within the Arctic. Other species enter the Arctic via the Barents Sea and the Bering Strait. In the Pacific, some species may persist in Arctic waters, for example heterotrophic nanoflagellates and Radiolaria (Terrado et al. 2009, Thaler and Lovejoy 2015). In the European Arctic, because of the complex hydrography around Svalbard, for example, there is often a mix of Arctic and North Atlantic species (von Quillfeldt 2000). Recent evidence has found that Boreal-Arctic *Thalassiosira* spp. exit the Arctic though Davis Strait and likely contribute to the North Atlantic spring bloom (Luddington et al. 2016).


Bacteria and the nuclei of single celled eukaryotic plankton.
Photo: Connie Lovejoy


Ciliata (euplotes), an example of a microbial eukaryote.
Photo: Julia Ehrlich, Alfred Wegener Institute


Dinoflagellate Peridiniella catenata.
Photo: Michel Poulin


Calanus glacialis.
Photo: Russ Hopcroft, University of Alaska, Fairbanks

The interconnections between the Arctic and the Atlantic suggest that factors selecting for species in late summer and autumn in the Arctic, could have an influence on the species composition, timing and extent of phytoplankton production well outside of the Arctic. A list of 36 potentially harmful/ toxic marine unicellular eukaryote taxa have been recorded in phytoplankton across the Arctic (Poulin et al. 2011). The potential risk of these taxa being responsible for fish and aquatic bird kills and lowered fitness in marine mammals and potential public health threats is unknown at present. However, there have been reported algal toxins presence in marine mammals in the Arctic (Lefebvre et al. 2016).

In contrast to single-celled plankton, metazoan zooplankton are better able to maintain their position within the water column. Metazoan plankton include a wide array of invertebrates, as well as larval stages of fish (ichthyoplankton). The longer life span (months to years) of these organisms allows them to develop more specific life-history strategies, including daily and seasonal vertical migrations that also lead to predictable seasonal cycles, albeit with large inter-annual variability (Falk-Petersen et al. 2009, Berge et al. 2014, Daase et al. 2016). Additionally, most species are adapted to specific depth ranges, yielding characteristic communities that are shared across the Arctic's central basins (Kosobokova et al. 2011), with oceanic communities distinctive from those on the shelves (Grainger 1965, Smoot and Hopcroft 2016).

Arctic zooplankton cover a wide spectrum in terms of species and size range. By far the most well-studied zooplankton in the Arctic are copepods, which have been widely sampled using nets and more recent data from acoustic and optical techniques (e.g., Forest et al. 2012, Trudnowska et al. 2015). Copepods are estimated to account for 80-90% of the zooplankton biomass in the Arctic and are typically very lipid rich. They are directly consumed by many fish and some seabird species, as well as the baleen whales (Ástþórsson and Gislason 1997, Wassmann et al. 2006, Darnis et al. 2012), making them the best available Focal Ecosystem Components (FEC) for zooplankton monitoring. The copepods are dominated by three species of *Calanus* (*C. glacialis*, *C. hyperboreus*, *C. finmarchicus*) whose life cycles involve feeding in surface water during the productive spring and summer, then diapause (~hibernation) at depth during winter (Falk-Petersen et al. 2009). Over 150 other copepod species contribute to the ~350 species reported for Arctic zooplankton communities (Bluhm et al. 2011).

Macrozooplankton are the larger crustaceans, such as hyperiid amphipods and euphausiids, which are also important as prey for marine vertebrates and are further mentioned in the fish, mammal and seabird chapters (Chapters 3.4, 3.5, 3.6). While smaller life-stages of macrozoplankton are routinely sampled using the same nets that are typically used for *Calanus* sampling, the larger individuals require sampling with larger nets (e.g., Auel and Werner 2003, Dalpadado et al. 2016) that have not been routinely deployed in the Arctic due to its ice cover. Newer technologies such as calibrated acoustics (Ressler et al. 2015) promise to close knowledge gaps on euphausiid distribution. Arctic euphausiids are mostly reported in the gateways (Bering Sea and Barents Sea) and in regions where there is enhanced productivity associated with large riverine input, but almost absent from the central basins. Generally, free-living hyperiid amphipods (e.g., *Themisto* spp.) are more wide-spread and do well in cold water, including the Arctic (Percy 1993), with larger individuals generally being undersampled (Auel and Werner 2003). Sediment trap records are now being exploited to follow hyperiid species changes over time (Kraft et al. 2012) and have confirmed the widespread distribution of this group. Given the sparse data and lack of targeted monitoring, it is impossible to comment on the status and change of these larger macrozooplankton and for these reasons they are not currently treated as FEC by the Circumpolar Biodiversity Monitoring Programme (CBMP) Plankton Expert Network.

Around one-quarter of the metazoan zooplankton species found in the Arctic are truly restricted to the Arctic, with most other species shared with the North Atlantic or North Pacific (Kosobokova et al. 2011), especially in regions of inflow (i.e., the Barents and Chukchi Seas). Near major rivers, brackish-water species may contribute substantially to the zooplankton community (Abramova and Tuschling 2005), while larvae of benthic species become prominent seasonally on the shallow shelves (Questel et al. 2013).

3.2.2 Current monitoring

The motivation and potential funding sources for monitoring plankton varies by taxonomic group. For example, zooplankton species are sometimes monitored as part of fisheries habitat surveys and phytoplankton sometimes monitored in the context of harmful algal bloom threats. While the following summary takes a geographic approach, it is important to note that these different regions mostly have been monitored for different kinds of plankton.

Environmental Monitoring of Svalbard and Jan Mayen (MOSJ) is conducted as part of the Norwegian Government's environmental monitoring. Kongsfjorden is the only fjord in Svalbard where regular monitoring of zooplankton (during summer) has been reported since 1996. Phytoplankton and chlorophyll were added to the annual sampling from 2009. Rijpfjorden on Nordauslandet, north Svalbard, has been opportunistically sampled annually since 2006, but is not included in an established monitoring program (C. von Quillfeldt, pers. comm.). There are however, other cruises at different times of the year to both fjords, such as winter cruises in January conducted by UiT The Arctic University of Norway in collaboration with University Studies in Svalbard (UNIS). The Kongsfjorden marine ecosystem functions under the balance of influx of Atlantic and Arctic waters, and as a consequence the pelagic food web is composed of both boreal and Arctic species. Hop et al. (2002) concluded that Kongsfjorden is particularly suitable as a site for exploring the impacts of possible climate change, with both Atlantic water influx and melting of tidal glaciers being linked to climate variability. With Kongsfjorden receiving variable climatic signals between years, it functions as a climate indicator on a local scale. Subsequent reports suggested that the fjord zooplankton were sensitive indicators of Atlantic inflow during winter (Willis et al. 2008).

Norway is also monitoring phytoplankton and zooplankton species composition elsewhere, for example, in the Barents Sea along predefined transects, once or several times a year with status reports on the different trophic components (McBride 2016).

Systematic monitoring of zooplankton communities off Iceland can be traced back to 1960. Species-resolved analysis for both zooplankton and phytoplankton time series began in 1990 for transects extending from the southern and northern coasts of Iceland (Ástþórsson et al. 2007, Gislason et al. 2014). These transects highlight the different habitats found on opposite sides of the island (Atlantic in south and sub-Arctic in north), as well as the role of advection. More distant waters of the Iceland and Greenland seas have only been sampled periodically.

Monitoring sites are operating in different regions of Greenland including Nuuk (souhwest Greenland), Zackenberg (northeast Greenland) and Disko Bay (west Greenland). Zooplankton and phytoplankton data have been collected at all three locations for more than 10 years, thus comprising the most extensive plankton time series from Greenland. The Nuuk and Zackenberg locations are part of the Greenland Ecosystem Monitoring program (GEM), which collected a multitude of physical, chemical and biological parameters in the marine environment as well as terrestrial, limnic and atmospheric data. Marine monitoring in Disko Bay is planned to be expanded and become part of the GEM program (T. Juul-Pedersen pers. comm.). Together these three sites represent a climate gradient of coastal marine systems in Greenland, i.e., covering high Arctic, Arctic and sub-Arctic sites. The monitoring data collected as part of the GEM program are made publicly available.

There is no formal monitoring of plankton in Canadian waters. Partial monitoring of phytoplankton and zooplankton in Canadian waters has been related to several major research initiatives dating back to 1998 with the North Water Polynya project (NOW) followed by nearly annual campaigns under the Canadian Networks of Centres of Excellence ArcticNet and by the Institute of Ocean Sciences (IOS) Department of Fisheries and Oceans (DFO). Although such oceanographic campaigns occurred nearly annually in the Amundsen Gulf, Baffin Bay and the Canada Basin since 2002, not all planktonic groups have been studied consistently (Hunt et al. 2014). In addition, this work has been at the initiative of individual researchers and data are dispersed. Scattered studies have occurred in other regions. Metadata by Canadian researchers can be found in the Polar Data Catalogue. It is envisioned that a marine monitoring program including the use of molecular data to monitor protists, Bacteria and Archaea will be put in place off Cambridge Bay, once the Canadian High Arctic Research Station opens in 2017 (C. Lovejoy pers. comm.).

The U.S. and Russia have performed decades of zooplankton studies in the southern Bering Sea, the Bering Strait region and northward into the Chukchi Sea. Even though these are not consistent over time and space for monitoring purposes, the southern Bering Sea has been sampled regularly during recent decades (available on the Distributed Biological Observatory). More consistent observations of zooplankton in the Chukchi region began in 2004 under the RUSALCA program (Ershova et al. 2015a) and in 2003 by Pacific Scientific Research Fisheries Centre (TINRO) (Slabinsky and Figurkin 2014). Annual zooplankton observations in the northeastern Chukchi Sea have occurred since 2007 stimulated by oil and gas exploration in the region (Questel et al. 2013), with observations northeast of Barrow ongoing since 2005 (Ashjian et al. 2010). Zooplankton in the American sector of the Beaufort Sea was well studied from 2010-2014 (Smoot and Hopcroft 2016), but future prospects are unclear. For the zooplankton, all studies consistently show that communities are strongly associated with the water mass properties and origin. In nearly all cases, phytoplankton has only been measured as chlorophyll biomass, while Archaea, Bacteria and heterotrophic protists including microzooplankton have been largely ignored. The U.S. continues within the Pacific Arctic Group to encourage plankton collections as part of its internationally sampled Distributed Biological Observatories in the Bering, Chukchi and Beaufort Sea regions.

Despite its expansive shelf seas, Russia lacks long-term unilateral plankton monitoring activities. As noted above, sampling occurs in conjunction with the U.S. in the Chukchi Sea, in conjunction with Germany in the Laptev Sea and Norway in the Barents Sea. Data sharing with Russian programs remains a significant hurdle to overcome.

The CBMP Plankton Expert Network is not aware of any ongoing long-term monitoring for Bacteria and Archaea anywhere. As sequencing technology continues to improve and become affordable, the CBMP Plankton Expert Network envisions that Bacteria and Archaea will be more systematically monitored in the future. As with Bacteria and Archaea, the CBMP Plankton Expert Network is confident that molecular surveys of microbial eukaryotes can be incorporated into monitoring programs, but know of no routine monitoring at the current time.

Plankton in sample water.
Photo: Caitlin Bailey, The Hidden Ocean 2016, Chukchi Borderlands, NOAA

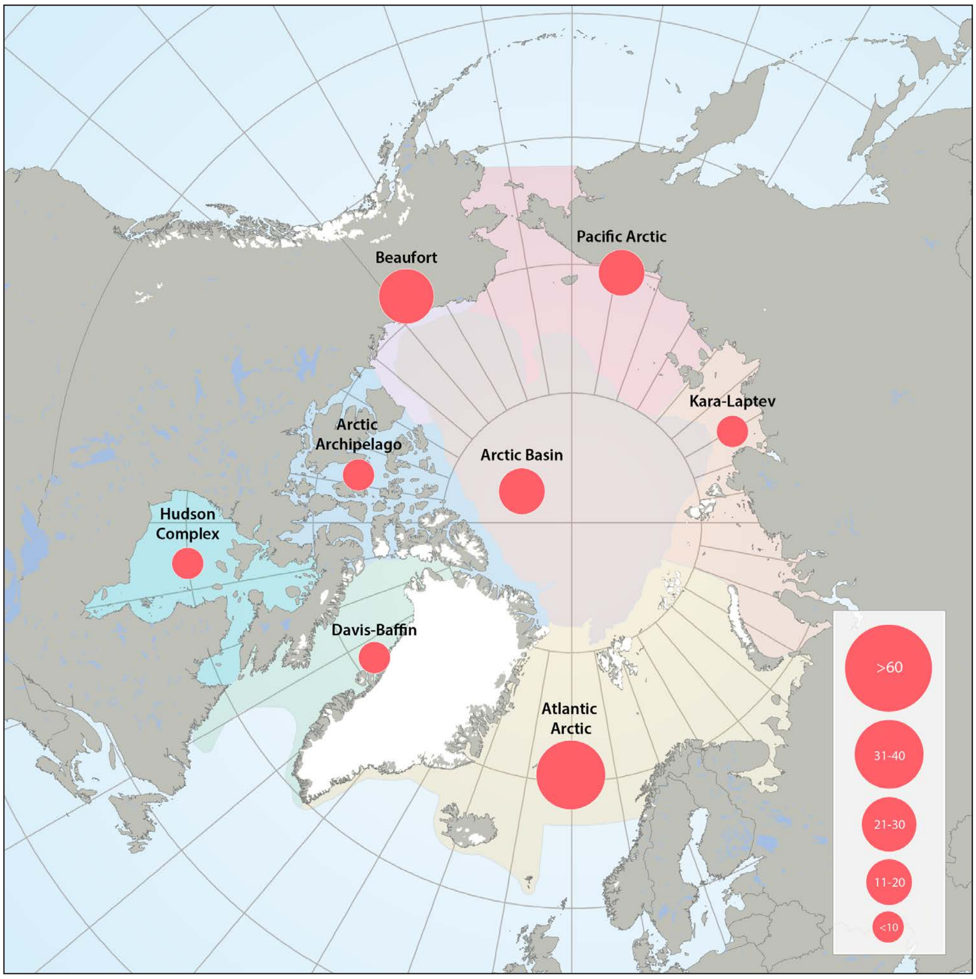


Figure 3.2.1a: Map of high throughput sequencing records from the Arctic Marine Areas.

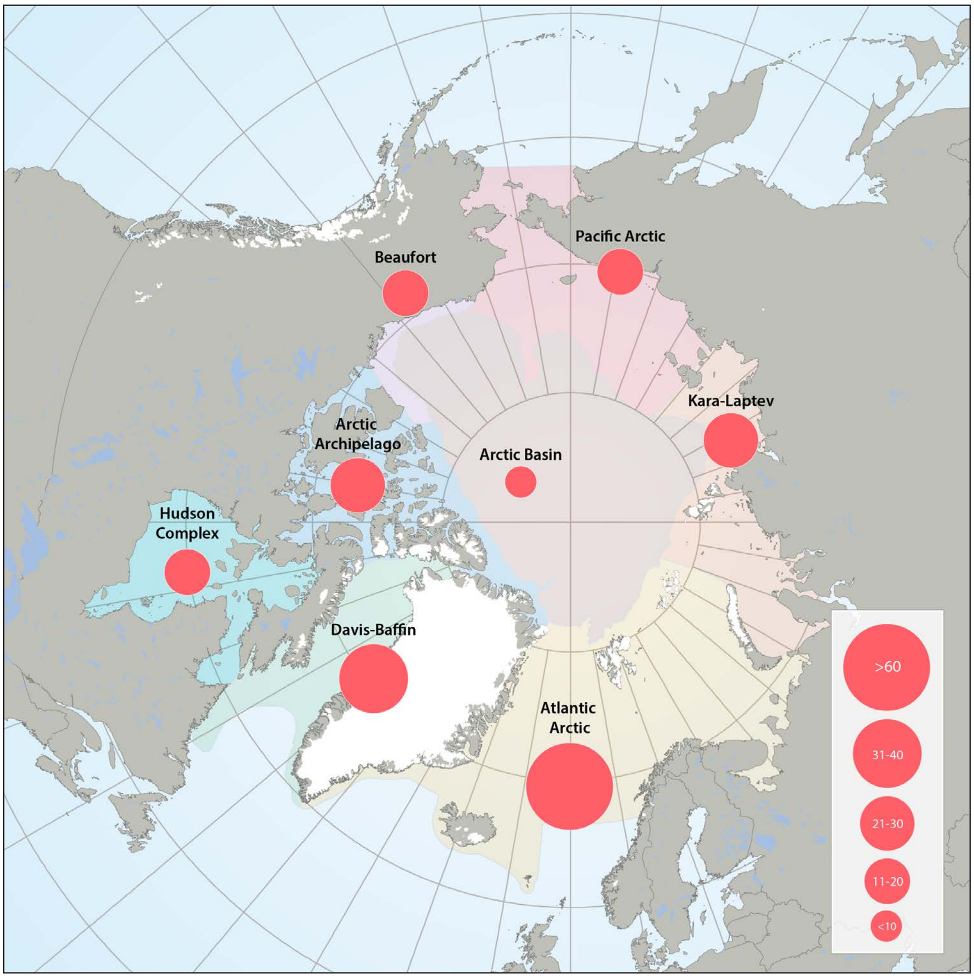


Figure 3.2.1b: Map of records of phytoplankton taxa using microscopy from the Arctic Marine Areas.

3.2.3 Status and trends of FECS

In the *Arctic Biodiversity Assessment* (ABA), plankton were treated under three separate chapters, with zooplankton very briefly mentioned in the Marine Invertebrate chapter (Josefson and Mokievsky 2013), phytoplankton and a few heterotrophic protists in the Plant chapter (Daniëls et al. 2013), and marine heterotrophic protists summarized along with Bacteria and Archaea in the Microbes chapter (Lovejoy 2013). At least for single-celled eukaryotic plankton, the split between heterotrophic and photosynthetic groups masks the true functional diversity and confounds interpretation of how changes in species assemblages could propagate up the food chain. Many single-celled plankton are mixotrophic and can act as both primary producers and grazers, which make trophic classification as phototrophic or heterotrophic deceptive. As different species exhibits different degrees of mixotrophy, there is need to identify species within these groups, without which it will be difficult to model or predict the flow of energy and carbon through the higher food web. Similarly, for zooplankton, knowing the relative abundance of key species is an essential component in predictive models of ecosystem health (Maps et al. 2012). The logistical challenges of accessing ice-covered regions and the slow pace of taxonomic sample processing make understanding seasonal and broad scale patterns challenging. Countries with the longest monitoring programs (e.g., Norway and Iceland) have used bulk wet-weight or displacement volume to estimate zooplankton biomass. However, most investigations in the Svalbard area have calculated biomass from abundance data by applying individual dry-mass values derived from species-specific length-mass relationships or applied published dry mass estimates for species and stages (e.g., Blachowiak-Samolyk et al. 2008). Since the late 1990s, remote sensing of chlorophyll and bulk mesozooplankton biomass from transects has become a standard approach for assessing fisheries productivity (Dalpadado et al. 2014). Such approaches result in a complete loss of the potential for gathering taxonomic information, which is essential for monitoring community changes driven by climate (Richardson 2008).

The density and type of data on plankton from different regions are highly variable and reflect national interests in some cases and the particular expertise of active researchers at different times in other cases. Here, recent compilations from molecular surveys targeting single-celled plankton are summarized, and then microscopy-based reports of phytoplankton species are followed by a review of the traditional approaches still used for zooplankton

Bacteria and Archaea

Bacteria and Archaea can only be identified using molecular techniques, with most work to date based on the gene coding for the Small Subunit of ribosomal RNA (SSU rRNA gene; 16S rRNA for Bacteria and Archaea). Molecular surveys of Bacteria and Archaea have tended to be more local and project specific and sampling effort maps have not been assembled. Comparison of data sets has also been hampered by the use of different primer pairs targeting different variable regions of the 16S rRNA gene. Nonetheless, the data available indicate that offshore oceanic bacterial groups at the level of phyla and proteobacteria class resemble temperate open-ocean Bacteria, while inshore Bacteria tend to consist of taxa preferring habitats richer in organic substrates (Pedrós-Alió et al. 2015). Time-series data are rare, although one from Amundsen Gulf (Beaufort Sea) suggested significant changes in the relative abundance of key microbial groups before and after the first record summer sea ice minimum in 2007. Over the eight-year study, there was a shift towards more oligotrophic taxa (Comeau et al. 2011). Interestingly, deep-water Arctic communities may be taxonomically similar to Antarctic deep-water communities (Ghiglione et al. 2012), but more extensive sampling is needed.

Microbial eukaryotes identified using molecular techniques

Similar to Bacteria and Archaea, most microbial eukaryotes < 3 μm can only be identified using molecular techniques, and molecular signatures can be used to identify ecotypes and species of nanoflagellates. Molecular identification of many 1-20 μm flagellates has become routine and can also be applied to diatoms and dinoflagellates. However, for these two groups that have well-established morphological taxonomies, microscopy-based verification of species is needed to reconcile molecular data to classic species description to enable comparisons with older literature (Luddington et al. 2012). The 18S rRNA gene, while robust for most groups, has not been able to resolve taxonomic identity within several clades of dinoflagellates and diatoms possibly because of their recent rapid-trait evolution compared to nucleotide changes in the 18S rRNA gene. More reference sequences of known species are needed to reconcile analyses with classical taxonomy. The first microbial eukaryotic 18S rRNA gene surveys date from 2002 (Lovejoy et al. 2006) with the greatest effort in Amundsen Gulf in the Canadian Arctic and where 35 datasets are published and available. Recent efforts around Svalbard have generated 40 datasets (Fig. 3.2.1a). Opportunistic sampling around the North Pole has added additional records of microbial eukaryotes (Bachy et al. 2011). Other records are more sporadic; high through-put sequencing has been used on samples from Baffin Bay, the Canada Basin, the Chukchi Sea, Canadian Arctic Archipelago, Hudson Bay, the Greenland Sea and Laptev Sea (Thaler and Lovejoy 2015; Fig. 3.2.1a). The majority of the raw sequence data are publically available in NCBI GenBank and the Sequence Read Archive (SRA).

For microbial eukaryotes, high through-put sequencing shows a consistent pattern of dominance by dinoflagellates, followed in relative abundance by ciliates and, in the European and Central Arctic Ocean, by marine alveolates (MALVs, see Box 3.1.2). Chlorophytes are consistently abundant, comprising 5-14% of all reads across different regions. By far the majority of the chlorophyte reads correspond to a single Arctic clade of Micromonas, which is 1-2 μm in diameter (Lovejoy et al. 2007, Balzano et al. 2012). Higher relative abundance in terms of reads (sequences) per sample by other groups is rare, for example, reports of higher proportions of haptophytes in the Central Arctic and Atlantic Arctic regions, diatoms in Baffin Bay and Rhizaria in the Pacific Sea and Atlantic Arctic regions (Fig. 3.2.2a).

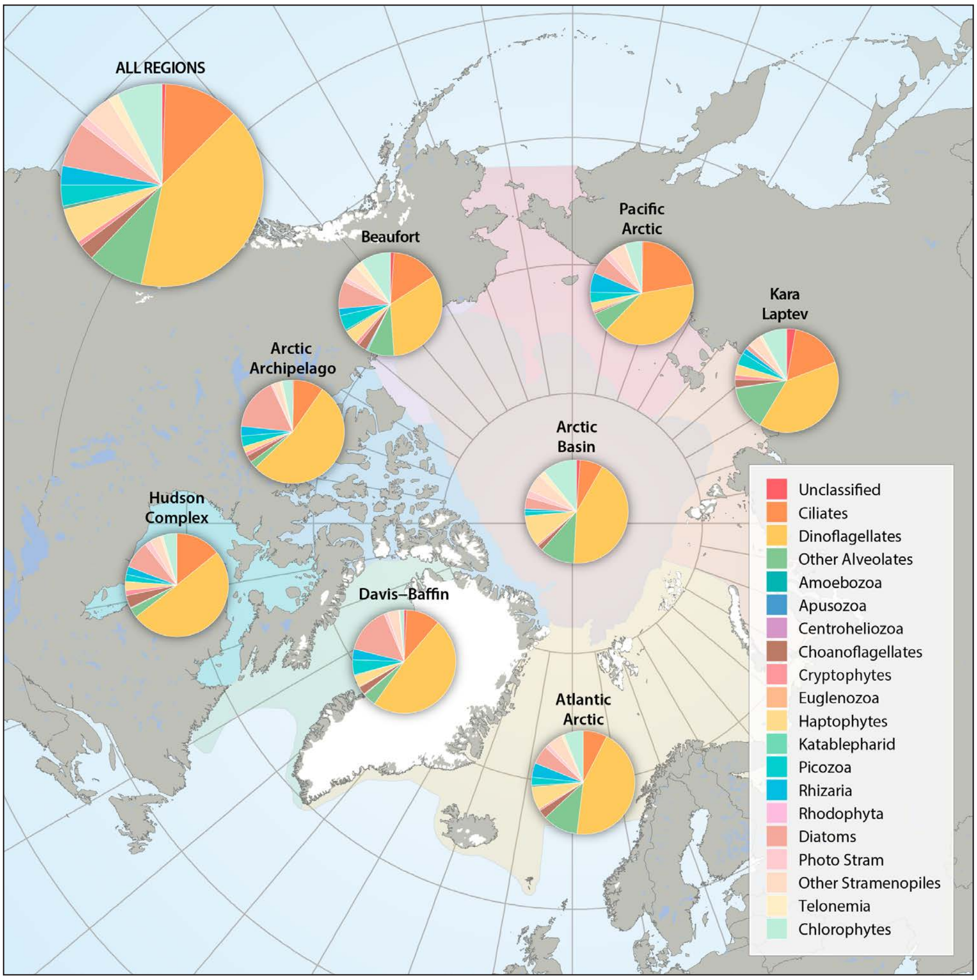


Figure 3.2.2a: Relative abundance of major eukaryote taxonomic groups found by high throughput sequencing of the small-subunit (18S) rRNA gene across Arctic Marine Areas.

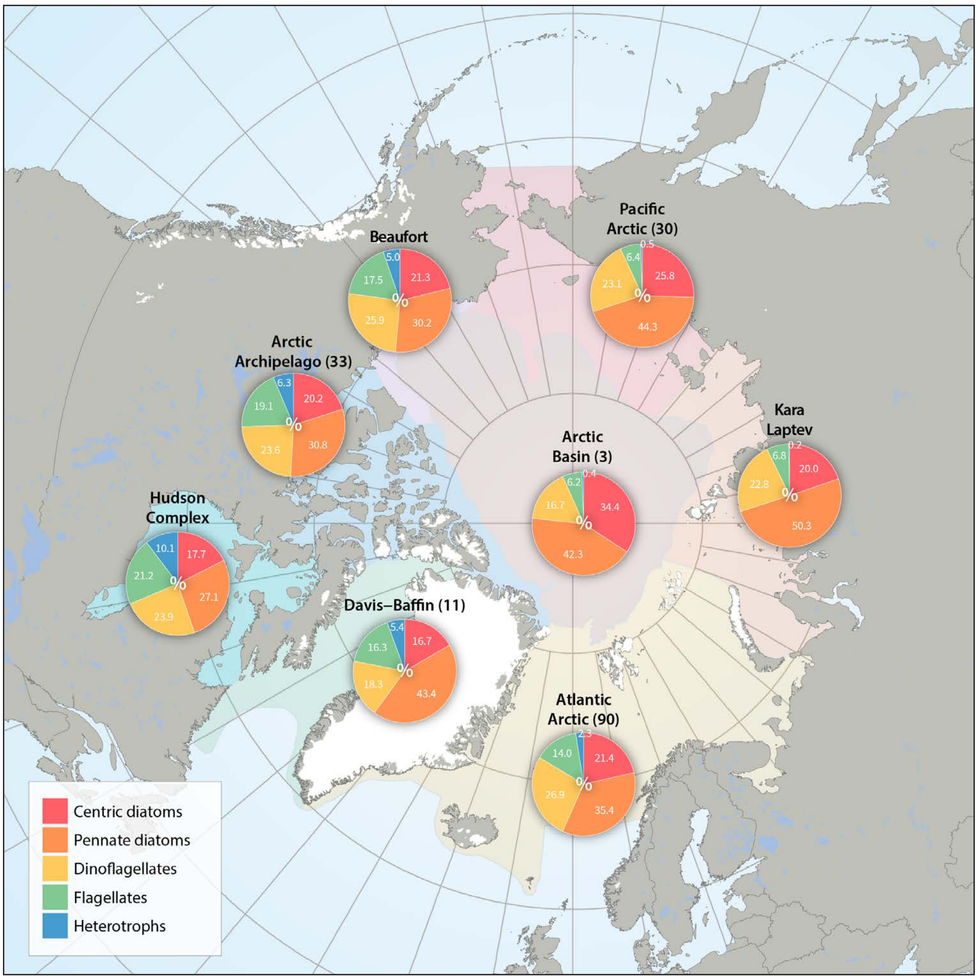


Figure 3.2.2b: Relative abundance of major eukaryote functional groups found by microscopy in the Arctic Marine Areas.

When a single site in the Amundsen Gulf was sampled monthly throughout a winter-spring period, a high degree of temporal structure emerged. Notably there was the gradual increase of haptophytes in the months leading up to the spring bloom, succeeded by an extreme dominance of diatom reads in mid-May and a dominance of chlorophytes in mid-June (Joli et al. 2017; Fig. 3.2.3). This study also highlighted the potential for viral control over the chlorophyte species, especially in winter.

Phytoplankton and larger protists

Traditional taxonomic data for phytoplankton have been recorded over much of the Arctic, but the bulk of knowledge is from Norway and Denmark (Greenland) which have a strong training record in phytoplankton taxonomy. Following up on Poulin et al. (2011) and the *Arctic Biodiversity Assessment*, records for phytoplankton species occurrences, which included other single-celled eukaryotes identified using microscopy, are updated here. The updated information on the phytoplankton sampling effort (Fig. 3.2.1b) and a compilation showing the phytoplankton inventory records for each designated area of the Arctic main regions (Fig. 3.2.2b) are shown. These regions follow the CBMP Arctic Marine Areas (AMAs): Arctic Archipelago, Hudson Complex, Davis Strait-Baffin Bay, Atlantic Arctic, Kara-Laptev, Pacific Arctic, and Arctic Basin. In an updated compilation (January 2016) the number of Arctic phytoplankton species records jumped from 1,874 taxa in 2011 to 2,241. The inventory or reporting effort of phytoplankton and other eukaryotes also reflects sporadic efforts to monitor certain regions in conjunction with other studies, for example the Barents Sea with 28 published papers, the Greenland Sea with 23 and the Svalbard region with 20. Outside of Scandinavian records, there have been 17 studies each for the Davis Strait, Hudson Bay (Canada) and the Laptev Sea (Russia), which are from more readily accessible sites that have been visited repeatedly. Inventories from the U.S. are mostly from the Chukchi and Western Beaufort Seas, corresponding to American territorial waters (Fig. 3.2.1b).

Few time series for microscopy records of phytoplankton are available to date. Most available data sets summarize major algal groups, with some information on the relative abundance of smaller groups. For example, there are records of algae collected from 2002 to 2013 at two stations in Eastern Canadian Arctic and two stations in Western Canadian Arctic. Other short-time series include data from ice-free Kongsfjorden and seasonally ice-covered Rijpfjorden in Svalbard (MOSJ and P. Assmy pers. comm.; Fig. 3.2.5a, b). Both fjords have been extensively sampled, especially during summer, and because of the complex hydrography of the Arctic and Atlantic currents around Svalbard the plankton occurring in fjords can be indicative of major changes in Arctic versus Atlantic currents. Arctic fjords are also indicators of melt, for example, in East Greenland waters the fjord assemblage close to the Greenland Ice Sheet is strongly influenced by the freshwater runoff in mid-summer (Krawczyk et al. 2015a). In general, the phytoplankton succession in the near coastal areas of Greenland is controlled primarily by ocean-fjord-glacier interactions (Krawczyk et al. 2015b).

Both Kongsfjorden and Rijpfjorden show inter-annual differences in taxonomic composition, abundance and biomass of phytoplankton during summer, but most taxonomic groups are present every year (Fig. 3.2.5a, b). Dinoflagellates, cryptophytes and other small flagellates from several different classes are among those often contributing to a great portion of the biomass. Diatoms are more common in spring (Hegseth and Tverberg 2013), but have also been recorded at greater depth during summer in Kongsfjorden, then often present as resting stages representing a post-bloom situation (Hasle and Heimdal 1998). According to Kubiszyn et al. (2014), impact from Atlantic inflow variability is not as clear as for the spring bloom in Kongsfjorden, but they concluded that the strength of Atlantic water inflow might also have consequences for the planktonic protist community structure in summer. Furthermore, they found that microplanktonic (ciliates and dinoflagellates) contribution was greatest in the warmest summers. A shift in phytoplankton community composition towards dominance of small-sized phytoplankton under warmer conditions has also been reported in Atlantic water masses west of Spitsbergen (Lalande et al. 2013). Of importance is also whether the inflow of Atlantic water into Kongsfjorden is along the bottom or near the surface (Hegseth and Tverberg 2013). Even though Rijpfjorden is a cold Arctic system during most of the year (January-July), transformed Atlantic water is recorded in the fjord during late autumn. Models suggest that this area north of Svalbard will become particularly affected by temperature increase because of increased advection of heat by the West Spitsbergen Current (Slagstad et al. 2011).

In recent years, the spring bloom in the Barents Sea has been dominated by diatoms, such as *Chaetoceros*, *Skeletonema*, *Thalassiosira* and the prymnesiophyte *Phaeocystis* (Kleiven et al. 2015). During summer, phytoplankton are often distributed in patches consisting largely of small flagellates and dinoflagellates (*Tripos* and *Gymnodinium*). In some years, species of diatoms (mostly *Chaetoceros* spp.) can be dominant during June-August.

Surveys indicate ongoing climate mediated changes, but that there are geographical differences. For example, less sea ice and an increase in atmospheric low pressure systems, which generate stronger winds (and deeper mixing of the upper ocean) as well as a warming and freshening of the surface layer, likely favours smaller species as observed in Canada Basin (Li et al. 2009) and Beaufort Sea of the Canadian Arctic (Ardyna et al. 2011, Tremblay et al. 2012). However, Terrado et al. (2013) found that some small-celled phytoplankton species may be specifically adapted to colder waters, and are likely to be vulnerable to ongoing effects of surface layer warming.

Zooplankton

Zooplankton have been sampled extensively, but not systematically, throughout the Arctic for over a century. True time series of consistently collected samples during the same season at the same locations are relatively rare. For zooplankton, they extend back to the 1960s in Iceland and Norway, but species level data only begin in the 1990s (Gislason and Ástþórsson 1998, Dalpadado et al. 2014), about

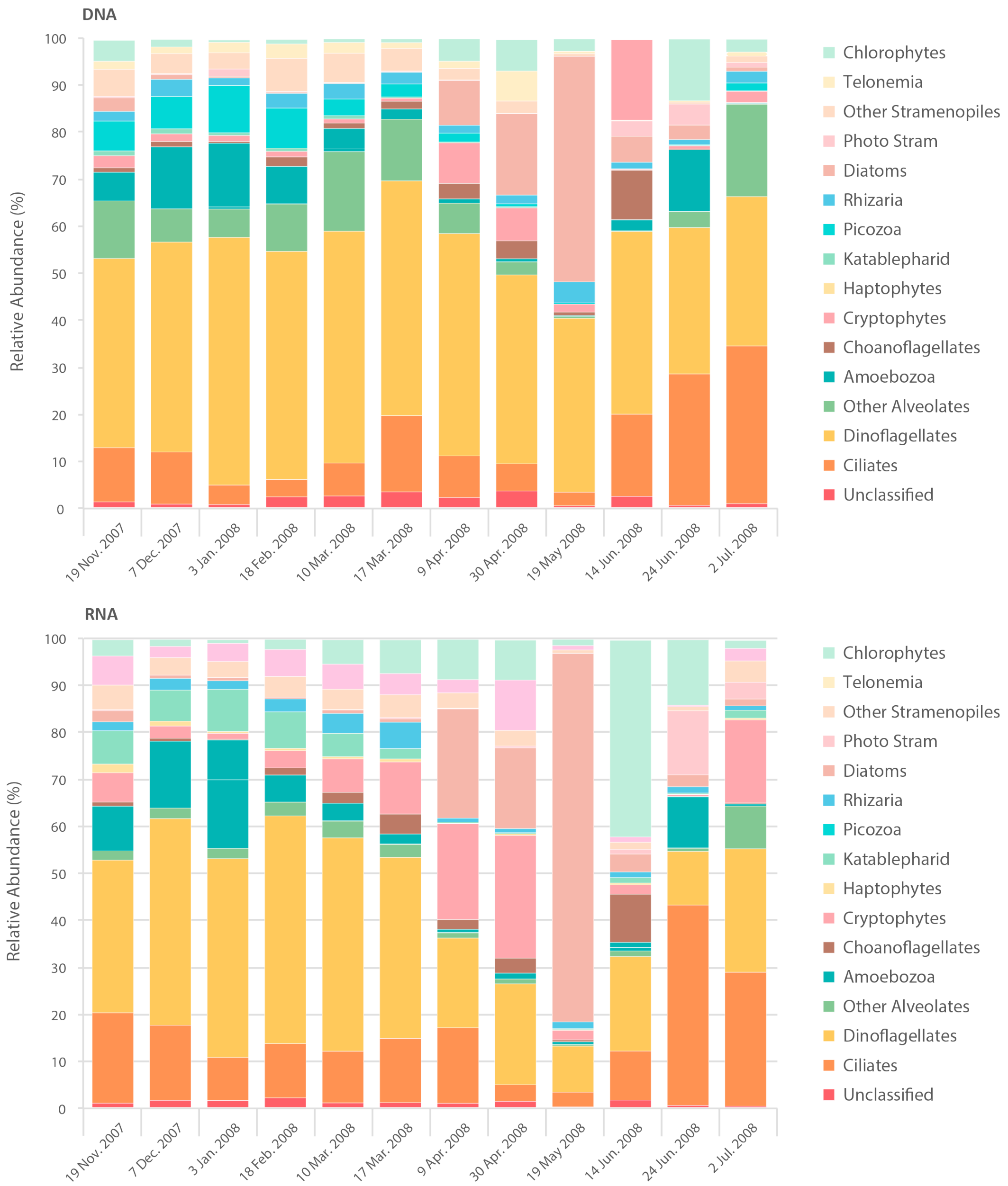


Figure 3.2.3: Relative abundance of major eukaryote taxonomic groups found by high throughput sequencing of the small-subunit (18S) rRNA gene. Time series collected by sampling every 2-6 weeks in Amundsen Gulf of the Beaufort Sea over the winter-spring transition in 2007–2008. Sampling DNA gives information about presence/absence, while sampling RNA gives information about the state of activity of different taxa.

the same time as time series began in Greenland, Canada and the U.S. (see Gill et al. 2011). Despite the relative recency of formal time-series, it is possible to assemble longer-term data for a few regions by pooling historical studies (e.g., Ershova et al. 2015b), although the CBMP Plankton Expert Network expects such time series to be inherently variable and consequently require a larger signal to detect change. Given the diversity and complexity of the Arctic, it is useful to consider separate systems related to their hydrography. As an inflow gateway, the Chukchi Sea has been sporadically sampled over nearly a century, with annual sampling for more than a decade. During this time, the extent and duration of open water has progressively increased. Recently, Ershova et al. (2015b) compiled much of the existing data on metazoan zooplankton to search for temporal trends, along with matching physical data to correlate with environmental forcing. The wide array of sampling gear employed across studies required the authors to focus on the larger copepod species that are captured with less bias across studies. Their analysis revealed that abundance of the four prominent large-bodied copepods (*Calanus glacialis*, *Eucalanus bungii*. *Metridia pacifica*, and *Neocalanus* spp.) in the Chukchi Sea had increased over the past 80 years. These increases correlated with temperature trends. While three of these species are considered Pacific expatriates, even the Arctic species *Calanus glacialis* had increased in response to regional warming (Fig. 3.2.6).

For Greenland, the abundance of *Microsetella norvegica* is strongly linked to the runoff from the Greenland Ice Sheet influencing the fjord environments in mid-summer (Arendt 2013). The abundance of the neritic copepod *Pseudocalanus* has declined while the abundance of the oceanic copepod *Microcalanus* has increased at Zackenberg. These data suggest that due to reduced sea ice and increased ablation of the Greenland ice sheet, the fjord is subjected to more flushing than in the early 2000s and that this has caused a change in zooplankton species composition (Arendt et al. 2016; Fig. 3.2.7.).

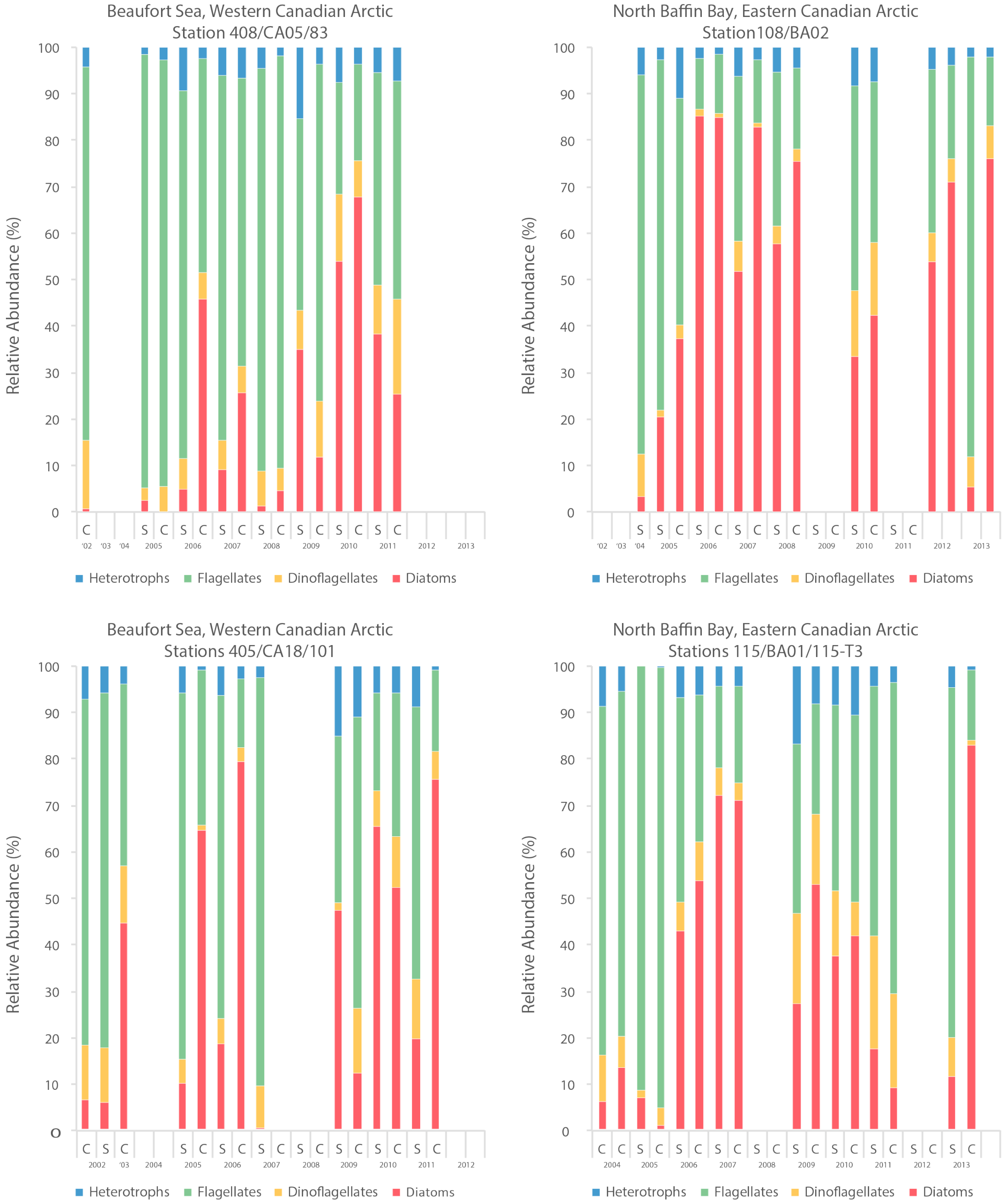


Figure 3.2.4: A time series of cell abundances, as determined by microscopy, of major phytoplankton groups from 2002-2013 for four sites, two in an east-west transect in Amundsen Gulf, Beaufort Sea and two in an east-west transect in northern Baffin Bay.

The zooplankton time series collected at a transect extending from the coast and across the shelf north of Iceland at the southern borders of the Iceland Sea shows that copepods are generally the most numerically abundant group (~40-70%) with the sub-Arctic *Calanus finmarchicus* as the most abundant species among the copepods (~20-60%; Fig. 3.2.8). The time series shows maxima in zooplankton abundance and biomass occurring approximately every five to 10 years (Marine Research Institute 2015). Also striking is the collapse in zooplankton biomass during the cold period in the North Atlantic and to the north of Iceland in the 1960s and it was not until the warm period in the 1990s that biomass levels recovered. These longer-term records indicate that zooplankton biomass variability and species composition to the north of Iceland are positively related to temperature, reflecting the inflow of Atlantic water into the area (Ástþórsson et al. 2007, Gislason et al. 2009, 2014). Ástþórsson and Gislason (1998) showed that the zooplankton biomass is almost two times higher in warm years than in the cold years. This may reflect the better feeding conditions for the zooplankton due to increased primary production, advection of zooplankton with the Atlantic Water from the south, and faster temperature-dependent growth of the zooplankton in warm years. Data from ships of opportunity fitted with Continuous Plankton Recorders (CPR) would be valuable for documenting such relationships, but these records are rare in the Arctic (Beaugrand 2015).

In Kongsfjorden, Svalbard, the abundance of *Calanus finmarchicus* and *C. glacialis* varied from year to year with periods of more or less equal abundance of the two *Calanus* species interspersed with periods when either the cold-water associated *C. glacialis* or the warm-water associated *C. finmarchicus* dominated (MOSJ, 2015). The larger *C. hyperboreus*, an Arctic deep-water species, is only present in low numbers in Kongsfjorden and contributes little to the total abundance of *Calanus*. Lower water temperatures characterize years with *C. glacialis* dominance whereas

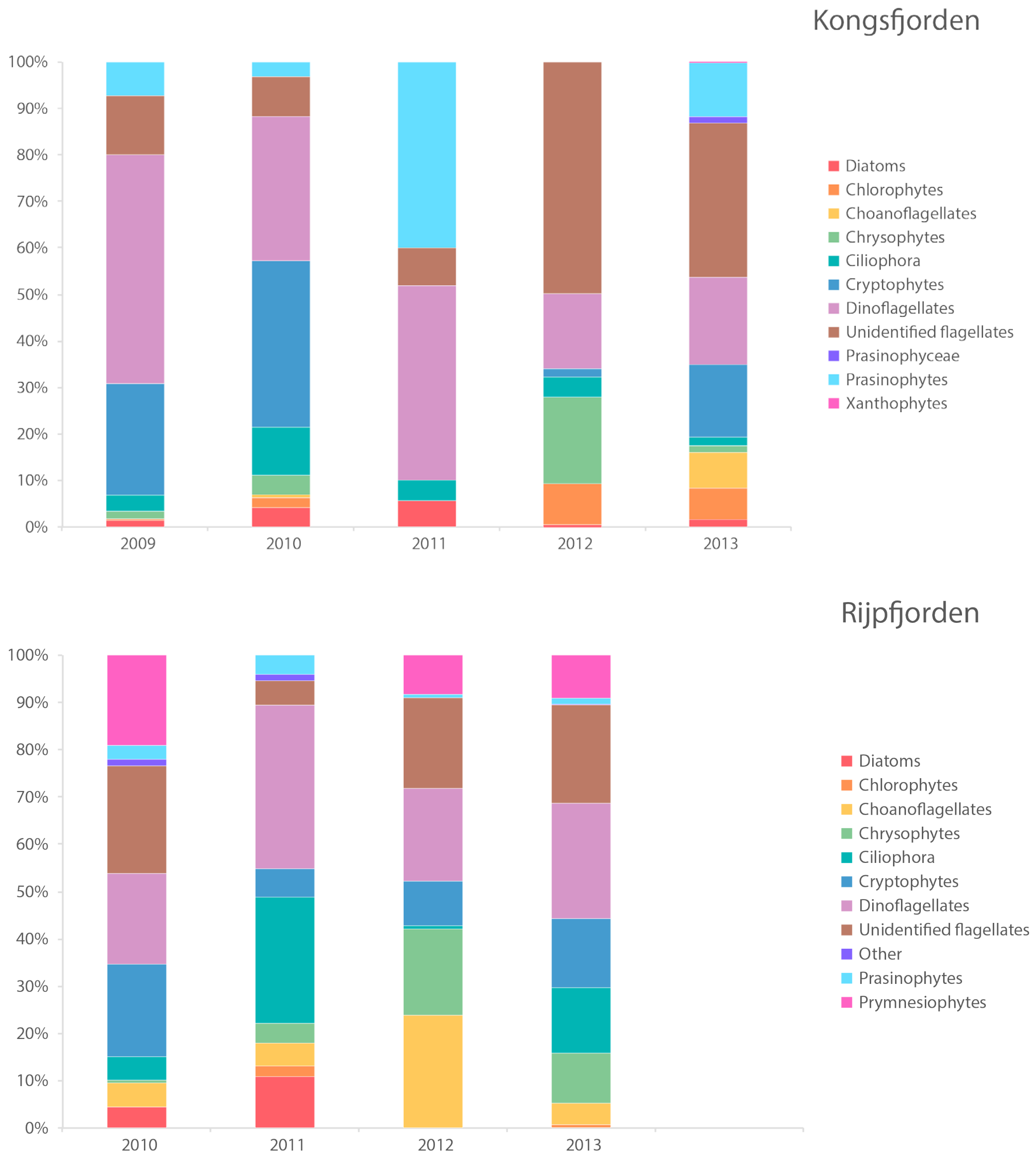


Figure 3.2.5: Interannual differences in taxonomic composition of phytoplankton during summer in a) Kongsfjorden and b) Rijpfjorden (Source: MOSJ, Norwegian Polar Institute).

dominance of *C. finmarchicus* usually coincides with periods with increasing water temperatures (Fig. 3.2.8a). Research from Rijpfjorden, considered a true Arctic fjord, shows that *C. glacialis* contributes a larger proportion than *C. finmarchicus* inside the fjord, with the latter dominating outside the fjord within the Atlantic water masses. The increase of *C. finmarchicus* in 2007 coincided with a massive influx of warmer water from the shelf areas north of Rijpfjorden, indicating that intrusion of Atlantic water into the fjord sustains its population (Fig. 3.2.8b).

The Arctic *C. glacialis* has decreased further south in the Barents Sea, while *C. finmarchicus* is more stable, but fluctuates from year to year (van der Meeren et al. 2014). Furthermore, a gradual decrease in the quantity of zooplankton has been observed recently in the Norwegian part of the Barents Sea. Typical cold-water species, such as the amphipod *Themisto libellula*, has decreased, whereas the more Atlantic *T. abyssorum* has increased in both the Barents Sea and Fram Strait (Advisory Forum on Monitoring and Institute of Marine Research 2015). In addition, southerly euphausiid species such as *Meganyctiphanes norvegica* and *Nematoscelis megalops* are occurring in the Barents Sea (Eriksen et al. 2016).

3.2.4 Drivers of observed trends

By far the most relevant driver influencing plankton in the Arctic is changes in the climate system, which has a major influence on currents in the Arctic, with impacts on the plankton community. Climate also affects the duration of open water versus seasonal sea ice and the extent of seasonal ice cover. Deeper wind-driven mixing during an extended open water season could favour smaller species of phytoplankton due to lower average light levels in the resulting deeper mixed layer. Increased freshwater in the surface could also shift species composition to species with wider salinity tolerances, replacing the marine Arctic species. The seasonal extent of ice cover is relevant to the timing and duration of the spring bloom and the species of phytoplankton that may be favoured, with small flagellates able to begin growth earlier in the year, because of their ability to use lower light levels compared to diatoms. Early blooms of flagellates such as *Phaeocystis* would tend to draw surface nutrients down leaving little for diatoms that are better adapted to higher light levels near the summer solstice. Similarly, as the major remineralizers in this ecosystem, bacteria also experience some seasonal fluctuations.

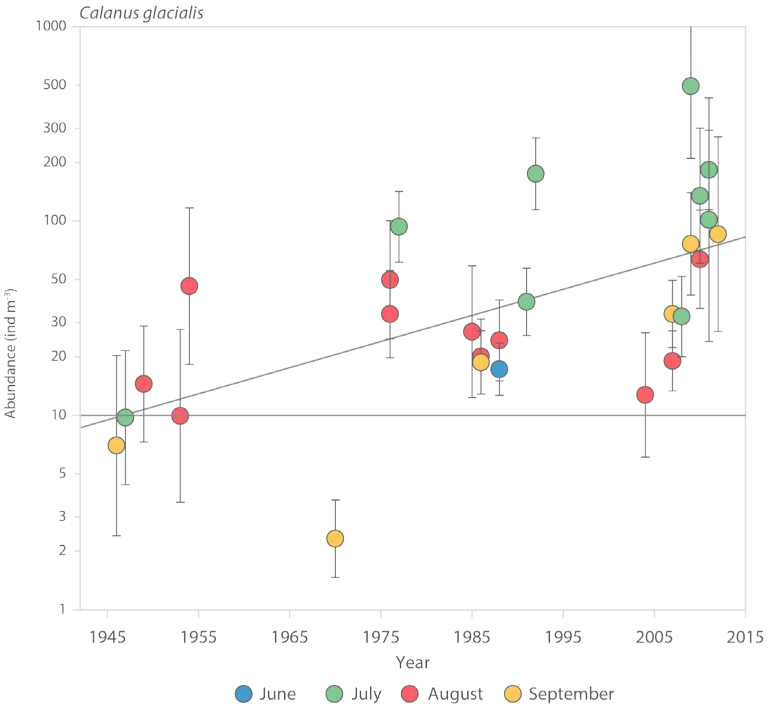


Figure 3.2.6: Abundance of the copepod Calanus glacialis *in the Chukchi Sea, 1945-2012 (after Ershova et al. 2015b).*

The ***duration and extent of ice cover*** impact the larger zooplankton that have life cycles closely tied with spring maximum phytoplankton production, when they rapidly grow and accumulate lipids for the long winter. Depending on the species and quantity of lipid reserves, they may have an annual life cycle or reproduce after two or three years. Zooplankton communities living in deep water likely still experience some seasonality due to higher fluxes of surface production into the deep ocean shortly after spring maximum. Although climate change can result in increased water temperatures in the upper water column (10-20 m) of the polar mixed layer, the deeper layers show little seasonal or long-term variability. Consequently, changes in the timing, magnitude, and total annual productivity of the phytoplankton and microzooplankton, which include ciliates and dinoflagellates that compete with zooplankton as grazers but are also sources of food, are thought to have the greatest potential impact on metazoan zooplankton.

A scenario of increased annual production from a longer and more spatially extensive ice-free summer could be expected to enhance zooplankton productivity. Concurrently, shifts in the seasonal timing (phenology) of species life-history traits can be anticipated. Such enhanced secondary productivity has been shown to operate in the North Water Polynya (Ringuette et al. 2002) and more recently suggested as the cause of long-term increases in zooplankton in the Chukchi Sea (Ershova et al. 2015b). More open water, with an extended duration, may favour stronger wind events that increase upwelling in autumn and therefore add nutrients to surface water that act to precondition the extent of the following spring bloom. However, in other regions of the Arctic, such as the Canada Basin and large parts of the Beaufort Sea, no net increase in productivity is expected because early ice melt would increase stratification and prevent nutrient input into the euphotic zone (Monier et al. 2015). A region-specific, lower annual production could have a consequent effect on zooplankton productivity.

3.2.5 Knowledge and monitoring gaps

Approach to monitoring temporal and spatial changes

Traditional Knowledge (TK)

Because of the small mostly invisible nature of plankton, there is likely only indirect Traditional Knowledge (TK) on plankton across the Arctic. TK that might be related would include narratives of brown water consistent with high biomass blooms of diatoms, *Phaeocystis* or pelagophytes, feeding frenzy by cod or other vertebrates, indicative of zooplankton or larval concentrations. Local reports of "red feed", dense aggregations of copepods, off the coast of Norway could provide a long-term record of *Calanus finmarchicus* populations (Wiborg 1976). Reports of episodes or seasonal occurrence of strong sea smell would also be consistent with high dimethylsulfoniopropionate (DMSP) concentrations indicative of phytoplankton blooms. There are also records of jellyfish piled upon beaches. Such knowledge needs to be recorded.

Traditional net hauls and microscopy

Biological collections to create basic planktonic species inventories for Arctic waters can be traced back to some of the earliest science expeditions over a century ago. For example, quantitative zooplankton data in the Pacific Arctic began in the 1930s (e.g., Johnson 1934, Stepanova 1937a, b) and noted the significant influence of Pacific fauna in the Chukchi Sea. The use of what are now considered coarse meshes (i.e., 50-100 µm, for phytoplankton and 0.5-1 mm for zooplankton) severely biased our historical impression of community composition. For phytoplankton, only larger species or groups with robust cell walls, such as thecate dinoflagellates and diatoms, would have remained intact

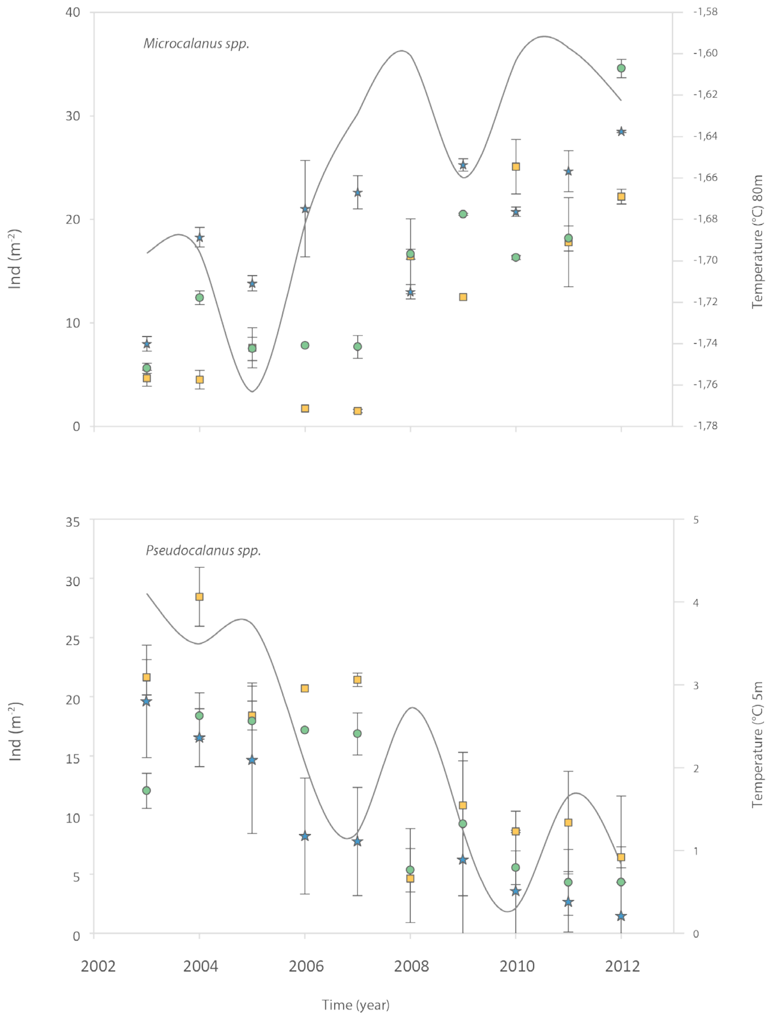


Figure 3.2.7: Temperature and copepod abundance in Zackenberg, northeastern Greenland. Temperature is measured at 80 m for Microcalanus *and 5 m for* Pseudocalanus *(Arendt et al. 2016).*

after the rough handling and use of harsh preservatives at that time. Lack of standardized collection tools, especially mesh size for zooplankton and nets versus whole water samples for phytoplankton, collection depths, and inconsistent sampling locations (see maps in Gill et al. 2011) has greatly hampered attempts to assemble and interpret data. Changes in taxonomy, particularly the splitting or merging of species, have further complicated analysis. Consequently, although zooplankton have been extensively sampled over many regions of the Arctic, basic maps of species distribution and abundance are not readily available and are only now emerging for the some of the larger and most prominent crustaceans.

The inflow gateways have always contained large numbers of expatriated species from the Atlantic or Pacific that are considered to be non-viable in the Arctic (Nelson et al. 2009, Wassmann et al. 2015). While there is some indication that the prominence, penetration and duration of expatriate zooplankton species are increasing (Weydmann et al. 2014, Ershova et al. 2015b, Kristiansen et al. 2016), it is still thought that the sub-zero temperatures that occur during winter will make it difficult for non-Arctic species to gain a permanent year-round presence. The situation for microbes and phytoplankton is unknown. Late-summer and mid-winter sampling programs at coastal communities would be useful to test these assumptions. Metagenomic approaches may provide practical means of assessing shifting biodiversity as well as the presence of invaders.

Future directions

The CBMP Plankton Expert Network will continue to search out existing data (see below), while encouraging Arctic nations to extend existing time series and fill in regions were data is sparse. Standard microscopy has been used to monitor larger phytoplankton (Canada, Norway, Svalbard, and Greenland), and remains the method of choice in most zooplankton studies. Microscopy is the practical choice for larger planktonic groups, as the equipment needed is readily available and not technically complex. However, comparability of data from different laboratories requires taxonomic expertise, which is becoming rare. An alternative or complement to microscopy identification is the use of marker genes to identify species, although this approach requires infrastructure and access to sequencing facilities. Comparative molecular studies on a pan-Arctic scale would also benefit from the harmonization of classification systems. The utility of molecular approaches depends on curated reference databases, which are now becoming increasingly populated. In principle, zooplankton species can be identified provided suitable markers are found, and at finer levels different populations of the same species have been mapped (Nelson et al. 2009, Questel et al. 2016).

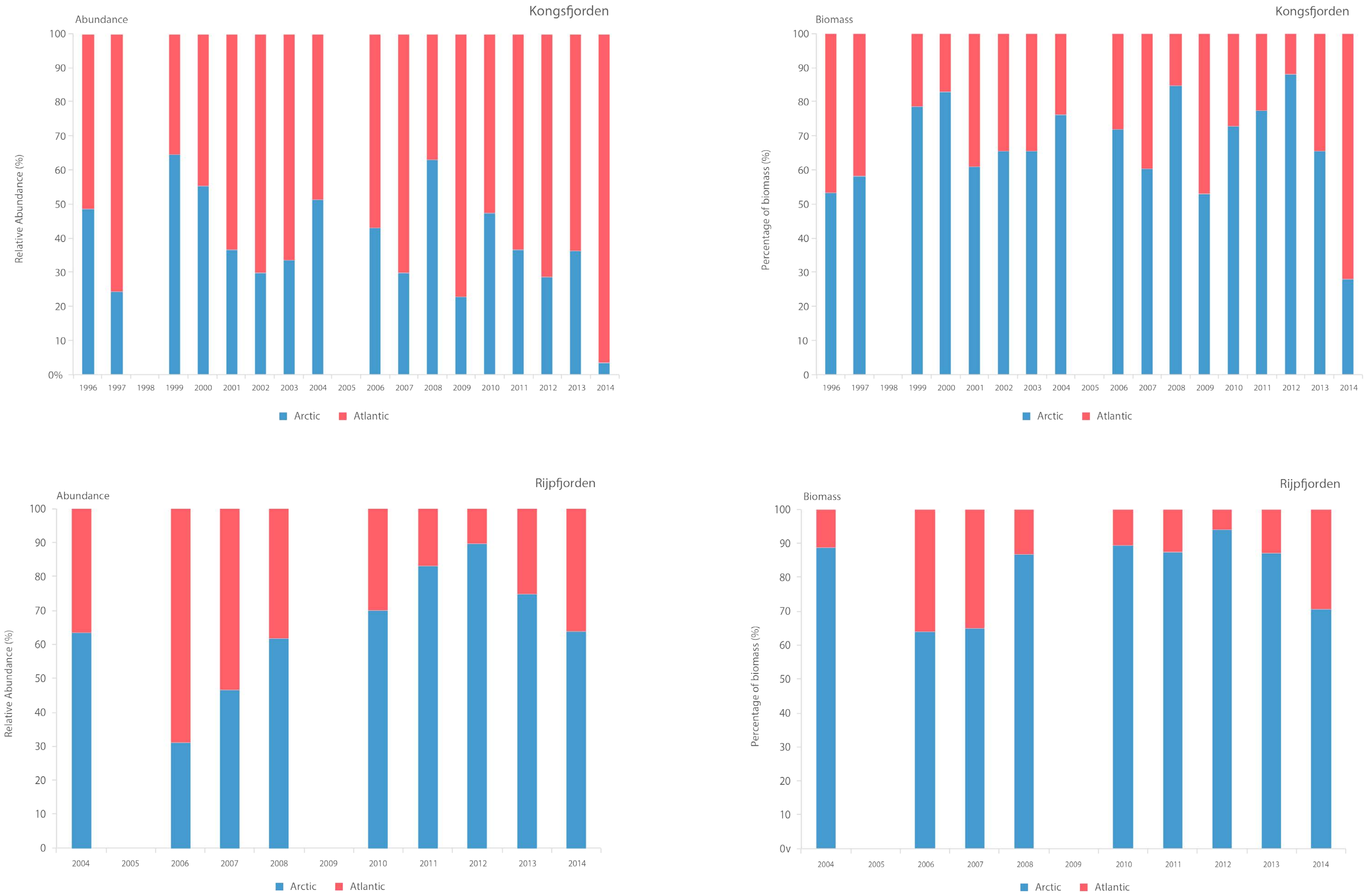


Figure 3.2.8: Time series of relative proportions of Arctic and Atlantic Calanus *species in Kongsfjorden (top) and Rijpfjorden (bottom) (Source: MOSJ, Norwegian Polar Institute).*

The recent advent of high through-put multiplex sequencing, where many samples can be analysed simultaneously, will facilitate monitoring of the smallest species. Although uptake of these methods into long-term monitoring protocols has been slow, standardized protocols are being developed (C. Lovejoy pers. comm.). The CBMP Plankton Expert Network recommends the use of both traditional visual identification and, particularly for the unicellular groups, molecular approaches to determine biodiversity. The persistent water mass layering of Arctic seas and the close coupling between microbial communities and water masses (Monier et al. 2013) suggest that monitoring could be based at key easily accessed sites and depths. For instance, for phytoplankton, the CBMP Expert Network suggests sampling in focal regions with a history of monitoring using Niskin-like bottles targeting samples collected from the surface and at the subsurface chlorophyll maximum depths. By knowing the basic oceanography of those areas, results can be extrapolated over larger areas. Over the last 10 years the CBMP Plankton Expert Network has worked towards identifying key plankton species that are indicative of the state of the ecosystem and have relevance to other biological FECs. The CBMP Plankton Expert Network will continue to develop species distribution indices, using the approach exemplified in Luddington et al. (2016), with defined Arctic and Boreal-Arctic species complexes.

Currently there is little (or no) monitoring of the vast majority of single-celled species, with most information available on the occurrence of zooplankton, especially larger calanoid copepods. Some (incomplete) time series exist for phytoplankton (cell abundance and biomass) in the Beaufort Sea and Baffin Bay from roughly 1999 to present and from the Barents Sea from 2005 and Svalbard, but inferring change from such sporadic samplings is difficult. These limited time series suggest trends, but it is not clear whether zooplankton species are following or leading the same climate-mediated trends detected in fish and mammal species distributions. In addition, our analysis of the relatively scant species data available for single-celled plankton, especially phytoplankton and heterotrophic protists, indicate that they too are influenced by climate-driven change and species data would contribute to the understanding of ecosystem status. It can be argued that changes at the base of the food web would be the first sentinel signals of overall ecosystem shifts.

Significant amounts of old data still need to be recovered, especially for zooplankton. Historical data are invaluable in extending the window of observation backward at a faster pace, and at lower cost than what we gain by moving forward. For older data, the major limitation is locating the station-resolved data, either in researcher's unpublished notes or the grey literature. While many older projects are published, the tendency to average data when preparing publications, and ignoring rarer taxa, makes the data that can be recovered of limited value for modern reanalysis. The significant changes that have occurred in taxonomy of zooplankton over the last century, and interest in examining shifts in phenology, further suggest that existing historical collections should be re-examined to resolve their species and life-stage composition. The greatest challenge in existing contemporary data sets remains a commitment of funds to keep these time-series operating.
While it is possible to look for synchronicity in trends across datasets, it is difficult to pool them into a quantitative analysis if they differ in collecting or processing protocols. Efforts should continue to standardize methods across researchers, with more opportunities for different research groups to interact. However, if dominant species changes are reported that are dramatically different from historical records, this would be a good indication of regime changes or crossing a tipping point (Wassmann and Lenton 2012). While summer through late-summer provides little information on the dominant spring bloom species, it is a period when species composition can be less variable—at least in the Beaufort Sea (Comeau et al. 2011). However, given the importance of the timing and extent of ice melt to stratification and light penetration there is a need to better understand early season bloom dynamics that may set the stage for the remainder of the growing season. Broader seasonal sampling is needed to establish baselines and detect possible trends in species composition. Summer

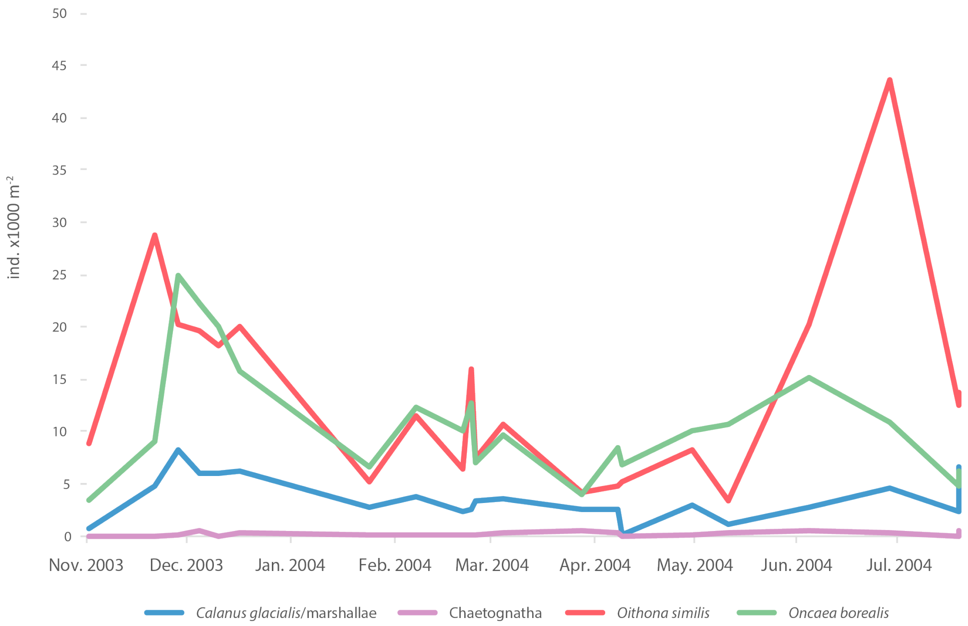
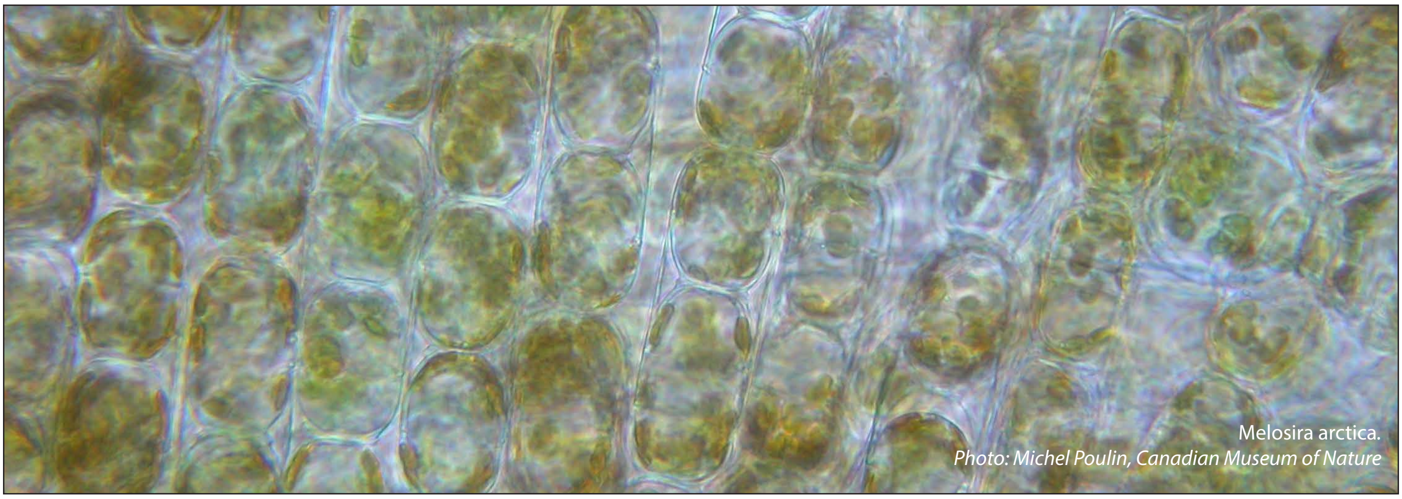


Figure 3.2.9: Seasonal time series of the major zooplankton in Franklin Bay, Canada.



Melosira arctica.
Photo: Michel Poulin, Canadian Museum of Nature

sampling is more acceptable for zooplankton monitoring, given the large existing data records, but some late-summer and autumn sampling would be useful for exploring phenological changes in life-stages.

In closing, most planktonic studies are concentrated around summer and early autumn. While drifting ice stations have provided year-round observations over the basins (e.g., Kosobokova 1982, Ashjian et al. 2003), except for Svalbard and the Barents Sea, the shelves are comparably understudied during winter. Recent observations from Franklin Bay in the Canadian Beaufort Sea (Fig. 3.2.9) (Darnis and Fortier 2014) and Svalbard fjords (Berge et al. 2015, Grigor et al. 2015) suggest that winter is a more active period than previously believed. Thus, more attention and monitoring should be carried out in winter. Working from research stations with easy access to the sea could facilitate year-round studies of some species provided field-ready infrastructure becomes available.

Access to data

Smaller, single-celled eukaryotes have been studied using molecular techniques with data mostly targeting variable regions of the 18S rRNA gene. The majority of this work has been carried out in Canadian waters, but with the cost of sequencing and development of easy to use bioinformatics pipeline, many more regions are being sampled at least once. However, except for ArcticNet regions sampled since 2005 in the Beaufort Sea and northern Baffin Bay, the Canada Basin since 2012 and more recently around Svalbard (Norway) (Vader et al. 2015, Marquardt et al. 2016), most studies report only one or few isolated samples. The majority of the raw data are available in archives such as GenBank Sequence Read Archive (SRA), and for most journals that publish such studies, it is required that data should they be publicly available. In terms of stations sampled, the greatest sampling effort of high through-put sequencing in Arctic marine water columns have been in the Beaufort Sea/ Amundsen Gulf region and around Svalbard. High through-put sequencing has also been used on samples from the Chukchi Sea, Canadian Arctic Archipelago, Baffin Bay, Hudson Bay, the Greenland Sea and Laptev Sea. For net-based sampling of phytoplankton and zooplankton, there is still no universal repository for data, either globally or for the Arctic specifically. Clearer policies on data release and incentives for release of older data appear warranted.

3.2.6 Conclusions and key findings

The functional and taxonomic diversity of microbes in the Arctic is vast and a scientifically underappreciated source of biodiversity.

Phytoplankton are a species-rich domain of the Arctic marine environment, containing half of the diversity reported for the world oceans. Heterotrophic and mixotrophic species are similarly diverse, with many species likely restricted to Arctic waters.

Plankton are the base of the Arctic marine food web, and knowledge of species distributions over space and time is inadequate despite the fact that changes at the base of the food web will be the first sentinel sign of overall ecosystem shifts. More information is essential for our understanding of ecosystem structure and processes and, thus, relevant for ecosystem-based management of ocean areas.

Changes in the hydrography will have a profound effect on the species living in the Arctic due to their intimate relationship with physical oceanography and specific water masses.

The lack of taxonomic information from bulk zooplankton and chlorophyll sampling during recent decades impedes our ability to assess ecosystem changes in the Arctic. Species-specific information is essential for monitoring community changes driven by climate.

With Arctic governments increasingly interested in the Arctic region, both geopolitically and as an indicator of climate change, there are initiatives to build and run research stations year-round. A key consideration for site selection should be access to the sea and inclusion of full-spectrum plankton monitoring.

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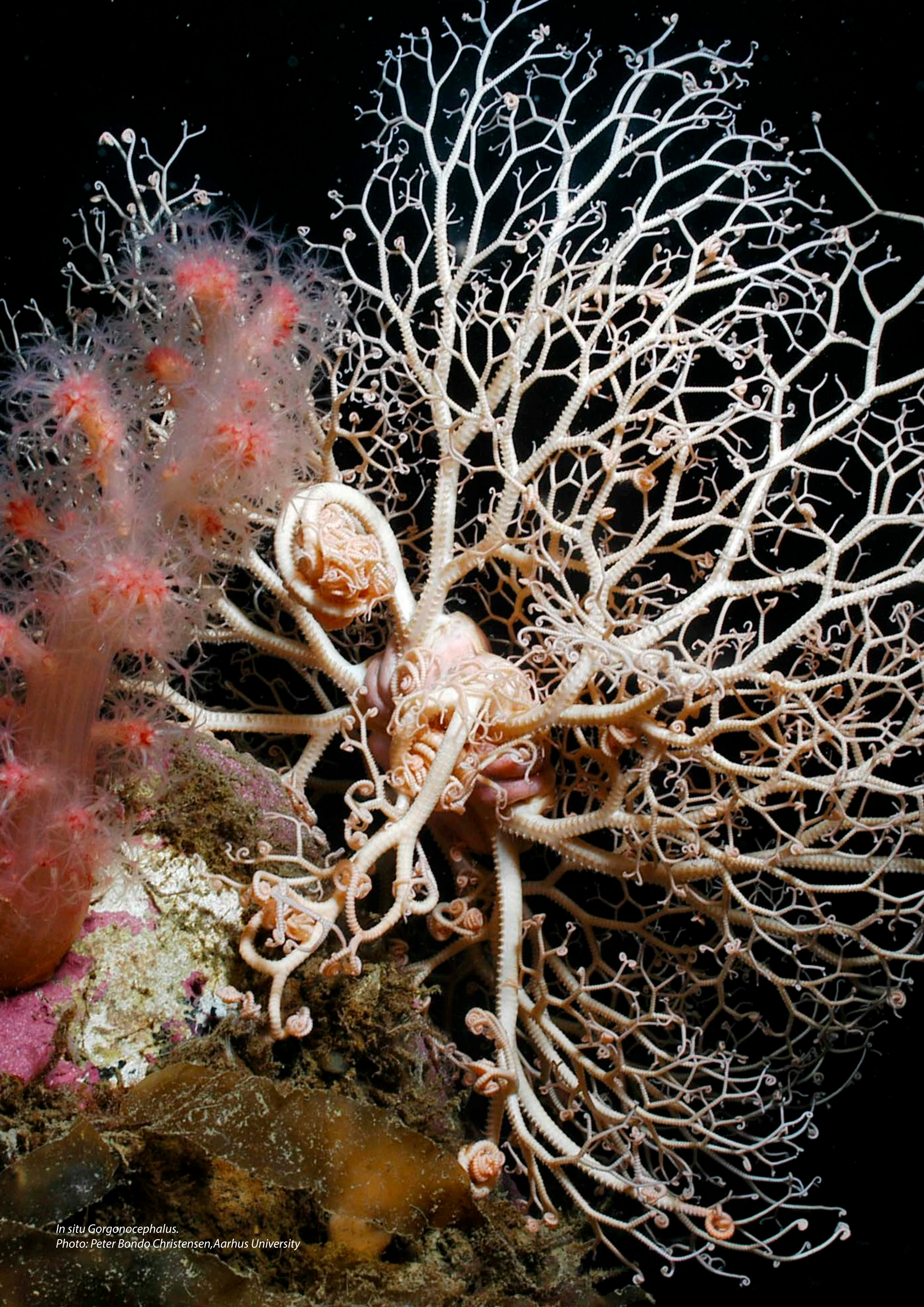

In situ Gorgonocephalus.
Photo: Peter Bondo Christensen,Aarhus University

3.3 Benthos

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Snapshot

- Currently, > 4,000 Arctic macro- and megabenthic species are known, representing the majority of Arctic marine faunal diversity. This estimate is expected to increase.
- Benthic invertebrates are food to fishes, marine mammals, seabirds and humans, and are commercially harvested.
- Traditional Knowledge (TK) emphasizes the link between the benthic species and their predators, such as walrus, and their significance to culture.
- Decadal changes in benthos biodiversity are observed in some well-studied regions, such as the Barents Sea and Chukchi Sea.
- Drivers related to climate-change such as warming, ice decline and acidification are affecting the benthic community on a pan-Arctic scale, while drivers such as trawling, river/glacier discharge and invasive species have significant impact on regional or local scales.
- Increasing numbers of species are moving into, or shifting, their distributions in Arctic waters. These species will outcompete, prey on or offer less nutritious value as prey for Arctic species.
- Current monitoring efforts have focused on macro- and megabenthic species, but have been confined to the Chukchi Sea and the Barents Sea. Efforts are increasing in waters of Greenland, Iceland, the Canadian Arctic, and in the Norwegian Sea. All other Arctic Marine Areas are lacking long-term benthic monitoring.
- As a first step towards an international collaborative monitoring framework, we recommend to develop a time- and cost-effective, long-term and standardized monitoring of megabenthic communities in all Arctic regions with regular annual groundfish assessment surveys. Expanding monitoring on micro-, meio- and macrobenthic groups is encouraged.

3.3.1 Introduction

The seabed environment includes a great variety of physically diverse and biologically distinct habitats that, collectively, add to regional biodiversity of benthic fauna. Large spatial and temporal variation in community structure of benthic fauna is related to water depth (from shallow intertidal zones to the deep abyss), currents, temperature, food availability, irradiance, and type of substratum, ranging from hard and rocky, to soft, muddy floors (e.g., Gray 2002, Piepenburg 2005). Sea ice is an additional environmental driver that influences benthos, because it modifies hydrographic features, scours in shallow water, and affects primary production, amongst other effects (Sejr et al. 2009). Arctic benthic fauna act as long-term integrators of overlying water-column processes because of life spans on the order of years or decades (e.g., Sejr et al. 2002, Blicher et al. 2007). Although some benthic organisms are mobile, many remain relatively stationary on or in bottom sediments and their community patterns are thus directly affected by local hydrographic conditions and the export production regime from the overlying water column (Roy et al. 2014). Consequently, the distribution, abundance and biomass of benthic invertebrate species vary on multiple spatial scales. Benthic organisms are key components of remineralization processes (Blicher et al. 2009, Link et al. 2013 a, b) and also provide an important food source to higher trophic levels, such as many fishes, seabirds and marine mammals (Stirling 1997, Born et al. 2003, Bluhm and Gradinger 2008, Blicher et al. 2011). Despite their importance in Arctic food webs and other functional roles in the ecosystem, relatively little is known about diversity of some taxonomic groups and regions, distributional patterns, and the environmental factors that may drive benthic invertebrate community patterns across larger spatial extents, especially on a pan-Arctic scale.

Benthic invertebrates live within the sediment (infauna) or are either attached or move along the seafloor (epifauna) or inhabit the water column just above the bottom (supra- or hyperbenthos). Benthic invertebrates are typically divided into size categories: organisms that can be identified from seafloor photographs or are caught by trawls (megafauna); organisms > 1.0 mm (macrofauna); organisms that are 0.1–1.0 mm (meiofauna); or organisms < 0.1 mm (microfauna). Members of all these groups comprise the full diversity of benthic communities. A wide range of different types of specialized sampling gears, including trawls, corers, grabs, remotely operated vehicles (ROV), and scuba diving, are needed to sample all faunal components and/or a given habitat appropriately (see Eleftheriou 2013).

Standardization across gears is rather challenging, as slight differences in even the same gear types can cause differences in catch efficiencies. It also is often not possible to apply the full suite of different sampling gear types at a given location to gather a complete range of benthic organisms. For these reasons, the compilation presented here includes only the subtidal mega- and macrofauna, for which the most complete data are available on the pan-Arctic scale. However, meio- and microfauna are also discussed in the Arctic Basin section of this chapter. The exclusion of the smaller-sized benthic components (meio- and microfauna, but see "Arctic Basins") greatly underestimates the actual number of benthic invertebrate species in the Arctic Ocean, but this provides the most practical approach at this time due to the feasibility, capacity and logistical focus of many biodiversity studies on epibenthic fauna for monitoring purposes.

This chapter has two major purposes; first to utilize existing benthic biodiversity information (from grab, box core, benthic trawl, dredge and sledge methods) to map biodiversity (Box 3.3.1), status and trends (Fig. 3.3.4-3.3.6). Second, to use megafaunal data from bottom trawls to establish a current reference state (Box 3.3.2) against which future changes (Fig. 3.3.2) can be compared for eight Arctic Marine Areas (AMAs) defined by the Circumpolar Biodiversity Monitoring Program (CBMP). Currently, data collected via annual fish assessment surveys are the most comprehensive data sets (spatially and temporally); therefore, monitoring recommendations on a Pan-Arctic scale are restricted to such megafaunal data. The CBMP Benthos Expert Network recommends to develop a collaborative, cost-effective, long-term and standardized monitoring of megabenthic communities in all Arctic regions with regular annual groundfish assessment surveys.

3.3.2 Current monitoring

Present state of knowledge – species richness and sampling effort

Benthic investigations in the Arctic started centuries ago and include the British expeditions of the *Lightning* and *Porcupine* (1860-1880), the Norwegian *Michael Sars* expeditions, and the early Danish expeditions of the *Ingolf* (1895-1896), *Thor* (1903) and *Dana* (1920-22). Together, these early investigations provided considerable taxonomic knowledge of Arctic benthic invertebrate fauna. Initially the primary goal was to register new species, but since the 1920s the quantification of biomass, abundance, and species richness became more important (Zenkevich 1963). Recent estimates of total species richness in the Arctic suggest that benthic invertebrates comprise >4000 species (CAFF 2010).

To date, the most studied areas are the Chukchi Sea and the Barents Sea, while information about fauna in other areas such as the Canadian Arctic Shelf and the Greenland region was limited until recently, and is still sparse for some groups including the central Arctic, Faroes Archipelago and Iceland (Box 3.3.1 and 3.3.2). A lack of consistency and methodological standardization has been recognized as a major obstacle to assess large-scale (from regional to pan-Arctic) and long-term dynamics in benthic communities (Bluhm et al. 2011, Piepenburg et al. 2011, Weslawski et al. 2011), although it is generally accepted that this information is urgently needed to assess effects of anthropogenic activities and a changing environment. To foster pan-Arctic comparisons of benthic species assemblages, the CBMP Benthos Expert Network presents historical baselines per region and describes current sampling activities, which are cornerstones towards establishing a coordinated pan-Arctic long-term monitoring plan.

Small amphipod with Chaetognath.
Photo: Liz Lindal Jørgensen

Megafauna bottom trawl results from the Chukchi Sea shelf near the Canada Basin including sea stars, brittle stars, clams, some snails and crabs.
Photo: Bodil Bluhm, University of Alaska Fairbanks

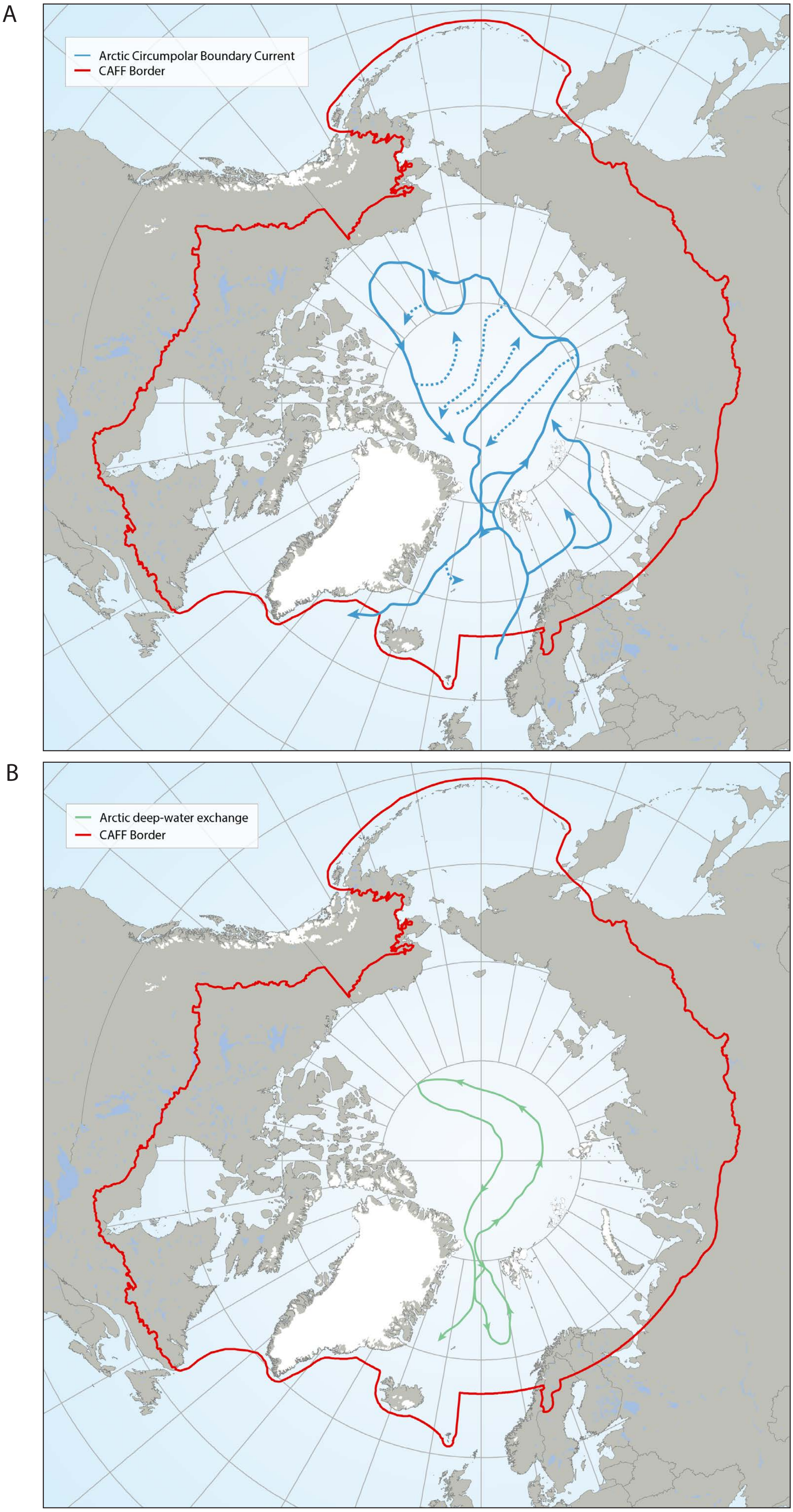
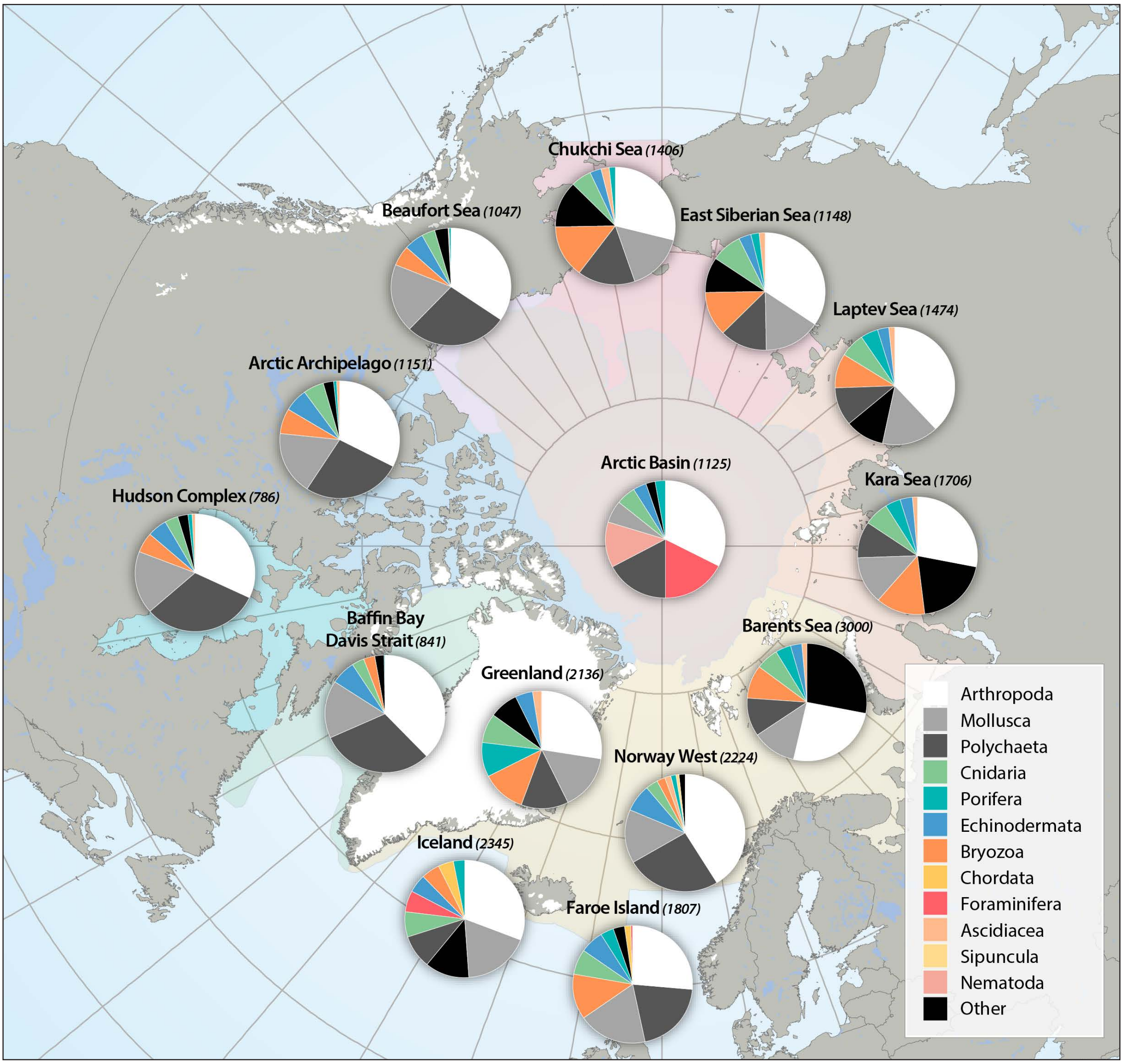


Figure 3.3.1. The Arctic Basin where suggested future long-term monitoring of trawl-megafauna should capture possible changes along the flow of the Arctic Circumpolar Boundary Current (Figure A, blue line) and the Arctic deep-water exchange (Figure b, green line). Adapted from Bluhm et al. (2015).

Box 3.3.1: Benthic macro- and megafauna

Distribution of major benthic invertebrate groups in the Arctic

Arthropods (e.g., shrimps, crabs, sea spiders, amphipods, isopods) dominate taxon numbers in all Arctic regions, followed by polychaetes (e.g., bristle worms) and mollusks (e.g., gastropods, bivalves). Other taxon groups are diverse in some regions, such as bryozoans in the Kara Sea, cnidarians in the Atlantic Arctic, and foraminiferans in the Arctic deep-sea basins. This pattern is biased, however, by the meiofauna inclusion for the Arctic Basin (macro- and meiofauna size ranges overlap substantially in deep-sea fauna, so nematodes and foraminiferans are included) and the influence of a lack of specialists for some difficult taxonomic groups.



Box figure 3.3.1 Regional pie charts showing the species/taxon number (in brackets) per region and the relative proportion of certain taxa in species richness. Regions have been sampled with one or several types of sampling gears, including different grabs, sledges and trawls, but also subjected to different levels of taxonomic resolution for the different taxon groups. Data from: Icelandic Institute of Natural History, Iceland; Marine Research Institute, Iceland; Faroese Museum of Natural History, Faroe Islands; University of Alaska Fairbanks, U.S.; Natural History Museum of Denmark, Denmark; Zoological Institute of the Russian Academy of Sciences, Russia; Université du Québec à Rimouski, Canada; Canadian Museum of Nature, Canada; Fisheries and Oceans Canada; and Institute of Marine Research, Norway. For the Arctic Basin, data sources are listed in Bluhm et al. (2011).

Eastern Atlantic Arctic (incl. Barents Sea, the Faroe Islands, Iceland, but excluding eastern Greenland)

Barents Sea and Norwegian Sea

Historical benthos sampling
Between the end of the 19th Century and 2004, about 3000 stations had been sampled in the Barents Sea at depths from the tidal zone to 1,200 m, using a variety of different grabs, trawls, and dredges (Denisenko 2013). The latest report lists 2,435 macro- and megafaunal species for the Barents Sea (Sirenko 2001), but this figure does not include the species/taxa inhabiting the west of the Nord Cape nor new records collected in the recent two decades. Predictive models suggest that the 'true' species richness may be up to 3,200 taxa (Denisenko 2013).

In Norway, the program MAREANO, running from 2006 to 2017 (ongoing), created a baseline understanding of biotopes and habitats along the western shelf of northern Norway and in the southern Barents Sea. From 2 m beam-trawl, an epibenthic sampling sledge and Van Veen grab samples, a total of 2,225 epi-, in- and hyperbenthic macro and megafauna species/taxa have been recorded. This type of multi-equipment approach showed that Arthropoda, Annelida and Mollusca are the most speciose taxa (Box 3.3.1).

Current benthic megafauna monitoring by trawl
Since 2005, a Long-Term Monitoring for Benthic Megafauna program has been part of the annual ground fish surveys conducted in the framework of the Joint Annual Norwegian-Russian Ecosystem Survey in the Barents Sea (Anisimova et al. 2010, 2011, IMR Norway 2015, Jørgensen et al. 2015, 2016), where two benthic taxonomic experts identify megabenthic organisms in the bottom-trawl catches to the lowest practical taxonomic level on every cruise, and assess megabenthic abundance and biomass of each taxon. In the Long-Term Monitoring for Benthic Megafauna approach, selected specimens are photographed and voucher specimens were preserved for taxonomic reference purposes. Benthic bycatch information is used to assess distribution patterns of megabenthic communities and their changes over space and time in relation to potential drivers. This program has recorded a total of 380 species/taxa for the Barents Sea through increasing taxonomic knowledge, a Russian-Norwegian taxonomic exchange program and taxonomic standardization to international databases of accepted names (e.g., World Register of Marine Species, Ocean Biogeographic Information System). Species/taxon richness per station in 2011 varied from 2 to 72, with lowest values in the southeastern Barents Sea and highest in the central Barents Sea (Box 3.3.2). Out of 241 2-m-beam-trawl hauls along the western coast of Norway, MAREANO recorded more than 100 species/taxa at 32 stations, with a maximum number of 330 species/taxa (Box 3.3.2).

Multiple approaches to deep sea monitoring
The Long-term Ecological Research (LTER) Observatory HAUSGARTEN in the eastern Fram Strait is an array of stations at depths of 1,200-5,600 m. It has been photographically sampled regularly since 2000 in the framework of a long-term scientific program of the German Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (Bergmann et al. 2011). In the photographic time series, a total of 27 megabenthic taxa have been identified, but around 50 megabenthic species have been recorded when adding supporting trawl material (Bergmann et al. 2011). While the sampling method (seabed imaging) is not the same as that regularly applied in the other regions (trawl surveys), it is strongly advised that the HAUSGARTEN location will be integrated in the CBMP, as it represents the only existing Arctic deep-sea benthic observatory.

The Faroe Islands

Historical benthos sampling
The BIOFAR project (1988 to 1990) conducted benthic investigations at about 600 stations at depths from 20 to 2,420 m, with grabs, trawls, sledges and dredges, especially in the deeper parts of the Faroese Economic Exclusive Zone (EEZ). Although not complete, the Natural History Museum of the Faroe Islands today holds records of about 1807 mega- and macrofaunal species/taxa from this region (Box 3.3.1).

Current benthic megafauna monitoring by trawl
The annual trawl surveys on the Faroe Shelf and Faroe Bank are monitoring 100 stations in early spring, and 200 stations in August. Although only fish data have been recorded to date, the Fisheries Research Institute aims to begin to also include benthic invertebrate bycatch as part of the annual surveys by 2019. Benthic monitoring will be conducted in much the same way as in Norway (see the Long-Term Monitoring for Benthic Megafauna program, above), Iceland and Greenland (see below), where experts in marine megabenthic taxonomy will participate in ground fish survey cruises and identify invertebrate bycatch to the lowest taxonomic level and register the abundance and biomass of each taxon.

Iceland

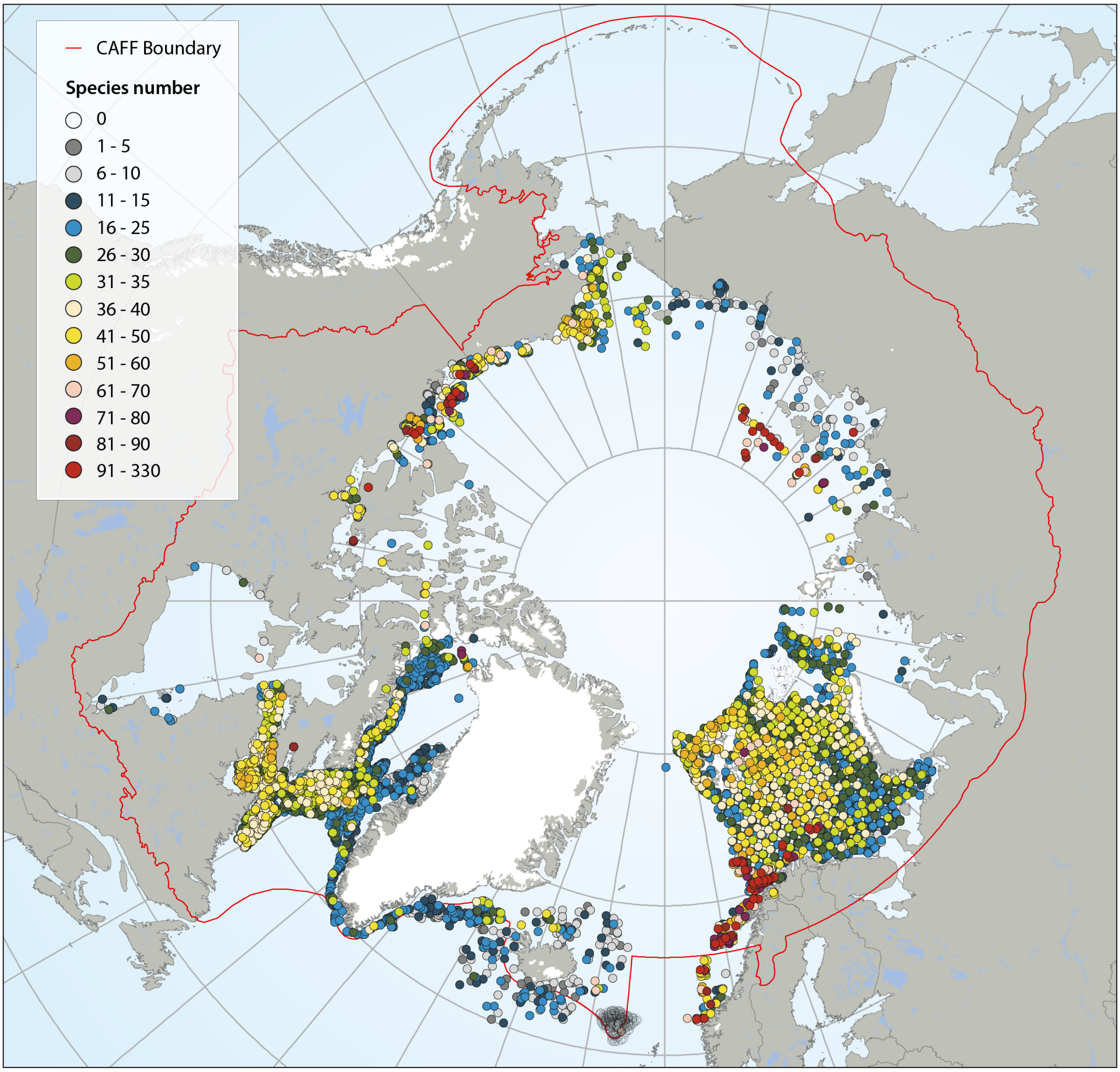
Historical benthos sampling
The main objective of the ongoing BIOICE project is to revise a taxonomic inventory of the marine invertebrates found in the waters of the Icelandic EEZ and to update knowledge on their geographic distribution in this region (Box 3.3.1). Sampling was completed during 1991-2004 and included the biogeographic boundary between boreal and Arctic regions of the North Atlantic, comprising 579 stations at depths between 20 and 3,100 m, at various bottom types with water temperatures ranging from -1°C to over 9°C. In the course of the project, over 2,345 benthic species/taxa, have been registered so far with voucher specimens in museum collections.

Current benthic megafauna monitoring by trawl
In line with the Russian-Norwegian Long-Term Monitoring for Benthic Megafauna approach, the Marine Research Institute (MRI) of Iceland implemented a three-year pilot project in 2015 in order to make the identification of all benthic invertebrate bycatch an integral part of the annual Icelandic Autumn Groundfish Survey. This pilot program is also related to the Greenlandic three-year pilot study (see below) to standardize methodologies, including taxonomic identifications of megabenthos, across the Atlantic Arctic. The survey includes approximately 400 fixed stations within

Box 3.3.2: Benthic megafauna

Pan-Arctic taxon richness in trawl benthos

More than 100 megafaunal species/taxa have been recorded at trawl stations (red) in the eastern Beaufort Sea, the deeper parts of the Laptev Sea, and the west coast of Norway. The lowest numbers (blue/grey) have been recorded in around Greenland and Iceland, in the southeastern Barents Sea and southern Chukchi Sea, as well as the shallower parts of the Kara, East Siberian, and Laptev Seas. Intermediate species/taxon richness (yellow) have been recorded in the Baffin Bay-Davis Strait/Hudson Complex, the central and northern Barents Sea, the western Beaufort Sea, the northeastern Chukchi Sea, and the Canadian Archipelago.



Box figure 3.3.2 Number of megafauna species/taxa in the Arctic (7,322 stations in total), based on recent trawl investigations. Stations with highest species/taxon number are sorted to the top, meaning that dense concentrations of stations (e.g. Eastern Canada, Barents Sea), with low species numbers are hidden behind stations with higher species numbers. Also note that species numbers are somewhat biased by differing taxonomic resolution between studies. Data from: Icelandic Institute of Natural History, Iceland; Marine Research Institute, Iceland; University of Alaska, Fairbanks, U.S.; Greenland Institute of Natural Resources, Greenland; Zoological Institute of the Russian Academy of Sciences, St. Petersburg, Russia; Université du Québec à Rimouski, Canada; Fisheries and Oceans Canada; Institute of Marine Research, Norway; and Polar Research Institute of Marine Fisheries and Oceanography, Murmansk, Russia.

the Icelandic EEZ, encompassing sites at the continental shelf and slope to 1,500 m depth. The research area is divided into a shallow-water area (0-400 m) and a deep-water area (> 400-1,500 m), but currently benthic megafauna bycatch is only analyzed for the deep-water area. Photos of voucher species will be included in a benthos identification catalogue of Icelandic waters and will be part of an overarching catalogue of the benthic fauna of the greater Arctic area. Data are stored in a relational database (Oracle) jointly run by the MRI and the Icelandic Institute of Natural History. Preliminary findings for the first cruise in 2015 showed that the cold-water habitats (<0°C) north and east of Iceland comprise on the average less than 15 species/taxa per haul, whereas over 19 species/taxa per haul occurred in more temperate waters (>0°C) south and west of Iceland. The total number of megabenthos species/taxa found in both regions is 160 (Box 3.3.2).

Greenland (west and east coasts)

Historical benthos sampling

The compilation of species/taxon richness and distribution across phyla for Greenland waters (Box 3.3.1) is based on all available faunistic information from more than 500 sources from the late 1700s until 2003, providing information about Greenlandic marine benthos down to 1,000 m depth (Tendal and Schiøtte 2003). The complete data set encompasses more than 2,100 species of benthic invertebrates, with arthropods, mollusks and polychaetes representing 55% of the species/taxa. However, these figures are strongly affected by sampling effort. The number of species/taxa registered in each of 18 sub-regions is significantly correlated with number of sampling stations. Still, this extensive data compilation is an extremely valuable baseline for current and future benthic studies in Greenland waters.

Current monitoring of megafauna by trawl

In a three-year pilot study, (Initiating North Atlantic Benthos Monitoring, INAMon) starting in 2015, the Long-Term Monitoring for Benthic Megafauna approach of bycatch surveys (see above) was adopted for Greenland waters, with the participation of benthos experts from all Atlantic Arctic countries. Benthic bycatch data are being collected during annual shrimp/fish assessment trawl surveys at more than 400 trawl stations. The goal is to make the documentation of benthos bycatch an integrated part of the standard protocol on the six annual shrimp/fish trawl surveys of the Greenland Institute of Natural Resources in the waters off west and southeast Greenland. INAMon works as a platform for international knowledge-exchange aiming to ensure standardized methodology, including taxonomic identification, across regions to assist in regional comparisons of future monitoring data. More than 400 megafauna species/taxa were registered in 2015. The average number of species/taxa per trawl station was 14 for the entire survey area, with a range from 1 to 44 (Box 3.3.2). The shrimp/fish trawl surveys in Greenland currently cover only areas of current or previous commercial trawling. Therefore, the results will inevitably be biased towards more trawling-impacted habitats, since un-trawled areas that may sustain a more diverse fauna are poorly represented in the data set. Preliminary data suggest that shallow offshore banks may represent oases with high benthic biomass and species richness. There are currently no shrimp/fish surveys in the northernmost part of Greenland, and the monitoring of benthos will continue to rely on occasional project-based research surveys.

Kara and Laptev Seas

Historical benthos sampling

Despite a long history of biological studies, knowledge of benthic species diversity in the Kara and Laptev Seas remains incomplete. A compilation of benthic species numbers from a variety of historic sampling campaigns (Sirenko 2001, 2003) created an important baseline, including a total of 2,489 macro- and megabenthic species/taxa, with arthropods, mollusks, bryozoans and polychaetes being the most diverse groups (Box 3.3.1). Benthic species richness in this Arctic region decreases toward the east, very likely due to a decreasing influence of the Atlantic water inflow. In the Kara Sea, species richness can be 20 to 25% higher for many benthic groups than in the Laptev Sea (Piepenburg et al. 2011, Denisenko and Grebmeier 2015).

Benthic megafauna monitoring by trawl

No regular bottom trawl surveys are currently conducted in the Laptev and Kara Seas. The Zoological Institute of the Russian Academy of Sciences carried out the most comprehensive, recent bottom trawling sampling in the Laptev Sea in 1993 to 1995. Species/taxon numbers in the trawl catches varied from 1 to 64 (mean: 16; unpublished data). The trawl samples collected in the Kara Sea (1931 to 1938) have not yet been fully processed. In total, more than 150 species (Gorbunov, 1946) have been found (Box 3.3.2). It is essential to continue benthic investigations in both Arctic seas to gauge the effects of declining sea-ice cover and the potential effects of an expected increase in ship traffic.

Pacific Arctic (incl. East Siberian Sea, Chukchi Sea, northern Bering Sea)

East Siberian Sea

Historical benthos sampling

The East Siberian Sea is characterized by the lowest known macrobenthic species richness among all Eurasian Arctic seas (a total of 1,148 species; Sirenko 2010). Similar to other Eurasian Arctic seas, the most diverse groups are arthropods, mollusks, and polychaetes (Box 3.3.1). The Zoological Institute of the Russian Academy of Sciences conducted the most intensive benthos sampling using bottom trawls in 1930s and at the beginning of the 2000s, although the latter was restricted to the inner shelf. According to current knowledge, the East Siberian Sea bottom fauna has highest species/taxon richness at the northwestern border to the Laptev Sea and at the southeastern border to the Chukchi Sea.

Historical benthic megafauna monitoring by trawl

No current trawl surveys are being conducted in the East Siberian Sea. Species number from historical trawl samples established from collections in 2004 vary from 1 to 28 (mean of 8) per station, which is considerably lower than in the Laptev Sea, despite the expected higher diversity based on the transitional Pacific Arctic characterization of the East Siberian Sea neighboring the Chukchi Sea (Box 3.3.2). This pattern in the Laptev Sea may be partly due to differences in gear and sampling effort. Benthic diversity is expected to be higher in the deeper part under ice cover. In the northwestern East Siberian Sea, the local benthic diversity has been recorded with 110-120 species (Gorbunov 1946) (Box 3.3.2).

Chukchi Sea and northern Bering Sea

Historical benthos sampling

Most systematic benthic sampling in the northern Bering and Chukchi Seas dates back to the early 1970 to 1990s, with published records for both epi- and macrofauna (e.g., Feder et al. 2005, 2007, respectively). Examples of some of the larger research endeavors include the Joint U.S.-USSR Central Pacific Expedition (BERPAC), St. Lawrence Island Polynya Project in the northern Bering Sea (SLIPP), and the Outer Continental Shelf Environmental Assessment Program (OCSEAP). A total of 1,406 macrozoobenthos species/taxa have been recorded in the Chukchi Sea, with the most diverse groups being arthropods, mollusks, polychaetes and bryozoans (Box 3.3.1).

Current benthic megafaunal monitoring by trawl

In the U.S., regions of commercial fisheries in the southern Bering Sea are monitored through annual trawl surveys, which routinely also record benthic invertebrate bycatch in addition to fish (NOAA RACE database). Commercial trawling activities may be a cause of reduced biodiversity found in fished compared with unfished regions of the Bering Sea (McConnaughey et al. 2000). With a decline in sea-ice cover and the potential of increased regular ship traffic in the high Arctic, the possibility of a fisheries development in the Chukchi and Beaufort Seas is increasingly possible. In response, an Arctic Fisheries Management Plan has been formulated, which sets a baseline for sustainable harvests, but currently does not permit commercial fisheries (NPFMC 2009) and no annual surveys are currently being conducted. Future annual groundfish surveys could be expanded into the Arctic Chukchi and potentially Beaufort Seas. Current benthic assessments in the Chukchi Sea are being done through individual research projects (e.g., Chukchi Sea Offshore Monitoring in Drilling Area – Chemical and Benthos (COMIDA—CAB), Arctic Ecosystem Integrated Studies (Arctic EIS), and the Chukchi Sea Environmental Studies Program (CSESP), also see Grebmeier et al. 2015b). In some cases, such as the NOAA-funded Russian American Long-Term Census of the Arctic (RUSALCA) program or the Distributed Biological Observatory (DBO), research plans include repeated benthic sampling at the same stations over time. The recently installed Arctic Marine Biodiversity Observing Network (AMBON) aims to identify sampling schemes that could provide the basis for a long-term biodiversity monitoring program in the Arctic. More than 300 megabenthic species/taxa are regularly identified during each these research programs (e.g., Bluhm et al. 2009, Blanchard et al. 2013, Ravelo et al. 2014), providing a solid baseline of megabenthic species/taxon occurrences in the Chukchi Sea region (Box 3.3.2) despite the lack of fisheries-based monitoring surveys.

Beaufort Sea

Historical benthos sampling

One of the earliest documented benthic grab and trawl investigations on the U.S. (western) side of the Beaufort Shelf was the Western Beaufort Sea Ecological Cruise (WEBSEC) study in the early 1970s, reporting the occurrence of > 100 polychaete species/taxa and ~150 gammarid amphipod species alone (Carey 1976). Subsequent U.S. Beaufort explorations focused mostly on fishes, but also yielded information on benthic invertebrates (Frost and Lowry 1983), or on the nearshore lagoon systems. The Canadian Arctic Expedition, 1913 to 1918, was the first scientific expedition to provide a comprehensive collection of marine benthos from the Canadian (eastern) Beaufort Sea. Interest in this region was revived nearly 50 years later when hydrocarbon exploration spurred ambitious field programs (e.g., Wacasey 1975, Wacasey et al. 1977, Atkinson and Wacasey 1989a). With improved logistic capabilities, widespread field programs including macro- and megabenthic community assessments flourished in the last decade in projects such as the Canadian Arctic Shelf Exchange Study (CASES), the Northern Coastal Marine Studies (CCGS *Nahidik* program), the International Polar Year-Circumpolar Flaw Lead System Study (IPY-CFL), the Beaufort Regional Environmental Assessment (BREA), and research collaborations among the CCGS *Amundsen* program, ArcticNet, Canadian Healthy Ocean Network (CHONe), and various oil companies. By gathering historical and recent data from all different types of gear, a total of 1,047 epi-, in- and hyperfauna species/taxa have been recorded. In decreasing order, arthropods, polychaetes and mollusks were the most species/taxon-rich groups (Box 3.3.1).

Current benthic megafauna monitoring by trawl

Recent investigations commenced in 2008, when a trawl survey using the same methods as the annual groundfish surveys in the Bering Sea were conducted in the western U.S. Beaufort Sea, identifying 174 benthic invertebrate species (Rand and Logerwell 2011). Other investigations between 2011 and 2014 through the U.S. Bureau of Ocean Energy Management (BeauFISH and U.S.-Canada Transboundary projects) supported shelf and slope investigations including epibenthic trawls. Across the U.S. Beaufort Shelf, 133 epibenthic species/taxa from 71 trawls were identified (Ravelo et al. 2015), while up to 160 epibenthic species along the central Beaufort Sea shelf and slope were recorded (K. Iken, B.A. Bluhm, unpubl. data). Recent investigations in the Canadian Beaufort Sea started around 2007 at the onset of the IPY-CFL scientific program and continued mostly thereafter under the CCGS *Amundsen* program. The BREA scientific program carried out extensive fish surveys from 2012 to 2014, yielding a vast amount of data on benthos in bycatch (Majewski et al. 2016). There is, however, no recurring annual bottom trawl survey in the either part of the Beaufort Sea. For the entire Beaufort Sea region, total richness ranged from 1 to 119 megafaunal species/taxa per haul (Box 3.3.2).

Canadian Arctic Archipelago, Hudson Bay Complex, western Davis Strait-Baffin Bay

Historical benthos sampling

Few historic research-based studies have been carried out in the Canadian Arctic Archipelago (e.g., Thomson 1982, Atkinson and Wacasey 1989a), the Hudson Bay Complex (e.g., Wacasey et al. 1976, Atkinson and Wacasey 1989b) and the western Davis Strait-Baffin Bay region (e.g., MacLaren 1978), and if so, they were mostly based on grab sampling. Over the last decade, many research projects (Link et al. 2013a, Goldsmit et al. 2014, Roy et al. 2015) and programs (e.g., CCGS *Amundsen*, ArcticNet, CAISN II, CHONe) investigated benthos in parts of these regions. By gathering available historic and recent data from all research-based inventories, which used different types of gear, a total of 1,151 epi-, in- and hyperfauna species/taxa have been recorded in the Canadian Arctic Archipelago, 841 species/taxa in the western Davis Strait-Baffin Bay region and 786 species/taxa in the Hudson Bay Complex. In decreasing order, arthropods, polychaetes and mollusks were the most species/taxon-rich groups in all three regions (Box 3.3.1).

Current benthic megafauna monitoring by trawl

For the Canadian Arctic Archipelago and northern Davis Strait-Baffin Bay regions, the studies of Roy et al. (2014, 2015) represent the most recent research-based investigations on megabenthic communities. The Davis Strait-Baffin Bay region and the Hudson Bay Complex are the only two Canadian Arctic regions where commercial fisheries occur. Fisheries and Oceans Canada (DFO) has been conducting an annual multi-species depth-stratified bottom trawl survey to perform stock assessments of Greenland halibut (*Reinhardtius hippoglossoides*) and northern and striped shrimps (*Pandalus borealis* and *P. montagui*, respectively) since 1999, but it is also used for biodiversity monitoring (K. Hedges, pers. comm.). All bycatch invertebrate groups are identified, but there are not yet thorough and systematic surveys of benthic communities at species level (Siferd 2015). Across the three regions, estimates of total richness from research-based investigations at a total of 281 stations ranged from 1 to 119 species/taxa per station. In the Davis Strait-Baffin Bay and Hudson Bay Complex regions, estimates of total community richness from bottom trawl bycatch surveys, including a total of 3,477 stations, ranged from 3 to 59 species/taxa per station. Considering all types of trawl, most of the high-to-intermediate richness stations were distributed across the Canadian Arctic Archipelago, in the northern and southern areas of the Davis Strait-Baffin Bay region and the Hudson Strait, while low-to-intermediate richness stations occurred mostly in nearshore areas of Hudson Bay and along the northern end of the Baffin Island shelf (Box 3.3.2).

Arctic Basin

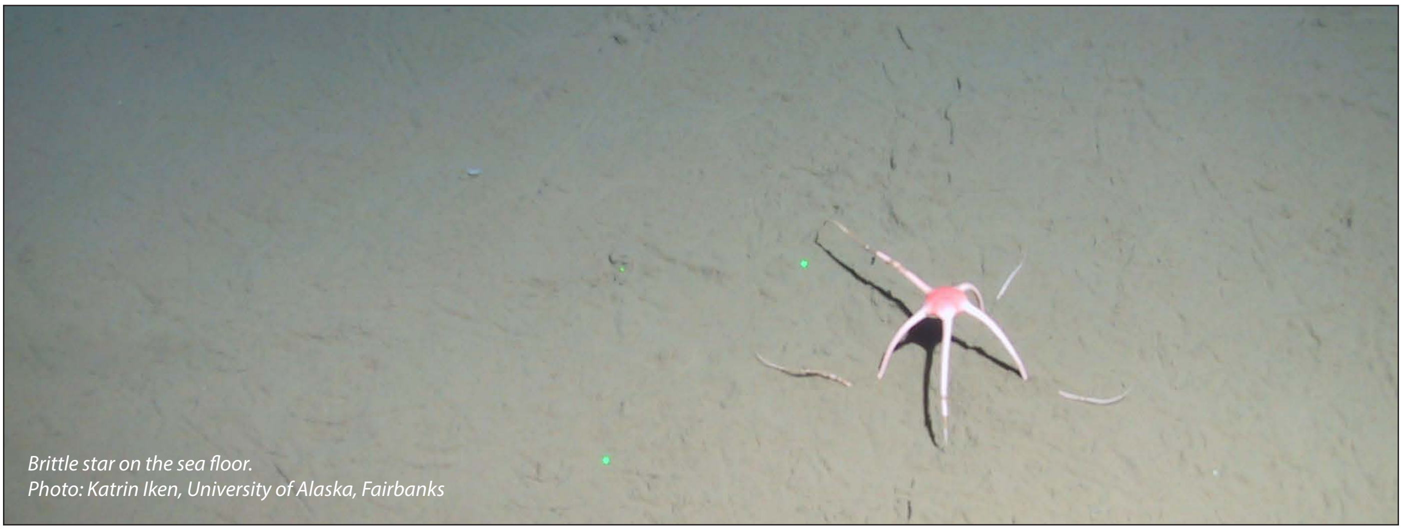
Historical benthos sampling

A number of early efforts such as the Norwegian *Nordhavs* expedition in 1876-1878 (Danielson 1890) and the Russian *Sedov* expedition in 1937-1940 (Gorbunov 1946, Gurjanova 1946), facilitated a first synthesis in which Sirenko (2001) summarized 712 taxa for the 'Arctic Basin' (although with undefined depth cut-off). More recent research efforts conducted between the late 1990s and 2010 increased the inventory to 1,125 benthic taxa found at stations deeper than 500 m and northwards of 80°N in Fram Strait (Bluhm et al. 2011). The macrobenthic species/taxon richness is dominated by arthropods and annelids, and within the meiofauna by foraminiferans and nematodes (Box 3.3.1). Also of note is that macrofauna decrease in body size with increased depth, and this happens more so than with meiofauna (Rex et al. 2006, Wei et al. 2010).

Within arthropods, amphipods are richest in species, followed by isopods and harpacticoid copepods. For few species, more than 20 records exist and about half of all taxa have been reported from only one or two stations.

Current benthic megafauna monitoring by trawl

Most benthic research efforts in the deep-sea Arctic Basin have focused on macrofauna (syntheses by Bluhm et al. 2011 and Mironov et al. 2013) and meiofauna (syntheses by Vanreusel et al. 2000, Soltwedel et al. 2009). Megabenthic communities have been studied by only few trawl catches or by photographic surveys mostly along slopes (Soltwedel et al. 2009, MacDonald et al. 2010), with recent efforts focused on the Beaufort Sea slope to ~1000 m (Norcross et al. 2015, Majewski et al. 2016). No regular benthic sampling is being conducted in the Arctic Basin by any nation. Specific monitoring locations in the Arctic Basin have not yet been identified, because of the sparse previous sampling. Locations, however, should be determined such that they would capture potentially changing benthic communities along the Arctic Circumpolar Boundary Current and Atlantic Deep Water inflow through Fram Strait, and into the American Basin (Fig. 3.3.1). This could be a curved transect crossing the Arctic Basin from west of Svalbard to the Bering Strait. When this transect is crossed by a research vessel the data could be added into the database of the Distributed Biological Observatory (DBO).



Brittle star on the sea floor.
Photo: Katrin Iken, University of Alaska, Fairbanks

3.3.3 Status and trends of FECs

Despite extensive benthic research in various regions of the Arctic, there are only few that have been systematically sampled over sufficiently long time periods to allow a reliable assessment of potential changes in benthos. In the following, the CBMP Benthos Expert Network presents three examples of documented scientific long-term studies evaluating changes in benthic community structure and biomass on annual to decadal scales.

Case study 1: Recent trends – Multiple impacts on Barents Sea megabenthos (2007-2015)

The Barents Sea trawl investigations (see above) found high megabenthic biomass in the cold waters along the southern and western coast of Novaja Zemlya (sponges, sea urchins, snow crabs, and crangonid shrimps), on the Spitsbergen Bank influenced by Atlantic water (sea cucumbers, Iceland scallop (*Chlamys islandica*), sponges, lyre crabs, and sea stars), and in the southwestern Barents Sea (sponge field) (Fig. 3.3.2). The south-central Barents Sea was characterized by lowest megabenthic biomass. A general decrease in biomass over the recent decade has been observed in the central Barents Sea, with a minimum in 2015. Whether the biomass reductions are due to rapid climate change, such as ocean warming, or rather to other natural (e.g., predation from snow crabs or benthivorous fishes) or human pressures (e.g., trawling) have not yet been fully identified. In 2007, megabenthic biomass increased northwest of Kap Kanin (Fig. 3.3.2) due to the invasion of the introduced king crab (*Paralithodes camtschaticus*) (Orlov and Ivanov 1978). This species has now spread to coastal areas in the Russian and Norwegian parts of the Barents Sea. Similarly, an increase in megabenthic biomass in the northeastern Barents Sea in 2011 has at least in part been attributed to an increasing population of the invasive snow crab (Fig. 3.3.2). As it is a coldwater species living at water depths from 20 to 700 m and temperatures below 5 to 8°C (Elner and Beninger 1992), it is expected to spread over most of the Barents Sea (Renaud et al. 2015). Pavlov and Bakanev (2012) consider the snow crab (*Chionoecetes opilio*) invasion as one of the most significant threats currently to biological diversity in the region. In addition, the recent warming in the Barents Sea is expected to lead to a borealization of megabenthic communities, similar to what has been observed for fish communities (Fossheim et al. 2015). The benthic communities of the southwestern and coastal areas of the Barents Sea are consistently boreal in terms of their biogeographic composition, i.e., they lack truly Arctic species, but it is recognized that the warming of the Barents Sea is pushing boreal species farther north. Northward migrating commercial fish stocks have already initiated new commercial trawling activity in the northern Barents Sea. This makes the area east of Svalbard a possibly vulnerable area subjected to multiple impact factors, including ocean warming, bottom trawling, and invasions of non-indigenous species, such as the snow crab.

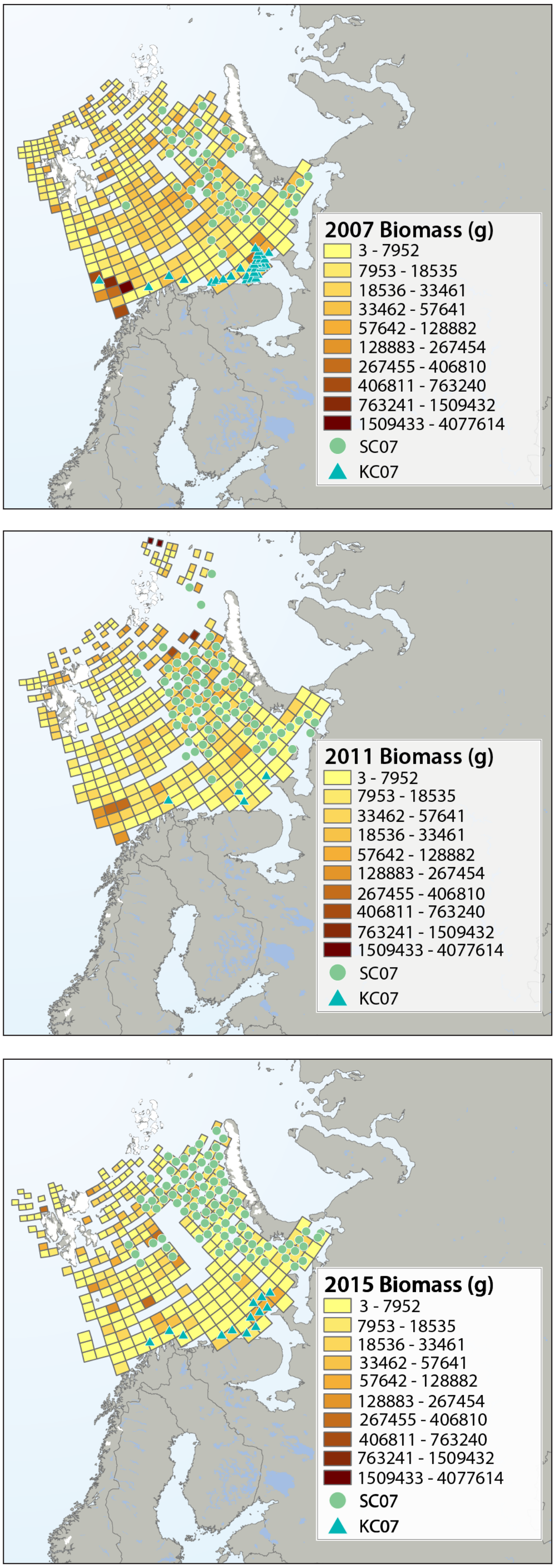


Figure 3.3.2: Megafauna distribution of biomass (g/15 min trawling) in the Barents Sea in 2007, 2011 and 2015. The green circles show the distribution of the snow crab as it spreads from east to west, and the blue triangles show the invasion of king crab along the coast of the southern Barents Sea. Data from Institute of Marine Research, Norway and the Polar Research Institute of Marine Fisheries and Oceanography, Murmansk, Russia.

Case study 2: Decadal trends – Barents Sea macrobenthic biomass fluctuations (1924-2003)

The distribution of macrobenthic biomass in the Barents Sea varied between 1924 and 2003 (Fig. 3.3.3). The average biomass values for the entire study region declined about 2.5-fold between the 1930s and the 1960s (from 147.0±11.7 to 59.5±4.3 wet weight g m^{-2}) (Denisenko 2001). In 2003, however, average biomass even exceeded the high values from the 1930s (Denisenko 2013). Despite the general dynamics in the distribution of macrobenthic biomass, some biomass hotspots persisted over time, especially south of Svalbard and within the central focus area (blue box in Fig. 3.3.3). It has been suggested that some of the biomass decline between the 1930s and 1960s was the result of bottom trawling (Denisenko and Denisenko 1991), whereas the increase observed between the 1960s and 2003 (within the focus area inside the blue box in Fig. 3.3.3) could be caused by climate change.

In the early 1990s, negative impacts of commercial fish trawling on the macrozoobenthos biomass in the Barents Sea were quantified (Fig. 3.3.4) (Denisenko and Denisenko 1991). A strong four-year lag relationship existed between total macrobenthos biomass and bottom trawl intensity (Fig. 3.3.5) (Denisenko 2001). Degradation of benthic communities was also detected in the 2000s, indicating the continuing impact of increased trawling activities in the region (Manushin et al. 2008).

About 30-50% of known cold water coral reefs along the northern coast of Norway have been damaged most likely due to bottom trawling in the Barents Sea (Fosså et al 2002) and biomass of sponges has decreased 20-fold in the southwestern part of the sea (Denisenko 2013). Strong damage was also observed in bottom communities as result of unsustainable exploitation of target species, such as the Iceland scallop (Denisenko 2013). Large concentrations of this megabenthic species were discovered in the Barents Sea in the late 1980s (Denisenko and Bliznichenko 1989) and commercially exploited during the following 20 years. These populations have now been completely depleted on Goose Bank, and the Svyatonosskaya population near the Kola Peninsula has been seriously reduced (Bakanev and Zolotarev 2012).

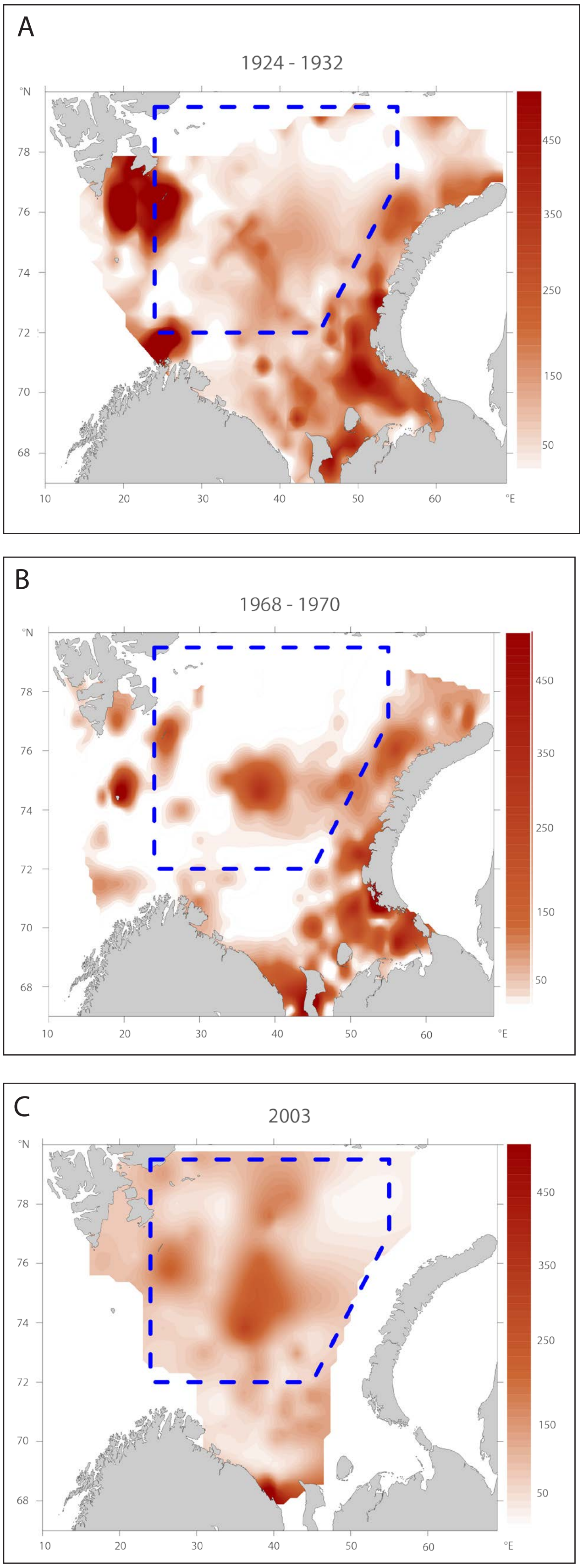


Figure 3.3.3: Macrofauna distribution of biomass (g wet fixed weight m^{-2}) in the Barents Sea over three time periods: 1924-32 (Figure A), 1968-70 (Figure B) and 2003 (Figure C, constructed from original archive data, except for area south of 72° N where digitized megafaunal-data taken from Anisimova et al. (2010) was used. Adapted from Denisenko (2013). Blue boxes delineate the areas within which the zoobenthos biomass values were compared.

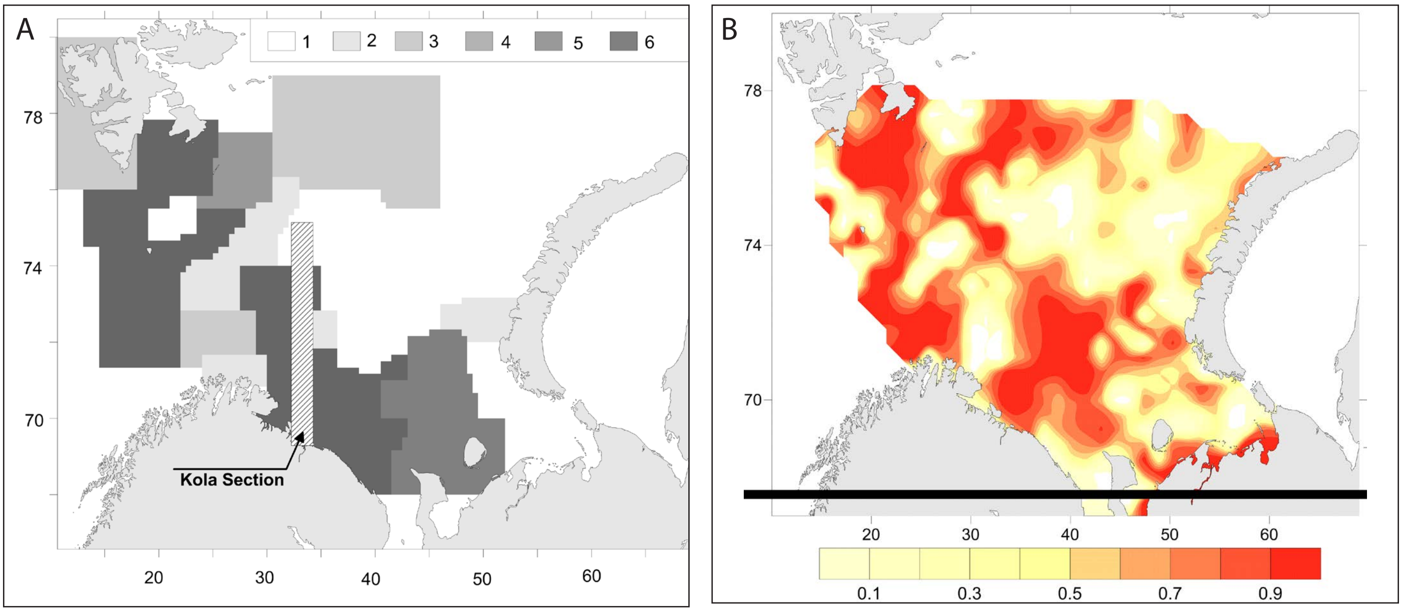


Figure 3.3.4: Commercial fishery impact on zoobenthos of the Barents Sea. Figure A) Intensity and duration of fishery efforts in standard commercial fishery areas in the Barents Sea. The darker the area the longer the fishery has been in operation. Figure B) Level of decline in macrobenthic biomass between 1926-1932 and 1968-1970 calculated as 1-b1968/b1930. The largest biomass decreases correspond to the darker colour, whereas lighter colour refers to no change (Denisenko 2013).

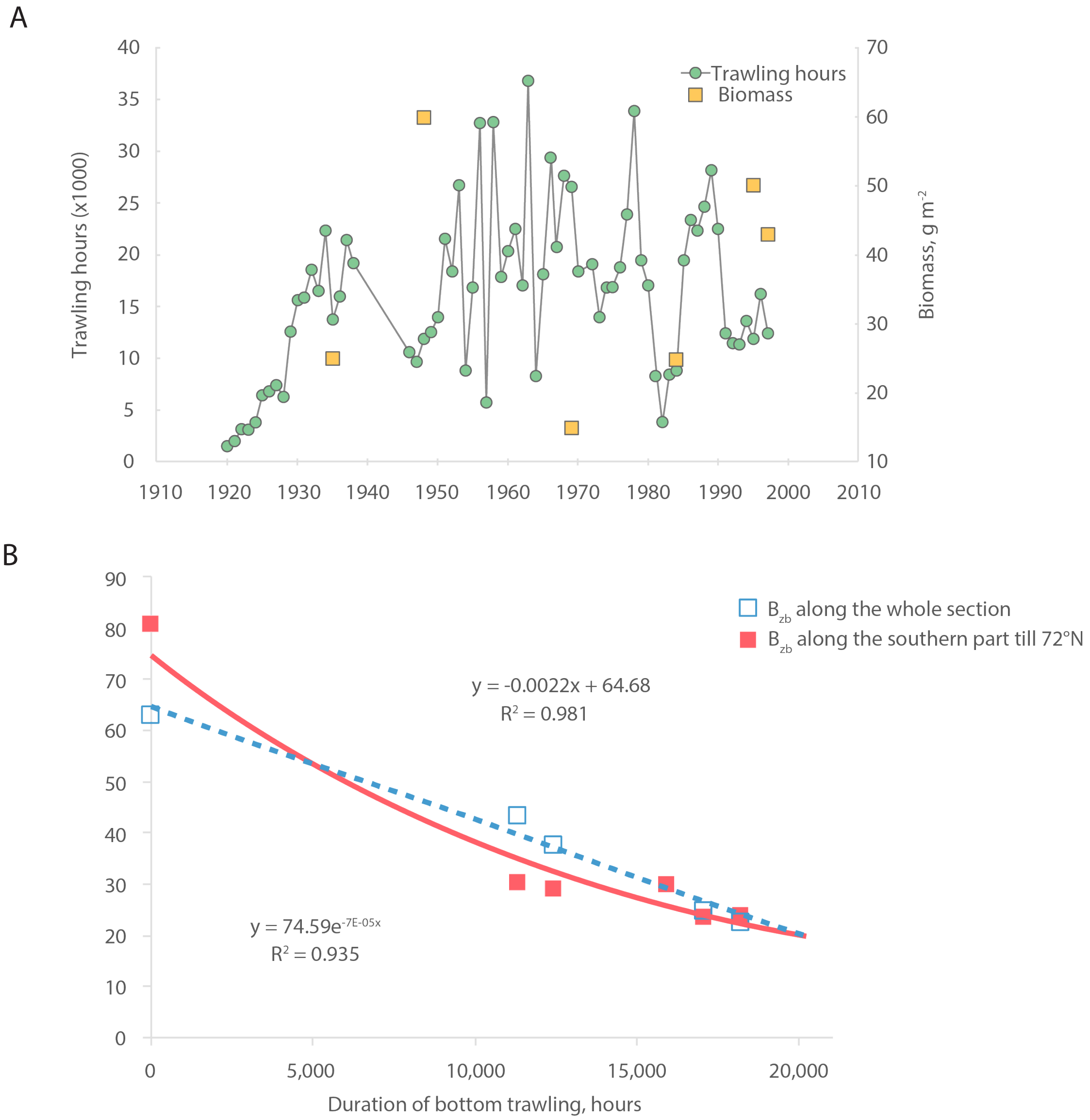


Figure 3.3.5: Variation of average annual trawling activity (in hours) and macrobenthic biomass (g m^{-2}), (a) and relationship of biomass with a four-year lag (mean value of time of the turnover in biomass value) to trawling activity, (b) along the Kola section of the Barents Sea during 1920-1997 (Denisenko 2001, 2013).

Case study 3: Decadal trends, Pacific Arctic – Northern Bering Sea and Chukchi Sea macrobenthic biomass distribution (1970-2000s)

Biomass distribution of infaunal macrobenthos in the Chukchi Sea was considered in the analysis of decadal patterns from the 1970s to the 2000s (Fig. 3.3.6). Several benthic biomass hotspots persisted over the decadal sampling. A biomass hotspot in the Chirikov Basin, just south of Bering Strait, has noticeably diminished in biomass since the 1970s. This is a traditional feeding area for gray whales, foraging on ampeliscid amphipods, but gray whales have declined in that region since the 1980s (Moore et al. 2003). The shift in gray whale foraging away from the Chirikov Basin is likely driven by a decline in their amphipod prey, perhaps in part from overexploitation from gray whale feeding but possibly also from climate-initiated ecosystem changes including shifts in currents causing changes in sediment grain size (Coyle et al. 2007, Grebmeier 2012). Another hotspot, in the south-central Chukchi Sea, has persisted over the study period since the 1980s, although a biomass reduction has become noticeable in the most recent decade (Grebmeier et al. 2015a). This hotspot is sustained by the slowing of fast-flowing water entering through the narrow Bering Strait, which causes an increase in settlement of nutrient-rich particles to the benthos (Grebmeier 2012). The benthos in this area is dominated by bivalves (Grebmeier et al. 2015a), which are important food for many benthic feeding marine mammals (e.g., walrus; Jay et al. 2012, Moore et al. 2014). The recent benthic macrofauna biomass declines in this region could be due to changes in flow dynamics through Bering Strait, changes in benthic habitat features such as sediment grain size, and possibly foraging pressures (e.g., Moore et al. 2003).

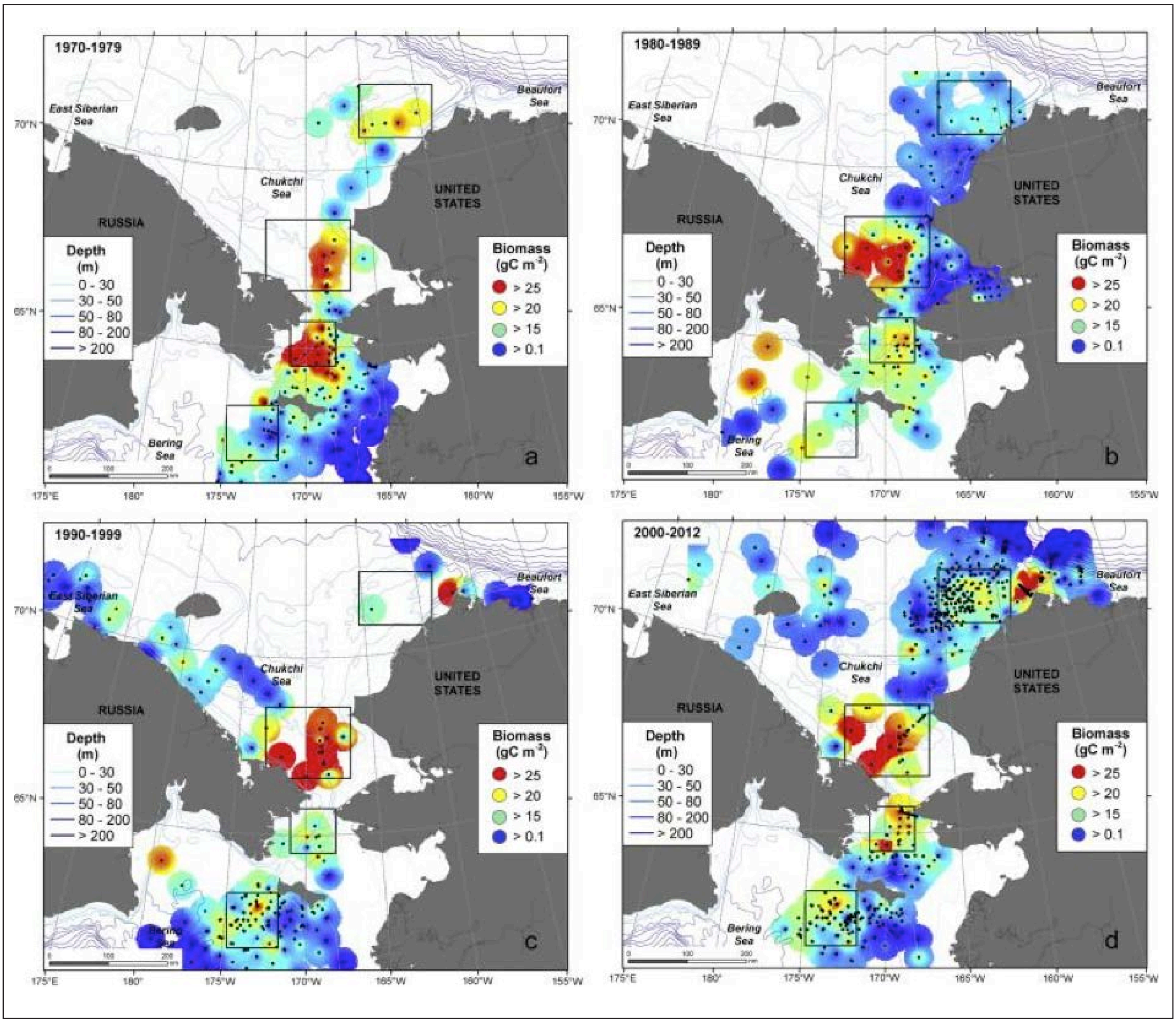


Figure 3.3.6: Benthic macro-infauna biomass in the northern Bering and Chukchi Seas from 1970 to 2012, displayed as decadal pattern Adapted from Grebmeier et al. (2015a) with permission from Elsevier.

Box 3.3.3 Indigenous Knowledge of benthic species

Vera Metcalf, Eskimo Walrus Commission, Inuit Circumpolar Council Alaska and Carolina Behe, Inuit Circumpolar Council-Alaska

There is a wealth of Indigenous Knowledge (IK) on benthic species within Inuit communities. This IK is an invaluable knowledge resource, reaching back thousands of years, to aid in the understanding of changes occurring within the Arctic.

Along Arctic coasts, benthic animals wash up regularly on shorelines mostly during autumn after a storm. Many of us enjoy these resources for food. After a storm, we often search along the beaches and collect the 'seafood'. Over time, we are able to see and recognize when and where there are changes in the distribution and quantity of these resources.

Our knowledge teaches the importance of understanding interconnections within the Arctic to determine how some of these changes may be occurring. For example, sea ice coverage, thickness, sand bar location, and ocean currents all play a role in the health of life in the Arctic, including benthic resource species.

Benthic species are also an important food source for walrus. Many of us rely on walrus and consider it a very important natural resource in our culture. When we hunt, harvest, and process walrus, we enjoy the benthic species found in the stomach. Over time, we observed a decreasing volume of benthic prey, particularly clams, and an increasing volume of pelagic fishes, or simply sand, in walrus stomachs.

The change in walrus stomach contents indicates that the distribution and availability of benthic resource species are changing in some areas. This information validates some Elders who have noted that this change is linked to a decrease in sea-ice coverage, dislocations of sand bars, and alterations of water currents.

Marine food sources for people around the Bering Sea include Ascidians (possibly *Boltenia ovifera* on stalk and other colonial ascidian species).


Photos: Carolina Behe

3.3.4 Drivers of observed trends

Benthic fauna are generally sensitive to variations in the surrounding environment and can respond at different ecological levels (species, populations, and ecosystems). Effects of climate change on benthic populations are complex and are mainly related to changes in bottom-water temperature, sea-ice dynamics, coastal erosion, freshwater and sediment inputs from rivers, melting glaciers and permafrost, and in the ocean carbon budget (ocean acidification) (Piepenburg 2005). Commercial bottom trawling is an anthropogenic driver that has been demonstrated to cause fluctuations in benthic biomass (Denisenko 2013). The impacts of such environmental and anthropogenic drivers may weaken existing community interactions and facilitate the invasion of non-indigenous species into Arctic regions (Renaud et al. 2015). Records of impacts from potential drivers of change vary among Arctic regions. Here, the CBMP Benthos Expert Network provides their first assessment of the importance of six major drivers of change, along with their cumulative impact for different Arctic regions (Table 3.3.1). No attempt has been made, however, to weigh or prioritize these drivers because of the lack of quantitative information in many regions.

Sea ice extent and thickness influence benthic communities mostly indirectly through effects on hydrographic conditions and primary production (Link et al. 2011). Thus, changes in sea-ice dynamics will alter benthic energy flow with subsequent effects on standing stock, community interactions and, hence, ultimately also biodiversity. In the Barents Sea, there is also evidence of warming bottom temperatures (Jørgensen et al. 2015), a second driver expected with climate change. Higher ambient temperatures modify the environmental conditions experienced by benthic organisms, exceeding the temperature limits of some stenothermal (e.g., Arctic) species but opening these regions to taxa that require warmer conditions for growth and reproduction (e.g., boreal species). This factor is especially expected in inflow regions of the North Atlantic and North Pacific (Table 3.3.1).

As many large river systems and heavily glaciated areas around Greenland and the Eastern Arctic Archipelago drain into the Arctic Ocean, freshwater influence from increased melting and discharge of these sources is expected to be a strong driver in these Arctic regions. Reduced ***salinity*** will directly affect the osmotic balance of benthic species and may also cause indirect effects through changes in stratification patterns and associated primary productivity regimes. Witman et al. (2008) showed a significant effect of chlorophyll *a*, which co-varied with the salinity in the Canadian Arctic, on benthic biodiversity suggesting that environmental stress as well as productivity influence diversity in these marine systems.

The potential impacts of ***ocean acidification*** on benthic biodiversity are not well known. Although several regions have been identified to experience reduced alkalinity, such as the Chukchi and Beaufort Seas, the exact biological sensitivities are still to be determined. However, it is well known that many non-Arctic calcareous species have reduced shell-building capacity and metabolic and behavioral effects. Ocean acidification will likely impact Arctic benthic species in both their adult benthic and/or pelagic larval stages, and juvenile stages are generally found to be the most sensitive.

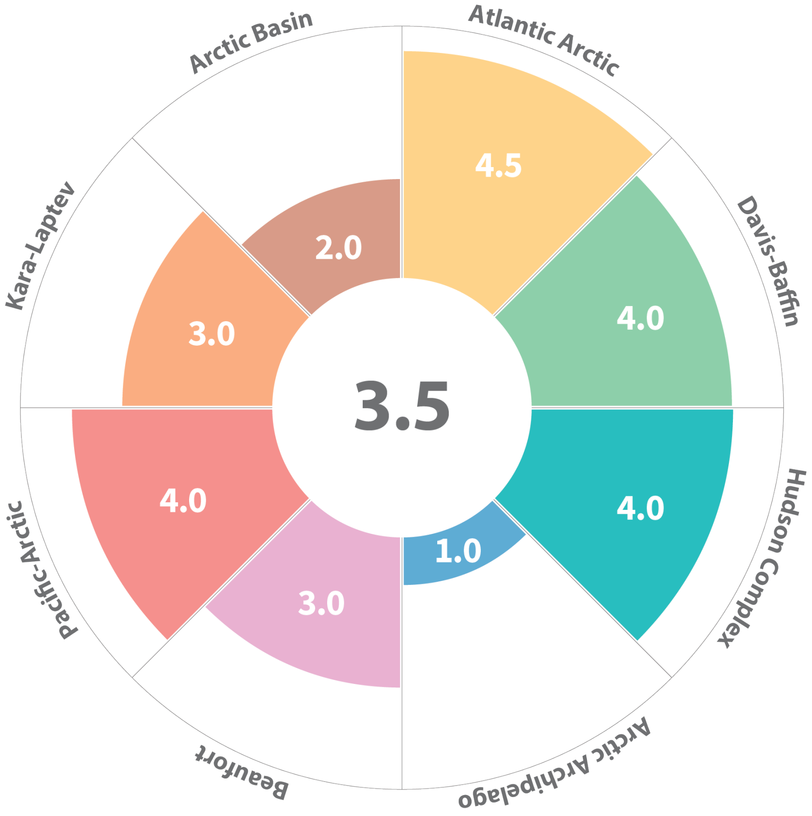


Figure 3.3.7: Cumulative scores of various environmental and anthropogenic drivers of change of the benthic ecosystem across the eight Arctic Marine Areas (AMA). A cumulative score is the median score of sub-regions per AMA (Table 3.3.1). Median score for the whole Arctic is given in the centre.

Table 3.3.1. Presence or absence (1/0) of various environmental and anthropogenic drivers of change of the benthic ecosystem across the different Arctic sub-regions. Median score of sub-regions per Arctic region is given in bold. A cumulative score of 1-2 is considered low, 3-4 intermediate, 5-6 high, and a score of na indicates a lack of information. NIS indicates non-indigenous species.

Arctic Region **Sub-Region**	**Sea-ice Dynamics**	**River or Glacier Influence**	**Bottom Water Temperature Change**	**Ocean Acidification**	**Commercial Bottom Trawling**	**Risk of Introduction of NIS**	**Cumulative Score**
Atlantic Arctic	**0**	**1**	**1**	**0.5**	**1**	**1**	**4.5**
Greenland (northeast)	1	1	na	na	0	na	2
Greenland (southeast)	1	1	na	na	1	na	3
Iceland (north)	0	1	1	1	1	na	4
Iceland (south)	0	1	1	0	1	na	3
Faroe Islands (shallow)	0	0	1	na	1	1	3
Faroe Islands (deep)	0	0	0	na	1	1	2
Norwegian Shelf (northwest)	0	0	1	na	1	na	2
Barents Sea (northwest)	1	1	1	na	1	1	5
Barents Sea (southwest)	0	0	1	na	1	1	3
Barents Sea (northeast)	1	0	1	na	0	1	3
Barents Sea (southeast)	1	1	1	na	1	1	5
Kara-Laptev	**1**	**1**	**1**	**na**	**0**	**na**	**3**
Kara Sea	1	1	1	na	0	na	3
Laptev Sea	1	1	na	na	0	na	2
Pacific Arctic	**1**	**0**	**1**	**1**	**0**	**1**	**4**
East Siberian Sea	1	0	1	na	0	na	2
Chukchi Sea (Russia)	1	0	1	na	0	1	3
Chukchi Sea (USA)	1	0	1	1	0	1	4
Northern Bering Sea	1	1	1	1	1	1	6
Beaufort Sea	**1**	**1**	**na**	**1**	**0**	**na**	**3**
Beaufort Sea (USA)	1	1	na	1	0	na	3
Beaufort Sea (Canada)	1	1	na	na	0	na	2
Arctic Archipelago	**1**	**0**	**na**	**na**	**0**	**0**	**1**
Hudson Bay Complex	**1**	**1**	**na**	**na**	**1**	**1**	**4**
Davis Strait-Baffin Bay	**1**	**1**	**na**	**na**	**1**	**1**	**4**
Canada (west)	1	1	na	na	1	1	4
Greenland (northwest)	1	1	na	na	1	na	3
Greenland (southwest)	0	1	na	na	1	na	2
Arctic Basin	**1**	**0**	**1**	**na**	**0**	**na**	**2**

Trawling impacts on certain benthic communities are particularly strong in regions with regular commercial trawling activities, such as in the Barents Sea (Denisenko 2001) and other Atlantic Arctic regions, also in the Davis Strait-Baffin Bay Complex (Yesson et al. 2016). The constant disturbance erodes the resilience of these vulnerable bottom communities, and only few opportunistic species are able to survive. This may be exacerbated in cases where trawling targets specific species and, thus, further alters the overall community dynamics. Trawling in areas recently covered by sea-ice most of the year are very vulnerable due to large upraised species easily taken by a trawl-gear (Jørgensen et al. 2016).

Changes in environmental conditions (e.g., warmer inflowing currents) and vessel-related activities (e.g., ballast waters; see also Chapter 4) open opportunities for ***non-indigenous species*** to enter the Arctic systems. These non-indigenous invaders can have the potential to outcompete highly adapted, native species and cause major interruptions of existing communities. Some specific examples of invasive species with impacts on bottom communities are already known, for example king crabs (Britayev et al. 2010) in the Barents Sea region, and the possible impact from snow crabs are being evaluated from the same area.

3.3.5 Knowledge and monitoring gaps

As outlined above, a considerable amount of information about Arctic benthic communities has been collected over the past century. However, the lack of consistency and methodological standardization in combination with limited geographic coverage limits our ability to assess large-scale (from regional to pan-Arctic) and long-term dynamics in benthic communities, which is urgently needed to assess effects of anthropogenic activities and a changing environment.

A truly large-scale, long-term and internationally comparable monitoring of benthic faunal assemblages does not exist for the entire Arctic. The main reason for this is most likely the significant costs of running such monitoring programs, and the challenges to develop international standards. Therefore, there is a need to formulate some standards for benthos monitoring in the Arctic that 1) are realistic given the logistical, scientific and economic constraints existing in all Arctic countries, 2) will ensure a description of key components in benthic faunal communities, and 3) have the potential to document large-scale and long-term trends in the dynamics of selected benthic indicators with regard to drivers related to climate change, trawling impact, pollution and other potential anthropogenic and natural drivers. This has led to the suggestion of focusing on megabenthic invertebrate fauna caught by bottom trawls as being the most practical environmental indicator organisms for countries that have regular surveys in place (Blicher et al. 2015, Jørgensen et al. 2015). This monitoring can be implemented either as part of already existing long-term national, annual groundfish/shellfish assessment surveys, or alternatively, as part of shorter-term research projects.

For those areas where annual groundfish-shellfish assessment surveys take place, an expansion of the Long-Term Monitoring for Benthic Megafauna program, described in Chapter 3.3.1 and implemented in the Barents Sea by Norway and Russia, and recently off Greenland, may serve as a model to design a broader international monitoring program. The CBMP Benthos Expert Network suggests to establish a pan-Arctic scientific expert exchange program to stimulate a process of knowledge sharing and the implementation of a standardized approach to sampling, species identification, as well as data entry and storage. This approach to monitoring is cost-effective because it capitalizes on existing logistic platforms. In addition, it has already proven to be effective for documenting large-scale patterns in the distribution of benthic megafauna (Moritz et al. 2013, Jørgensen et al. 2015, 2016, Degen et al. 2016) and enables the initial detection of potential vulnerable habitats, valuable ecosystem components, or areas subject to change (e.g., hotspots of biodiversity and/or production, invasive species, feeding grounds for mammals). This approach can, therefore, assemble the groundwork to assess long-term changes and potential drivers of these changes.

For the vast areas of the Arctic without annual groundfish-shellfish assessment surveys, collection of benthic information will have to rely on intermittent research projects. Such project-based surveys will be less regular and will not sample the same regions repeatedly, but can eventually also produce comparable data to monitored regions, if standardized protocols are followed. It is advised that trawl sampling be applied for greatest comparability among Arctic regions and because it is relatively cost-effective. Great care should be taken to ensure consistent operating procedures, including the type and use of sampling gear, species identification, sample processing, data entry and storage. It is clear, however, that long-term assessments based on research projects are subject to changes in national research strategies and, hence, will very likely not produce time-series data with the same reliability as regular groundfish-shellfish assessment surveys.

While the focus here has been on megabenthic monitoring based on trawl surveys because of the existing infrastructure in several Arctic countries, macrofaunal collections are equally important. Macrofauna serve as important prey for upper trophic benthivores on shallow Arctic continental shelves and are valuable long-term integrators of overlying water column properties because they have generally little mobility. Also, macrofauna sampling leaves a much smaller footprint on the seafloor than trawling. Therefore, a strong biodiversity program would include multiple scales of benthic faunal sampling, including macro-infauna.

Seastar. Photo: NOAA

Laetmonice filicornis.
Photo: Olga Zimina, Greenland Institute of Natural Resources

3.3.6 Conclusions and key findings

Status of Knowledge on Biodiversity

- Knowledge of benthic fauna diversity in all regions based on historical and current studies has accumulated > 4,000 known Arctic macro- and megabenthic species. This number does not include what we expect to be a considerable number of micro- and meiofaunal species, which are often not part of regular sampling programs with bottom trawls or traditional grab-sampling projects.
- Across all regions, the highest macro- and megabenthic taxonomic richness is within arthropod, mollusk and polychaete groups.
- There is a great need of information about little-known regions, such as the deep-sea Arctic basins, the high Canadian Arctic Archipelago, cryptic or difficult-to-identify taxon groups, and biological hotspots.

Temporal Trends and Drivers

- In the Barents Sea, macro- and megabenthic biomass declines are attributed to trawling impacts, while biomass increases are linked to the spreading of non-indigenous boreal (e.g., red king crab) or more sub-Arctic (e.g., snow crab) species.
- Sea-ice dynamics, ocean mixing, bottom-water temperature change, commercial bottom trawling, ocean acidification, river/glacier freshwater discharge and introduction of non-indigenous species are regarded as major drivers of observed and expected changes in benthic community structure in the Arctic.
- Benthic species are important food sources for indigenous people and marine mammals and seabirds. According to Traditional Knowledge (TK), stocks of benthic prey have decreased in walrus stomachs, particularly clams, while pelagic fishes have increased. The knowledge of the people living at the coasts of the Arctic Ocean must be recognized as an invaluable resource for our understanding of changes in Arctic benthic communities.
- Increasing numbers of species are moving into, or shifting, their distributions in Arctic waters. These species will outcompete, prey on or offer less nutritious value as prey for Arctic species.

Long-term Monitoring

- From the perspective of long-term monitoring, we suggest that the systematic study of macrobenthic (grab investigations) and megabenthic (trawl bycatch in regular fishery surveys including both annual studies, as in the Atlantic Arctic, and Davis Strait-Baffin Bay including those conducted by Fisheries and Oceans Canada and Greenland Institute of Natural Resources, and periodical studies as in the Northern Bering and Chukchi Seas) are the most suitable and practical approach for a pan-Arctic biodiversity assessment. Standardization of methodology, including taxonomic identification, across regions will assist in pan-Arctic comparability.
- A formalized monitoring plan (updated from Gill et al. 2011) can build on existing national, annual groundfish-shellfish trawl surveys, such as the ones implemented successfully in the Atlantic Arctic regions and Greenland Similar efforts should be implemented in other regions where trawl surveys are done regularly.
- In regions without regular groundfish-shellfish trawl surveys, information should be gathered from research programs, which are usually short-termed and do not guarantee spatial consistency in sampling, but still provide valuable information on benthic biodiversity and community patterns.

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Polar cod hiding in ice habitat.
Photo: Peter Leopold, Norwegian Polar Institute

3.4 Marine fishes

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Snapshot

- Pelagic and benthic fish species are important in Arctic marine ecosystems because they transfer energy to predators such as seabirds, marine mammals, as well as people.
- Northward range expansions are underway and pose unknown consequences for Arctic species and their interactions such as predation and competition.
- Fishes are affected by environmental conditions such as temperature, sea ice availability and salinity, and are constrained by prey availability and predator pressure, which can be influenced by climate change
- The ecologically important polar cod declined in the Barents Sea from 2004 to 2015, potentially because of predation from Atlantic cod, a more southern species. The 2016 survey showed a notable increase in abundance, driven by an unusually high abundance of one-year-old fish.
- Indices and monitoring programs based on harvested species or that rely on fishery-related data are inherently affected by changes in stock size and exploitation rate, making them imperfect sources.
- Northward expanding capelin is less lipid-rich and has led to changes in seabird diet in northern Hudson Bay and may affect marine mammals.
- Greenland halibut have undergone declines and subsequent recoveries over the last two decades in the northeast Atlantic.

3.4.1 Introduction

Arctic marine fish communities are changing as the result of altered environmental conditions. Elevated ocean temperatures and altered stratification, wave action and the availability of ice habitats are driving changes in habitat use patterns. Changes in habitat allow the northward expansion of bordering species, often altering competitive and predator-prey interactions. For example, the northward movement of capelin (a complex of *Mallotus* species) in Canadian Arctic waters represents the appearance of a competitor for current keystone forage fishes such as polar cod (*Boreogadus saida*), whereas the expansion of Atlantic cod (*Gadus morhua*) has led to greater predation pressure on polar cod in the northern Barents Sea.

Anthropogenic threats to Arctic marine fishes are likewise changing. Increased accessibility because of reduced sea ice concentration, extent and changes in the timing of melt and onset are creating new opportunities for fishing, petrochemical and mineral exploration and extraction, transportation and tourism. Additional vessel traffic creates increased noise, erosion and pollution. Of particular note, commercial fisheries, such as those targeting the valuable Greenland halibut (*Reinhardtius hippoglossoides*), have the potential to expand spatially following changes in species distributions or as previously inaccessible areas become ice-free for extended periods.

The 2013 *Arctic Biodiversity Assessment* (ABA) listed 633 species of marine fishes that have been recorded in the Arctic Ocean and adjacent seas (Christiansen et al. 2013). Approximately 10% are harvested commercially and are assessed for the purpose of providing quota advice. Much less is known about the other 90%, and the ABA revealed fundamental knowledge gaps in taxonomic status and species distributions. Large areas of the Arctic have never been surveyed for marine fish biodiversity. Monitoring programs for marine fishes or communities occur in relatively restricted areas and frequently focus on commercial fisheries (Fig. 3.4.1). Short-term biodiversity surveys have occurred sporadically, and are generally unsuited for monitoring changes in biodiversity over time.

Here we selected three marine fish Focal Ecosystem Components (FECs) that were listed in the Marine Biodiversity Monitoring Plan (Gill et al. 2011): polar cod, Greenland halibut and the capelin complex. Polar cod is an Arctic species with a circumpolar distribution whereas capelin and Greenland halibut are Arctic–boreal fishes found in Atlantic and Pacific, as well as Arctic waters (Mecklenburg et al. 2013). Within this chapter the terms Arctic, Arctic–boreal, and boreal when applied to fish species, identify the zoogeographic group to which a species belongs. The selection of marine fish FECs is intended to draw attention to a few species that are of particular ecological, subsistence or commercial importance throughout the Arctic.

Capelin and polar cod are important, widely dispersed forage fishes. The latter species was discussed in the ABA report and is of special relevance to the Arctic because of its close linkage with sea ice. Greenland halibut and capelin are harvested commercially in large areas of the Arctic. Together, these selected FECs illustrate changes occurring in marine fish taxa and consequences for food webs and subsistence and commercial fisheries. This report focuses on changes in Arctic biodiversity and related drivers since the 2013 ABA, which examined overall patterns in marine fish biodiversity in the Arctic Ocean and adjacent seas and examined a few fishery-targeted species in greater detail (Christiansen et al. 2013). The analysis relied on a 2011 synthesis of Arctic marine fish biodiversity (Mecklenburg et al. 2011), a number of regional annotated species checklists and previously unpublished data from research, surveys and monitoring undertaken by ichthyologist and fishery science authors.

3.4.2 Current monitoring

Data on species distributions and abundances are derived from governmental, academic or industry-related field programs. Governmental programs often have longer time series, good consistency in methods and equipment for specimen collection, and function for ongoing monitoring. Academic programs are typified by short time series and methods can vary considerably among studies. Industry-related programs are normally conducted by consulting companies contracted by natural resource-extraction companies. Data collection methods are often standardized, but time frames are usually short (< 5 years). Databases are managed by agencies or entities that conduct marine fish surveys, monitoring and assessments, and identifying and accessing these databases often poses a difficult legal exercise. Within this chapter, surveys are considered short-term assessments of fish communities and species distributions; these programs are suitable for collecting baseline data on species and ecosystems. Monitoring programs involve long-term data collection that is suitable for assessing changes in populations, species or communities, ideally together with data on environmental conditions to detect causal relationships for observed changes.

Surveys of marine fish biodiversity are needed throughout the Arctic. Large areas of the Arctic remain unsurveyed and while short duration (one to several years) surveys can provide essential information on marine fish distributions and abundance patterns, only long-term programs can be used to monitor changes in biodiversity (e.g., species distributions and ranges, community composition).

Canada has a large Arctic territory. Primary marine fish biodiversity surveys have been completed in much of the eastern and western portions of the Canadian Arctic, but marine fish distributions in the Canadian Arctic Archipelago remain largely unknown. Monitoring programs that are suitable for assessing changes in marine fish biodiversity are currently limited to Baffin Bay, Davis Strait and inshore waters on the east coast of Baffin Island. Annual multispecies bottom trawl surveys are conducted in Baffin Bay and Davis Strait, primarily to support stock assessments for Greenland halibut and northern and striped shrimp (*Pandalus borealis* and *P. montagui*, respectively). These surveys are effectively used to monitor benthic fish and invertebrate biodiversity (Jørgensen et al. 2011), but the spatial extent and depth range (200-1600 m) sampled are focused on the ranges of the target species. Between 2012 and 2014, the Beaufort Regional Ecological Assessment (BREA), Fisheries and Oceans Canada (DFO), conducted a thorough survey of marine fishes in the Canadian portion of the southern Beaufort Sea. This survey collected valuable information on fish distributions, but unless the survey continues in the future, there is no ongoing marine fish biodiversity monitoring in the Canadian Beaufort Sea. Disparate surveys conducted by government, academia and industry can be cobbled together in other areas for meta-analyses, but this approach is problematic for robust biodiversity monitoring.

The Greenland Institute of Natural Resources, Nuuk, conducts annual multi-species bottom trawl surveys in Baffin Bay, Davis Strait, Denmark Strait and in inshore waters of West Greenland. Greenland and Canada use the same vessel for Greenland

Polar cod.
Photo: Shawn Harper, University of Alaska, Fairbanks

Capelin.
Photo: Carsten Egevang/ARC-PIC.com

Greenland halibut.
Photo: Fernando Ugarte

Figure 3.4.1. Map of contemporary marine fish data sources. Green squares indicate data from benthic trawl monitoring efforts, blue squares indicate data from benthic trawl surveys, while red triangles indicate data from pelagic trawl monitoring efforts.

halibut surveys in Davis Strait-Baffin Bay; the two countries regularly combine their data for stock assessments and have conducted joint assessments of marine fish biodiversity (Jørgensen et al. 2011). Arctic waters off northeast Greenland are regularly monitored by UiT, The Arctic University of Norway as part of the TUNU Euro-Arctic marine fishes – diversity and adaptation program (Christiansen 2012). This also includes the area around Jan Mayen Island (Arctic and Atlantic water), the Svalbard Archipelago (Atlantic and Arctic water) and, whenever feasible, the Franz Josef Land Archipelago (Arctic water).

The surface waters, continental shelf and slope bottom in the Icelandic Exclusive Economic Zone (EEZ) are fairly well covered by five annual trawl-based monitoring programs that are conducted by the Marine Research Institute. There are also regular monitoring programs for Atlantic cod (annual gillnet), scallop (biannual dredge) and several pelagic fishes (annual acoustics and pelagic trawl). All of these programs occur primarily to assess commercial stocks; however, all fishes caught are identified to species and counted (Björnsson et al. 2007, Marine Research Institute 2010), and individual lengths are measured for a sub-sample of each species from each tow. However, fish communities in deep waters below 1,500 m and the mid-water realm are poorly known due to a lack of commercially important species. A few irregular and single-year surveys have been conducted to examine marine fishes in areas outside the core area.

Norway's Exclusive Economic Zone encompasses three large marine ecosystems, two of which, the Norwegian Sea (the northern part only) and the Barents Sea, fall within the Circumpolar Biodiversity Monitoring Program's (CBMP) Atlantic Arctic Marine Area (AMA) boundary (red outline in Fig. 3.4.1). These two seas sustain large fisheries, and commercially important fish stocks are monitored annually by the Institute of Marine Research (IMR), Bergen, Norway, to provide stock assessment and quota advice. Monitoring in the Norwegian Sea is a joint effort between Norway, Greenland, the Faroe Islands and Iceland. The main monitoring program in the Barents Sea is a joint effort between Norway and Russia. During Institute of Marine Research (IMR) programs, all fishes including non-commercial species are identified, tallied and weighed, but time series have not been developed for most non-commercial species because historical data are unreliable and little effort has been made to create time series. Furthermore, there are ongoing problems with species identification, especially of Arctic marine fishes, and the area assessed in the northern regions has been variable, partially because of variation in sea ice cover or the spatial distribution of the target species.

The Arctic marine waters of the U.S. are the northern Bering Sea, the eastern Chukchi Sea and the western Beaufort Sea. The Russian–American Long-Term Census of the Arctic (RUSALCA), a joint program of the National Oceanic and Atmospheric Administration (NOAA) Arctic Research Program and the Russian Academy of Sciences, conducted multidisciplinary surveys in 2004, 2009 and 2012 focused on both the Russian (western) and eastern waters of Bering Strait northward through the Chukchi Sea. In 2009, the expedition reached the eastern East Siberian Sea and the continental slope of the Arctic Ocean. Larval, juvenile and adult fishes were collected. One of the main focuses of the fish investigations was to explore under-studied waters to determine species presence and abundance. Following a hiatus since the 1970s in surveys and monitoring of the Arctic region, NOAA Fisheries established a plan for the management of fish resources in the Arctic waters of the U.S. in 2009 (NOAA 2009). Information provided includes NOAA's 5-Year Action Plan, with reporting to the public via NOAA's Arctic website (NOAA 2017). Recent NOAA fish surveys in the Arctic include the U.S. Beaufort Sea in 2008 and the U.S. Chukchi Sea in 2007 and 2012. In addition to surveys, the NOAA Arctic Research Program has sponsored, in conjunction with RUSALCA, studies of voucher specimens from historical and recent expeditions in the Arctic and adjacent waters in museums throughout the Northern Hemisphere, and molecular genetic studies contributing to the determination of species and resolution of taxonomic problems affecting assessments of biodiversity. The taxonomic and distributional baselines produced from the RUSALCA investigations in the Pacific Arctic were recently published, including analysis of taxonomic issues, geographic distributions and a guide to species identification (Mecklenburg and Steinke 2015, Mecklenburg et al. 2016).

The University of Alaska Fairbanks (UAF) has recently conducted fisheries research in the eastern Chukchi Sea (e.g., Norcross et al. 2013) and western Beaufort Sea. The most recent UAF surveys in the Beaufort Sea were conducted in 2012–2014 in conjunction with Canada (BREA) in a transboundary program. Voucher specimens from the UAF surveys, including those in the Beaufort Sea in 2012–2014, were examined and the information was incorporated in the Pacific Arctic baseline documents (Mecklenburg and Steinke 2015, Mecklenburg et al. 2016).

When interpreting trends in monitoring data, it is essential that the exploitation history of the subject species or community is taken into consideration to understand whether historical data represent unexploited or altered states. This is particularly true in cases where fisheries once existed but have been discontinued, or when subsistence fisheries are conducted with little scientific documentation (Zeller et al. 2011, Misund et al. 2016). The incorporation of Traditional Knowledge (TK) and fishers' knowledge (Armitage et al. 2011) in study planning, analyses and decision making can be beneficial for placing surveys and their results in appropriate contexts.

The Food and Agriculture Organization of the United Nations (FAO), the International Council for the Exploration of the Sea (ICES) and the Northwest Atlantic Fisheries Organization (NAFO) maintain publically accessible databases on fish harvests and fish stock assessments. The FAO database is useful for finding information on total harvests of commercially important species that inhabit the Arctic, but the FAO areas are very large, rendering the database useless for estimating spatial distributions. Species identification in the FAO database is also an issue (Lleonart et al. 2006). For example, there are no records of ice cod (*Arctogadus glacialis*), only polar cod. Given their strong morphological similarities and frequent co-occurrence in trawl hauls, it is therefore likely that a portion of the reported polar cod catch is actually ice cod. FAO area 18 covers the high Arctic, but data on marine fish catches in that area have been shown to be highly inaccurate and the records do not include indigenous subsistence catches (Zeller et al. 2011). The NAFO and ICES catch databases record catches on smaller spatial scales, making them more useful for analyzing changes in harvesting patterns in Atlantic Arctic regions. In addition to fisheries management databases, several open biodiversity databases have been created, including the Ocean Biogeographic Information System, the Global Biodiversity Information Facility, FishSource and the Sea Around Us Project.

3.4.3 Status and trends of FECs

Checklists and identification guides for marine fishes in the Arctic

Up-to-date checklists and identification guides are essential tools for monitoring biodiversity. A group of ichthyologists and fishery biologists recently assessed species presence in the Arctic region and produced an annotated list, with common names in several languages, which was made available online by CAFF (Mecklenburg et al. 2013). This list is being revised for a 2nd edition. An atlas and guide in progress will provide global distribution maps, identification features and assessment of taxonomic issues pertaining to all marine fishes documented to occur in the Arctic region; publication is scheduled for 2018 (Mecklenburg et al. in prep.).

Marine fishes occurring in the waters off eastern Siberia, Russian Federation, Alaska, U.S., and the Yukon and Northwest Territories, Canada were assessed for the recently published baseline summary (Mecklenburg and Steinke 2015) and distributional atlas and identification guide to *Pacific Arctic Marine Fishes* (Mecklenburg et al. 2016). These works expand and update the information on Arctic fishes provided in the compendium on *Fishes of Alaska* (Mecklenburg et al. 2002), and are being expanded to include the Atlantic Arctic marine fishes for the pan-Arctic atlas (Mecklenburg et al. in prep.).

For Canada, the Coad and Reist (2004) annotated checklist of Arctic marine fishes of Canada is expected to be published in expanded form with dot-distribution maps early in 2017 as an Atlas of Canadian Arctic Fishes (Coad et al. in press).

The distribution of fishes around Greenland was recently assessed from scientific and fishery surveys, including literature and voucher specimens in the University of Copenhagen collection (Møller et al. 2010).

A book of all fish species known to occur in Icelandic waters is published regularly (Jónsson and Pálsson 2013) and, between editions, an article is published annually to report any new records (e.g., Pálsson 2014).

Fish diversity around Jan Mayen was assessed from IMR data and voucher collections at the University of Bergen (Wienerroither et al. 2011b). New data have also been incorporated in recent treatments on fishes of the Faroe Islands (Mouritsen 2007) and Norway (Pethon 2005). Fishes of Norwegian and Russian waters of the Barents Sea were treated in two atlases of information from IMR investigations: one from summer fish collections and one from winter collections (Wienerroither et al. 2011a, 2013).

Original data and summaries of published information on fishes of the Kara Sea have been provided in Borkin et al. (2008) and Dolgov (2013). An annotated catalog of *Fishes of Russian Seas* provides taxonomic synonymies as well as summary information on geographic distributions for all the marine waters of Russia, based on the collections in the Russian Academy of Sciences as well as the scientific literature (Parin et al. 2014).

*Figure 3.4.2. Distribution of polar cod (*Boreogadus saida*) based on participation in research sampling, examination of museum voucher collections and the literature (Mecklenburg et al. 2011, 2014, 2016; Mecklenburg and Steinke 2015). Map shows the maximum distribution observed from point data and includes both common and rare locations.*

Polar cod

Polar cod is the most abundant cod species around the Arctic. It is a key ecological species in the Arctic Ocean due to its pan-Arctic distribution (Fig. 3.4.2), large standing stocks and role as an energy transmitter to higher trophic levels (Bradstreet et al. 1986, Hop and Gjøsæter 2013). In bottom trawl surveys on Arctic continental shelves, it is typically one of the most numerous fishes caught and often the most numerous. Polar cod was the most abundant fish species in RUSALCA catches in the Chukchi Sea in 2009 and 2012, and in 2004 it was the fourth most abundant species (Mecklenburg et al. 2016). In deeper waters, it is not as abundant in bottom trawls but concentrates under the sea ice (Karamushko 2012, Mecklenburg et al. 2014). Polar cod feed on ice-associated fauna as well as shrimp, zooplankton, particularly hyperiid amphipods and *Calanus* copepods (Lønne and Gulliksen 1989, Hop and Gjøsæter 2013, Dalpadado et al. 2016, Majewski et al. 2016) and small fishes, and use the ice as a refuge from predation and as spawning habitat (Gradinger and Bluhm 2004, Gradinger et al. 2010). One-year-old polar cod follow the sea ice drift (David et al. 2015). Polar cod has antifreeze agents in its blood, which makes it possible for this species to use sea ice as habitat (Osuga and Feeney 1978).

Despite its circumpolar distribution, polar cod exhibits little genetic variation. DNA barcodes from the East Siberian and Chukchi seas eastward to the Greenland Sea illustrate this low variation. Although genetic variation has been found at both pan-Arctic and regional scales, and polar cod is clearly not genetically homogeneous across its range, the general structure is weak and population subdivisions, although they may exist, have not been revealed (Nelson and Bouchard 2013). No division into species or subspecies has been proposed and the Arctic zoogeographic pattern of polar cod is clear (Fig. 3.4.2).

Due to its particular characteristics, polar cod is a suitable indicator species for monitoring Arctic marine fish communities, as well as Arctic food webs in general. However, few monitoring time series exist for polar cod, except in the Barents Sea, where it is harvested commercially (Hop and Gjøsæter 2013). Acoustic time series data on the Barents Sea population dates back to 1986, but these data are inconsistent in spatial coverage and the sampling programs primarily targeted capelin (Ajiad et al. 2011). Since 2004, more comprehensive and reliable data are showing declines in Barents Sea polar cod (Fig. 3.4.3). Losses of sea ice habitat may have contributed to the recent poor recruitment (low 0-group index, Fig. 3.4.3). The 0-group index for 2013-2015 was < 10% of the average from 1980-2012 (4360 million individuals). Recruitment failure, migration, together with increased predation pressure from northward expanding Atlantic cod may have impacted the survival of polar cod (Box 3.4.3; Kjesbu et al. 2014, Ingvaldsen et al. 2015). A survey completed in 2016 showed a notable increase in polar cod biomass to 900,000 t, a level last seen in 2009, primarily because of an unusually high catch of age one fish (Joint Russian-Norwegian Ecosystem Survey unpubl. data, autumn 2004-2016). Studies and data are also available on polar cod from regular monitoring in Iceland (Ástþórsson 2015). As in the Barents Sea, these programs target other species such as Atlantic cod and northern shrimp, and therefore do not necessarily cover the entire distribution range of polar cod. It is still undetermined if the polar cod population in Icelandic waters is declining due to increasing water temperatures.

Polar cod is the only true Arctic species that has sustained considerable, although highly variable, commercial fisheries (Fig. 3.4.4). Fisheries expanded quite rapidly in the late 1960s, reaching 348.4 kt in 1971, but have fluctuated considerably since then at around 20 kt y^{-1}. Polar cod have primarily been fished by Russian vessels in the Barents Sea, but Norway, Germany and Greenland have also fished polar cod, albeit at much lower levels. Polar cod is considered a low value species by the Norwegian fleet and is harvested for fishmeal and oil (Cohen et al. 1990), but in Russia at least part of the harvest is meant for human consumption. In addition to harvest in directed fisheries, unreported bycatch of polar cod could be considerable in shrimp (Garcia 2007) and capelin fisheries (Vilhjálmsson et al. 2005).

Box 3.4.2: Polar cod and capelin

Polar cod and capelin are expected to respond differently to climate change based on key differences in life history characteristics and habitat associations (reviewed in Hop and Gjøsæter 2013). Reductions in sea ice will likely alter the reproductive success of polar cod due to loss of sea ice habitat for spawning (Bouchard and Fortier 2011), larval development (Bradstreet 1982) and as a predator refuge (Gradinger and Bluhm 2004). In contrast, periods of relatively warm water temperatures and reduced sea ice extent favour the northward expansion and increased abundance of capelin (Rose 2005a) leading to increased co-occurrence with polar cod (e.g., Orlova et al. 2009). Negative effects of sea ice declines on polar cod may be further compounded by interspecific competition with capelin for zooplankton resources, particularly large *Calanus* copepods (Orlova et al. 2009, Hop and Gjøsæter 2013, McNicholl et al. 2016). The consequences of interspecific competition and direct pressures from reductions in sea ice extent are likely to be significant given the key role of polar cod in Arctic marine food webs (e.g., Welch et al. 1992). Ongoing monitoring and collection of new baseline data are needed to report on patterns in polar cod and capelin distributions and abundances as key indicators of climate variability and impacts in Arctic marine ecosystems.

Polar cod.
Photo: Shawn Harper,
University of Alaska, Fairbanks

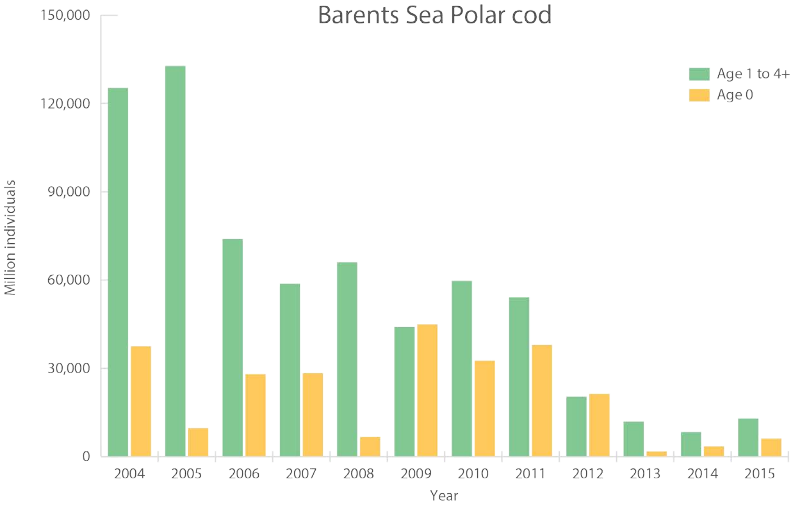


Figure 3.4.3. Polar cod in the Barents Sea. Acoustic estimate of polar cod 1-year-old and older (green) and pelagic trawl index of age 0-group abundance (yellow). Source: Joint IMR-PINRO ecosystem survey (Prozorkevich 2016).

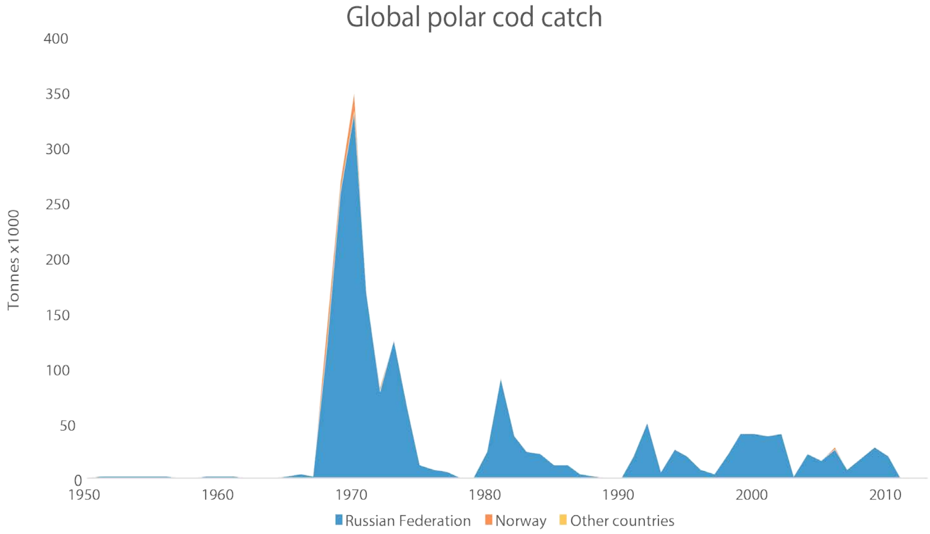
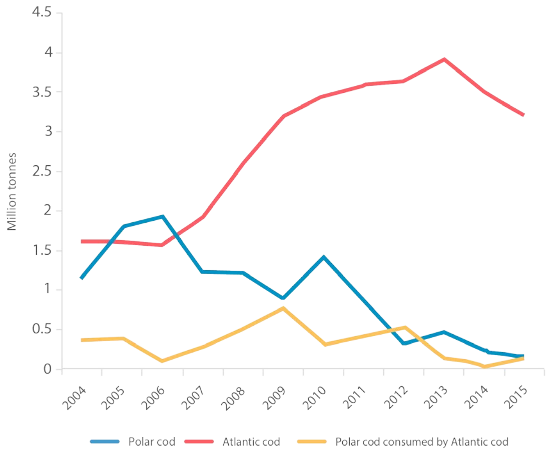


Figure 3.4.4. Global catches of polar cod from 1950 to 2011 (FAO 2015); 95% of the catches are from the Barents Sea.

Box 3.4.3: Polar cod and Atlantic cod in the Barents Sea

Atlantic cod is an important predator in shelf ecosystems of cold-temperate (boreal) North Atlantic waters. In the Barents Sea, the Atlantic cod has recently increased in both stock size and distribution area. Atlantic cod are currently found all over the Barents Sea shelf during summer, including the northern, colder parts that are inhabited by polar cod. This has led to increased spatial overlap between the two species. The larger-bodied Atlantic cod feeds effectively on polar cod in areas of overlap. The increased overlap has led to increased predation pressure on polar cod, most likely contributing to the observed population decline. Estimates of total consumption of polar cod by Atlantic cod peaked in 2009, exceeding 0.7 million tonnes (ICES 2016). In 2012, the estimated consumption was higher than the estimated standing stock (0.5 and 0.3 million tonnes, respectively). A high predation pressure can be withstood if polar cod recruitment is high. However, since 2013 there has been an almost complete recruitment failure of polar cod in the Barents Sea (Fig. 3.4.3).



Box figure 3.4.1 Estimated consumption of polar cod by Atlantic cod in the Barents Sea (yellow line) and biomass of the Atlantic cod stock in the Barents Sea (red line) (ICES 2016). The blue line is the biomass of the Barents Sea polar cod (Prozorkevich 2016).

Capelin

Capelin are pelagic forage fishes and play an important role in marine food webs in the Arctic as prey for Arctic marine mammals (Watts and Draper 1986, Dahl et al. 2000, Dolgov 2002, Bluhm and Gradinger 2008, Marcoux et al. 2012, Watt et al. 2013), seabirds (Erikstad 1990, Dolgov 2002, Gaston et al. 2003, Gjøsæter et al. 2009) and piscivorous fishes (Dempson et al. 2002, Dolgov 2002, Dennard et al. 2009, Harwood and Babaluk 2014). The migration of capelin at various life stages represents a significant transfer of energy between oceanic habitats and nearshore spawning grounds (Vilhjàlmsson 2002).

Populations of capelin represent several species, most of which are not completely resolved (Mecklenburg et al. 2011). The Pacific population was recently reclassified as a full species, the Pacific capelin (*M. catervarius*; Mecklenburg and Steinke 2015). Morphological and molecular data suggest a continuous distribution of Pacific capelin from the Sea of Japan, Sea of Okhotsk, the eastern Gulf of Alaska and the Bering Sea to the Laptev and East Siberian Seas and across Arctic Alaska and Canada to Davis Strait. Two populations that probably represent separate species include one from east Greenland to the Kara Sea, which is most likely the originally described *M. villosus*, and one from Hudson Bay, the Gulf of St. Lawrence and marine waters off Newfoundland, Labrador and Nova Scotia, which at present lacks a species name (Mecklenburg and Steinke 2015). Thus, we refer here to the capelin species complex, including the two or more unresolved, unnamed Atlantic species and the recently defined Pacific capelin. The overall distribution of the complex as well as that of the Pacific capelin is presented in Figure 3.4.5.

Several life history characteristics, including broad physiological limits, potential for fast population growth and thermal constraints on the timing of spawning, make capelin a relevant indicator of climate variability (Rose 2005a, b, Davoren et al. 2012). A variety of information sources indicates increasing trends in the abundance and distribution of capelin in Arctic waters. Capelin are

*Figure 3.4.5. Distributions of all capelin species (light green) and Pacific capelin (*Mallotus catervarius*; dark green pattern) based on participation in research sampling, examination of museum voucher collections, the literature and molecular genetic analysis (Mecklenburg and Steinke 2015, Mecklenburg et al. 2016). Map shows the maximum distribution observed from point data and includes both common and rare locations*

Box 3.4.1 Indigenous Knowledge and capelin

By Carolina Behe, Inuit Circumpolar Council-Alaska, Qaiyann Harcharek, Northslope Borough Wildlife Department, Dawn Miller and Marjorie Tahbone Indigenous Knowledge holders from Nome, Alaska

Capelin is a vital part of the ecosystem and is an important food source throughout the Arctic food web. In Alaska, capelin are often referred to as candlefish or cigar fish because of its heavy oil content (they are a fatty fish). In Iñupiaq (an Alaskan Inuit dialect), the name is paŋmaksraq, in Invialuktun (a Canadian Inuit dialect) the name is Anmagiak, and in Kalaallisut (a Greenlandic dialect) the name is Ammassaat.

Inuit Knowledge (Indigenous Knowledge held by Inuit) across the Arctic includes invaluable information on the capelin distribution, behavior, spawning periods, changes associated with change in water temperature, winds and currents, and knowledge of the role that capelin play in the overall food web. This includes the cultural and social importance that the animal holds within the Inuit culture.

Indigenous Knowledge holders in Alaska, Canada and Greenland have shared that this fish is sometimes found in the stomachs of piscivourous fish, such as Dolly Varden and salmon (Remnant and Thomas 1992, McDonald et al. 1995, Golder Associates Ltd. 2002, Brewster et al. 2010). Other marine mammals such as beluga, orcas and seals also rely on capelin as a food source (Remnant and Thomas 1992, McDonald et al. 1995, Olsvig and Mosbech 2003). In the Canadian Kugluktuk area, capelin spawn in shallow nearshore areas and the eggs come up on the beach (Golder Associates Ltd. 2002). Here, Inuit Knowledge shares that capelin are an important food source for ringed seals. When capelin become abundant on the coast in September the ringed seal also become abundant (Golder Associates Ltd. 2002).

On the North Slope of Alaska, from mid July to early August, schools of capelin let themselves wash ashore in the waves, and then wash back into the ocean. It is then, when people harvest them, scooping them from the beach or as they are washed to and from the beach. They are considered excellent food, but were in the past also widely used for dog food and fox trapping bait. The introduction of western culture, foods, cash and stores, meant that access to food was easier and there wasn't much need to spend the time and effort required to gather capelin, which many needed for a family meal. However today many people are experiencing a natural urge or instinct to reclaim their cultural identity, in this instance the gathering of capelin, and a new generation of harvesters is emerging (18-35 year-olds).

In the Nome, Alaska area capelin also come in with the currents in the spring and wash ashore. When birds, such as seagulls, begin to dive at the shore line, it is an indicator that the fish are there and people prepare to harvest. Some villages have reported a change in capelin associated with currents. For example, Raymond-Yakuobian (2013) reports that experts in in the Bering Strait region noted that capelin still come close to the beach but do not beach themselves or get pushed up by the waves like they used to.

This fish is an important food source for many Inuit. Especially those that do not have equipment to travel far from the shore to collect food. For the past couple of years, the fish have been coming in earlier and remaining a little bit longer. This year (2016) some people chose not to catch them, because the weather was not good for drying.

Drying capelin. Photo: Marjorie Tahbone commercially exploited in Arctic and sub-Arctic regions (Fig. 3.4.6), and recently, all major stocks exhibited northerly range displacements associated with periods of warmer water temperature and reduced sea ice extent (Rose 2005a, b, Pálsson et al. 2012, Ingvaldsen and Gjøsæter 2013). Similar trends of increasing occurrence and abundance of capelin are documented from the eastern Canadian Arctic and Hudson Bay complex based on long-term changes in the diets of marine mammals (Marcoux et al. 2012, Chambellant et al. 2013, Young and Ferguson 2014), fishes and seabirds (Gaston et al. 2003, Gaston and Elliott 2014). In addition, community-based observations suggest increased frequency of capelin occurrence in the coastal Beaufort Sea since the early 2000s based on observations of spawning events and predation by Arctic char (*Salvelinus alpinus*; (Paulatuk Hunters and Trappers Committee unpubl. Data). New survey data have provided valuable baselines of capelin occurrence and/or abundance in data-poor regions of the offshore Beaufort and Chukchi Seas (Logerwell et al. 2015, McNicholl et al. 2016).

Potential consequences of the increasing role of capelin and associated declines of polar cod in the diets of piscivorous seabirds and marine mammals are unknown, but may represent significant impacts on Arctic ecosystems. For example, while the two species have comparable body size and energetic content (reviewed in Hop and Gjøsæter 2013), and occupy similar trophic positions (Hop et al. 2002, Marcoux et al. 2012), capelin populations fluctuate widely and can exert strong bottom-up effects on predator populations (e.g., Gjøsæter et al. 2009, Hop and Gjøsæter 2013). Further, increased abundance of capelin in Arctic waters may exert additional pressure through intraspecific competition on populations of polar cod that are already negatively influenced by climate related changes with regards to habitat availability (Box 3.4.2).

In the northeast Atlantic, capelin and Atlantic cod are linked together in a close predator-prey relationship and the largest Atlantic cod stocks in the world occur where capelin is available as food (Vilhjálmsson 1997, Howell and Filin 2014, Rose and Rowe 2015). In general, the capelin has a more northerly distribution than the Atlantic cod, but needs to migrate to warmer shallow waters to spawn. It is during this period that northern Atlantic cod stocks feed intensely on capelin (Vilhjàlmsson 2002). Capelin fisheries are managed with this interaction in mind; sufficient capelin is allowed to escape the fisheries to be able to spawn and provide food for Atlantic cod and other species.

Capelin is one of the most fished fish species in the world, ranking 12th in 2013 (FAO 2015). In 1977, it was the second most fished species in the world after Alaska pollock (*Gadus chalcogrammus*). In a global comparison of fisheries, capelin is therefore a major species. The vast majority of catches occur in the northeast Atlantic from the Icelandic and Barents Sea stocks (Fig. 3.4.6). Catches in the northwest Atlantic are much lower and catches in the Pacific are negligible. Because of its short lifespan (five to seven years, Hansen 1943), fisheries generally harvest from mainly one cohort per year. Capelin fisheries are therefore characterized by large annual fluctuations depending on recruitment. In Iceland, for example, annual fisheries have fluctuated from zero to more than one million tonnes, and can exceed the combined catches of all other species.

Capelin stocks are assessed in the North Atlantic by ICES, NAFO and DFO. Assessments for the northeast Pacific are available from NOAA Alaska Fisheries Science Center. The stocks are generally considered well managed, but two issues complicate management (Vilhjálmsson 2002, Rose 2005, Ingvaldsen and Gjøsæter 2013). First, quotas are highly variable between years because of capelin's short life cycle, with maturation at age two to five (Hansen 1943), and highly fluctuating abundance. Second, when quotas are set it is important to keep in mind that capelin represents key forage for other more valuable commercial species, especially Atlantic cod and Greenland halibut. Any generalization on the current status of capelin stocks has to be considered cautiously due to the extreme fluctuations observed in the stocks. However, stocks off Newfoundland, Canada are growing after a long period of depletion. The northeast Pacific stock is large in comparison over the long-term, while the Icelandic and Barents Sea stocks are small.

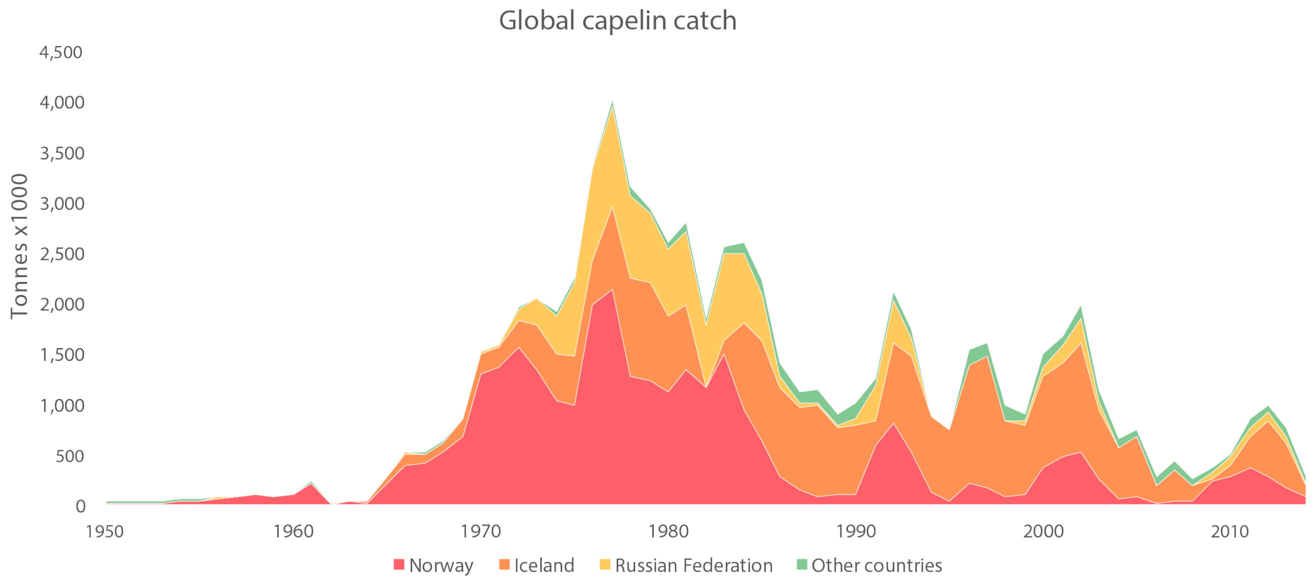


Figure 3.4.6. Global catches of all capelin species from 1950 to 2011 (FAO 2015).

Greenland halibut

Greenland halibut is a top predator, feeding on a variety of smaller species, including polar cod and capelin (Sólmundsson 2007). It is basically a benthic species, closely associated with the sea floor, but unlike other flatfishes it swims with ventral side downward like a non-flatfish and is wide-ranging in its behavior. Although there are gaps in its distribution between the Atlantic and Pacific and some taxonomists have long maintained that two species with slight morphological differences are represented, molecular genetic evidence has verified that only one species is represented (Mecklenburg et al. 2011, 2014, 2016, Roy et al. 2014). Northeast Atlantic stocks that are assessed separately probably originate from common nursery areas around Spitsbergen (Albert and Vollen 2015).

Large juvenile and adult Greenland halibut are typically found in water depths from 200 to 2000 m and in waters deeper than the continental shelf break. Catches at shallow depths on the shelf usually comprise juveniles (Bowering and Nedreaas 2000). In the Pacific Arctic, typically only juveniles are found on the shelf and they are not found there every year; for instance, juveniles were absent from RUSALCA trawl catches on the Chukchi shelf in 2004 and 2012, but were present in 2009. Relatively large individuals are common, although not abundant, on the upper slope in the Chukchi and Beaufort seas (Mecklenburg et al. 2014). This species is more abundant elsewhere in the Arctic and in the Pacific south of the Chukchi Sea, including the southern Bering Sea. On the eastern shelf of Baffin Island, immature Greenland halibut are regularly found throughout the open water season at depths as shallow as 400 m. Tagging studies have shown large-scale movements by adult Greenland halibut, with tagged individuals moving from Baffin Bay to the Grand Banks and western Iceland (Boje 2002). Greenland halibut have pelagic eggs and larvae; spawning generally occurs over several months in the winter (Gundersen et al. 2010, Sohn et al. 2010) and juveniles move higher in the water column as they develop, until settling in the late summer or autumn (Jensen 1935). This prolonged pelagic phase exposes eggs and larvae to a different suite of stressors than those affecting adults (pelagic versus primarily benthic).

*Figure 3.4.7. Distribution of Greenland halibut (*Reinhardtius hippoglossoides*) based on participation in research sampling, examination of museum voucher collections, literature and molecular genetic analysis (Mecklenburg et al. 2011, 2014, 2016, Mecklenburg and Steinke 2015). Map shows the maximum distribution observed from point data and includes both common and rare locations.*

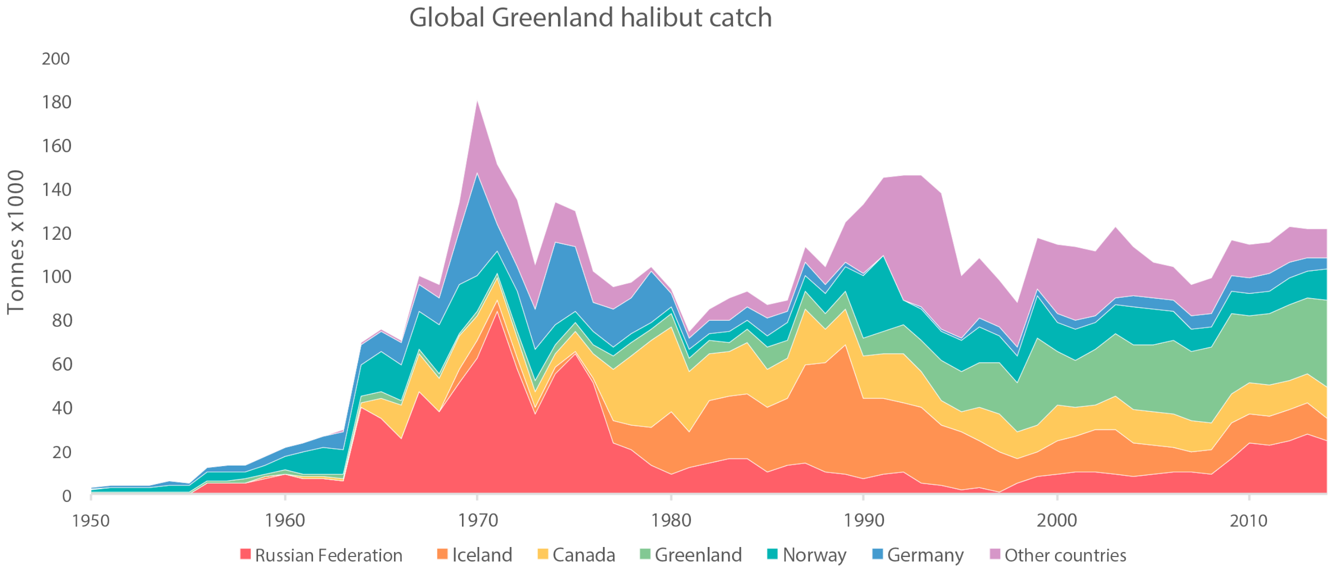


Figure 3.4.8. Global catches of Greenland halibut (FAO 2015).

Communities in the high north have relied on Greenland halibut throughout history as a valuable subsistence resource. Some commercial fisheries have been conducted north of Norway and along the Russian Murman coast since the 17th Century (Lajus et al. 2005). However, large-scale commercial fisheries are rather recent and started with Norwegian longliners (Godø and Haug 1989, Nedreaas and Smirnov 2004). In the mid 1960s, catches increased substantially when Soviet and German deep-water trawlers joined the fishery. Later, Canadian, Icelandic and Greenlandic trawlers, longliners and gillnetters joined as well. Several other nations participate on a smaller scale, including distant fleets from Spain, Portugal, Estonia and Poland. Old catch records for Greenland halibut are not considered reliable as the species might not have been differentiated from Atlantic halibut or were classified with "various pleuronectiformes" (Godø and Haug 1989).

Greenland halibut is one of the most valuable fishes in the Arctic. Per unit weight, Greenland halibut is two and a half times more valuable than Atlantic cod (Directorate of Fisheries Iceland 2015), which is already valuable. Greenland halibut is currently commercially fished in the Arctic waters of Canada, the Faroe Islands, Greenland, Iceland, Norway and Russia (Fig. 3.4.8). The largest fisheries are currently conducted by Greenland. Similar amounts are fished in the northeast and northwest Atlantic, but the catch in the north Pacific is much lower. For the last 40 years, fisheries have fluctuated around 100 kt y^{-1}, with several nations participating in the fisheries.

Stocks of Greenland halibut are assessed in the North Atlantic by ICES, NAFO and DFO. Formal assessments for the northeast Pacific are available from NOAA Alaska Fisheries Science Center. Greenland halibut stocks are generally considered well managed, but stock assessments have been hindered by difficulties in age-determination of individual fish (Treble et al. 2008). Fisheries in eastern Greenland, Iceland and the Faroe Islands harvest from a single stock. This northeast Arctic stock has undergone considerable declines since a maximum harvest in 1988, but rebuilding efforts have been successful (ICES 2015a). The stock trend for Bering Sea Greenland Halibut is very similar, with a long decline from 1993 to 2010 and subsequent increase (NPFMC 2015). The stock in the Barents Sea is considered to be in good condition and growing considerably since the 1990s (ICES 2015b). The Greenland halibut fishery in Baffin Bay and Davis Strait that is conducted by Canada and Greenland has been relatively stable (Jørgensen and Treble 2015).

The history of exploitation for Greenland halibut demonstrates the interest and energy related to expanding Arctic commercial fisheries. Fishing seasons and areas in Arctic waters can be heavily dictated by sea ice conditions. Reductions in the extent, duration and thickness of sea ice provide opportunities for the extension of fishing seasons and the expansion of fishing footprints, which will lead to new impacts on Arctic marine ecosystems.

The species is subjected to different stressors during its life stages as individuals' progress from pelagic to essentially benthic lifestyles. The value and apparent resilience of Greenland halibut practically ensure that fisheries will continue and likely expand in the future. Taken together, these factors make Greenland halibut a useful species for assessing fishery impacts on target species and supporting ecosystems in the Arctic.

3.4.4 Drivers of observed trends

The three marine fish FECs discussed here are indicative of different changes that are occurring in the Arctic and demonstrate the varied responses observed among species.

Polar cod has declined rapidly in the Barents Sea in the last decade and the stock is currently at a very low level (Fig. 3.4.3) although a survey in 2016 showed a notable increase in polar cod biomass, primarily because of an unusually high catch of age-one fish (Joint Russian-Norwegian Ecosystem Survey unpubl. data, autumn 2004-2016). There is no evidence of declines in other areas, but data are lacking. Catches of polar cod have declined since a peak in the 1970s (Fig. 3.4.4) and most of the catches are from the Barents Sea. The current harvest of polar cod is negligible and has not contributed to the recent decline. In addition to fishing

Fishing boat, Greenland. Photo: Carsten Egevang/ARC-PIC.com

pressure, polar cod is being affected by the northward expansion of boreal species, such as Atlantic cod, which impose new predatory or competitive pressures, and changes in sea ice, which provides important habitat for spawning and protection from predators.

Capelin stocks throughout the Arctic are shifting northward and have exhibited rapid demographic changes. Capelin stocks are typified by large interannual fluctuations, making it difficult to detect trends in abundance, but the recent environmentally-driven northward displacement of capelin is a consequence of changes in sea ice and water temperature. Greenland halibut has undergone declines and subsequent recovery over the last two decades in the northeast Arctic. Populations in the Barents Sea, Baffin Bay and Davis Strait are considered stable or increasing. Greenland halibut has supported various commercial fisheries, which have been spatially and temporally limited by sea ice duration and extent.

Most of the drivers affecting marine fishes in the Arctic are linked, directly or indirectly, to climate change. As ocean temperatures increase, the distributions of zoogeographical groups can change both south to north (Wassmann et al. 2011, Hollowed et al. 2013) and across Pacific and Atlantic Arctic waters (Mecklenburg et al. 2014, Wisz et al. 2015). Increases in the relative abundance of warmer water species have already been documented in the Bering Sea (Mueter and Litzow 2008), Barents Sea (Fossheim et al. 2015), Eastern Canadian Arctic (Mullowney et al. 2014), Greenlandic (MacKenzie et al. 2014) and Icelandic waters (Stefánsdóttir et al. 2010, Valdimarsson et al. 2012). Spatial overlap among species from different zoogeographical groups will increase as the distributions of fish species shift northward because larger-bodied boreal species are shifting northwards at a faster rate than Arctic species are retreating. This can cause increased predation on Arctic species, higher competition for food and possibly elevated risk of disease (Harvell et al. 1999, Bradley et al. 2005). As a consequence, food web structure becomes altered (Kortsch et al. 2015). The increasing inter-specific overlap and consequent predation by Atlantic cod on polar cod in the Barents Sea is illustrative of this pattern (Box 3.4.3), and there has been an overall decline in occurrence of Arctic fishes in the Barents Sea from 2004 to 2015 (Johannesen et al. 2017). Similarly, the northward expansion of capelin in some areas of the Arctic has resulted in novel competition with polar cod for zooplankton prey (Box 3.4.2). In addition to the direct effect on polar cod, this change in the marine fish community can have bottom-up effects on marine mammals, seabirds and piscivorous fishes that experience a change in their prey field and consequently their diet and nutritional status.

The effects of acidification on Arctic fishes are still unclear, but recent studies on Atlantic cod showed higher juvenile mortality with elevated acidification (Stiasny et al. 2016). The geographic extent, temporal extent and thickness of sea ice all have influence on Arctic marine fishes. Sympagic species, such as polar cod use sea ice as a critical habitat and reductions in sea ice cover and concentration, or changes in the timing of freeze-up and break-up, represent a loss of spawning habitat and refuges from predation (Bradstreet 1982, Gradinger and Bluhm 2004, Bouchard and Fortier 2011). Because polar cod rely on sea ice for spawning habitat and refuge from predation, changes in sea ice conditions can have fitness consequences for polar cod. The marginal ice zone is particularly relevant in this regard. Sea ice cover, thickness and concentration are limiting factors for marine fish surveys and fisheries (Bowering and Nedreaas 2000, Albert et al. 2001). Increase in the duration of the ice-free period permits fisheries to operate for longer periods within a year and reductions in sea ice extent allow access to previously unsurveyed habitats. Decreases in sea ice concentration and thickness allow smaller vessels to fish commercially without risking ice damage. Sea ice cover can also provide refuge from fisheries, protecting both fish stocks and ecologically important bottom features such as corals and sponge beds (Garcia et al. 2006).

Northward advance of valuable boreal species, retreat of Arctic species and increased accessibility due to less ice cover will increase the total fishing pressure and open new areas for fishing in northern areas. Overfishing of target fish species is generally not of concern, as these fisheries are considered well managed (ICES 2015a, ICES 2015b, NPFMC 2015). However, side effects, such as possible damage from bottom trawling to important benthic ecosystems and bycatch of vulnerable Arctic fishes are of concern (Christiansen et al. 2014). Greenland halibut fisheries have been generally stable. The decline in the northeast Arctic stock marks a notable decline in a commercial Greenland halibut fishery, but the subsequent recovery of the stock demonstrates the resilience of this species to harvest. The pan-Arctic distribution of Greenland halibut makes the expansion of current commercial fisheries likely as sea ice continues to decline. Greenland halibut are fished using bottom trawls, gillnets and longlines, all of which contact the sea bottom, albeit with substantially different intensity. Previously unexplored or exploited areas in the Arctic may harbour sensitive coral and sponge communities that provide important marine fish habitat. Given our generally poor understanding of the reproductive ecology of marine fishes in the Arctic and the drivers of marine fish productivity, bottom contact surveys and fisheries in new areas must proceed with considerable forethought. The central Arctic Ocean is of particular interest for fisheries because it falls outside the boundaries of national EEZs. Most of this area is currently inaccessible to fisheries due to almost constant ice cover, but the area could open-up and attract international fishing fleets (Pan and Huntington 2016).

3.4.5 Knowledge and monitoring gaps

Monitoring and even baseline assessments of Arctic marine fish biodiversity remain limited, but considerable progress has been made in recent years in conducting baseline biodiversity assessments (e.g. Møller et al. 2010, Mecklenburg et al. 2011, 2016, Wienerroither et al. 2011a, b, 2013; Jónsson and Pálsson 2013). Short-term data collections have provided occurrence data in many locations, but quantitative assessments and monitoring remain the exception instead of the norm. Surveys need to be conducted in previously un-assessed areas of the Arctic to provide baseline data. Areas that have been surveyed in the past, but not in recent years, need to be revisited to identify changes in local biodiversity. Regular biodiversity monitoring programs are needed throughout the Arctic, not only in areas that support commercial fisheries.

Accurate identification of fishes caught is essential to the success of monitoring efforts. The taxonomic uncertainties, which have made identification of some species difficult in the past, are a major focus of researchers around the Arctic. Several issues identified (e.g., Mecklenburg and Steinke 2015) have already been resolved. For instance, a recent molecular and morphological analysis reduced nine nominal species of *Gymnelus* eelpouts reputed to be present in the Arctic to two species (Mecklenburg and Anderson 2015). Many others remain to be resolved; for instance, the species limits and distributions of the capelin complex. Although such studies do not always pertain to "important" species, all species need to be accurately represented in biodiversity monitoring, and some may be more important ecologically than currently understood. The recently published atlas and guide to Pacific Arctic marine fishes coupled with the ongoing pan-Arctic atlas are intended to fill the distributional atlas and identification guide gaps.

Gaps in knowledge of the physical environment are also problematic. Seabed mapping is limited in Arctic waters. The spatial coverage of navigational charts covers the small fraction of the Arctic that experiences regular marine traffic, and in many cases the underlying data date back to the 1950s or 1960s (e.g., Canadian Arctic waters). Existing charts require updating to account for factors such as changes in global water levels and glacial rebound. With the opening of new waters due to reductions in sea ice extent and duration, hydrographic surveys need to be conducted to allow safe passage of commercial and recreational vessels. Hydrographic data are also essential for fish habitat mapping to support fisheries management within an ecosystem context.

3.4.6 Conclusions and key findings

- Conduct pan-Arctic taxonomic analyses to clarify zoogeographic patterns that are important for detecting and understanding change.
- Indices and monitoring programs based on harvested species or that rely on fishery-related data are inherently affected by changes in stock size, exploitation rates and exploitation history.
- TK holders have a considerable wealth of information regarding marine fish FECs that is needed to increase our knowledge of interconnected systems.
- Areas that are not fished commercially have been poorly surveyed, and when examined the programs are typically of short duration creating snap-shots of biodiversity but not being sufficient for monitoring changes.
- Ice conditions affect both species distributions and the ability to monitor Arctic marine fish biodiversity.
- Range expansions (northward) pose unknown consequences for resident species and inter-specific interactions (predator-prey, competitive). Species range expansions depend on changes in environmental conditions and are constrained by prey availability and predation pressure.
- The main commercial marine fishes in the Arctic, Greenland halibut and capelin, do not yet seem to be adversely affected by climate change although their distributions appear to be changing. However, boreal species moving north seem to be negatively affecting the abundances of polar cod. Little is known about effects on non-commercial marine fishes in the Arctic.
- Polar cod are both culturally and ecologically a keystone species. It is a valuable indicator species because it relies on sea ice as spawning habitat.
- Capelin provide a robust example of the northward expansion of Arctic-boreal species and the consequences for Arctic species. Capelin provide novel competition for other forage fishes and prey for piscivores.
- Greenland halibut are important predatory fish in the Arctic seas and they are commercially harvested in large areas of the Arctic. In some areas, it is the only commercially harvested fish species and therefore the sole reason for fishery-related ecosystem impacts. Greenland halibut and related fisheries have the potential to expand further into the Arctic Ocean with climate change, given the availability of suitable topography and prey.

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Common eiders gather together in a polynya near the Belcher Islands, Nunavut, Canada.
Photo: Vicky Johnston, Environment and Climate Change Canada

3.5 Seabirds

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Snapshot

- Although seabird trends are variable, many species have declined within the Atlantic Arctic, including colonies in Norway, Iceland, and the Faroe Islands.
- The sea-ice-associated ivory gull has declined in the Arctic Archipelago and Atlantic Arctic by an estimated 80-90% over the past 20 years. In Russia, ivory gull distribution has shrunk, which correlates with the summer ice edge moving northward.
- Some seabird species have adapted their feeding behaviours because of shifts in their food supply due to climate change and reduced ice-cover—in some cases travelling farther for food or foraging on less nutritious species. The consequences vary, but have resulted in lower breeding success for some species, including black guillemots.
- Reduced ice cover has led to increased bear predation on ground-nesting common eiders and cliff-nesting murres, potentially leading to local population declines.
- More southern seabird species are now more commonly reported in Arctic regions, for example, albatross in the Bering and Chukchi Seas and ancient murrelets in the Pacific Arctic, which are thought to follow northward-moving prey species and/or currents. There is also evidence of individuals moving between Atlantic and Pacific Arctic regions.
- Most Arctic States have at least one long-term seabird monitoring program that makes it possible to examine population trends. Colony-based monitoring occurs regularly or annually, although most sites do not have fully implemented plans (diet and survival data are often lacking). At-sea surveys are more opportunistic, and often occur in conjunction with resource exploration and extraction.

3.5.1 Introduction

Seabirds link marine and terrestrial ecosystems because they nest on land but forage at sea, and, thus, they are important components of Arctic ecosystems and are part of the Circumpolar Biodiversity Monitoring Program (CBMP). Seabirds provide ecosystem services, notably as human food in many Arctic regions, major tourist attractions, as well as being an important link to the Arctic food web and returning nutrients from the oceans to coastal areas (Şekercioğlu et al. 2004, Şekercioğlu 2006, Merkel and Barry 2008, CAFF 2010, Ganter and Gaston 2013, Green and Elmberg 2014). Changes in seabird populations and diversity will affect regional sustainability for Arctic communities and ecosystems. Seabirds are also widely distributed and easier to observe than other marine taxa, making them useful study subjects. Seabirds function as indicators of the condition of their marine habitats, because they integrate the effects of abiotic stressors acting on lower trophic levels (Piatt et al. 2007, Sydeman et al. 2012, Green and Elmberg 2014). The CAFF *Arctic Biodiversity Assessment* (Ganter and Gaston 2013) also recognizes that the migratory behavior of most seabird species requires international cooperation throughout the circumpolar regions to address conservation needs.

The *Circumpolar Seabird Monitoring Plan* (CSMP; Irons et al. 2015) recognizes 64 species as part of the Arctic ecosystem: five tubenoses, six cormorants, four sea ducks, four skuas and jaegers, 18 gulls, six terns, 20 auks, and the northern gannet (*Morus bassanus*). Of these 64 species, about half (30) breed only within the Conservation of Arctic Flora and Fauna (CAFF) boundaries of the Arctic. Based on circumpolar distribution and factors such as importance to society, national priorities, conservation, science, or as ecological indicators, 23 species were initially chosen as priority species, and by applying further criteria, four species or species groups were selected as Focal Ecosystem Components (FECs; Gill et al. 2011).

The FECs represent different foraging strategies, including black-legged kittiwakes (*Rissa tridactyla*) (surface-feeders), murre species (thick-billed (*Uria lomvia*) and common (*Uria aalge*); sub-surface divers), and common eiders (*Somateria mollissima*) (bottom feeders). While birds are ideally identified to species, they have at times been combined into a 'murre' group when conducting census counts or visual productivity plots.

While most seabird species can eat a variety of prey, the CSMP uses the primary prey preferences and foraging behavior of seabirds to categorize birds into six basic foraging guilds: surface piscivores, surface planktivores, diving piscivores, diving planktivores, benthic feeders, and omnivores (Petersen et al. 2008, Gill et al. 2011, Irons et al. 2015). The Circumpolar Seabird Expert Group identified eight 'priority species' (Table 3.5.1) that represent five of the foraging guilds (there were no surface planktivore species that adequately represented either the Pacific or Atlantic). The black-legged kittiwake (an FEC) represents surface piscivores, and diving planktivores are represented by two species of small auks (one for the Pacific and one for the Atlantic Arctic). The two murre species (also FECs) represent diving piscivores, and the common eider (an FEC) represents benthivores. Omnivores are represented by two gull species. However, national monitoring programs also continue for species that may be or are not on the priority list, if they are already part of national efforts planned or underway (Appendix 1).

Although the CBMP identified eight Arctic Marine Areas (AMAs), the CSMP recognizes 22 ecoregions, which reflect geographic differences in seabird ecology and habitat, and includes geographic areas outside the AMAs (i.e., northern Gulf of Alaska, the southern Bering Sea, North Sea, and the Baltic Sea; Fig. 3.5.1). While this report focuses on the AMAs, the Circumpolar Seabird Expert Group notes where CSMP ecoregions are relevant to seabird trends in the AMAs.

Table 3.5.1. Seabird species selected as priority species for monitoring by the Circumpolar Seabird Expert Group (CBird). Asterisks indicate which species are also FECs (Gill et al. 2011).

Foraging guild	Common name	Scientific name	Distribution
Omnivore	Glaucous gull	*Larus hyperboreus*	Circumpolar
	Ivory gull	*Pagophila eburnea*	Atlantic
Diving planktivore	Least auklet	*Aethia pusilla*	Pacific
	Little auk	*Alle alle*	Atlantic
Diving piscivore	Common murre*	*Uria aalge*	Circumpolar
	Thick-billed murre*	*Uria lomvia*	Circumpolar
Surface piscivore	Black-legged kittiwake*	*Rissa tridactyla*	Circumpolar
Benthivore	Common eider*	*Somateria mollissima*	Circumpolar

Glaucous gull.
Photo: Kristine Sowl/USFWS, Alaska

Ivory gull.
Photo: Martha de Jong-Lantink, Flickr.com

Least auklet.
Photo: R. Duggan/USFWS

Little auk.
Photo: Carsten Egevang/ARC-PIC.com

Common murre.
Photo: David Thyberg/ Shutterstock.com

Thick-billed murre.
Photo: Morten Ekker

Black-legged kittiwake.
Photo: Robin Corcoran/USFWS, Alaska

Common eider.
Photo: Micha Klootwijk/Shutterstock.com

3.5.2 Current monitoring

The CSMP emphasizes the importance of established monitored plots (at key sites) or transects (at-sea surveys) that are surveyed regularly over the long-term to update seabird population trends, productivity (recruitment), survival, diets, phenology, and distribution at sea. In all ecoregions, monitoring efforts are balanced against other national priorities and limited resources.

The broad distribution of breeding colonies and post-breeding movements of species require collaborative efforts and technological innovations (Ganter and Gaston 2013). However, there is wide disparity among AMAs and countries in both the amount and completeness of monitoring activities (Fig. 3.5.2, Table 3.5.2). Nonetheless, colony-based monitoring occurs almost annually or at regular intervals at selected colonies in most countries. At-sea surveys are more opportunistic and often occur in conjunction with resource exploration and extraction (e.g., the Chukchi Sea in the Pacific Arctic, or the Davis Strait-Baffin Bay region).

Most circumpolar nations have at least one long-term seabird monitoring program that makes it possible to examine population trends. These long-term data sets and monitoring efforts are crucial to examining the effects of environmental drivers on seabird populations. The national recommendations and currently monitored parameters are provided in Irons et al. (2015). Key sites (CSMP-recognized colonies) must have two or more parameters collected per priority species, and have been categorized by the level of implementation relative to the monitoring plan. A 'fully implemented' site has data collected on half or more of the prioritized species, with at least one of the following: population trends, productivity and survival, conducted at the recommended interval. 'Partially implemented' sites do not have monitoring conducted at the recommended interval on at least one of the following parameters: population trends or productivity. 'Not implemented' sites have no data on population trends or productivity currently being collected.

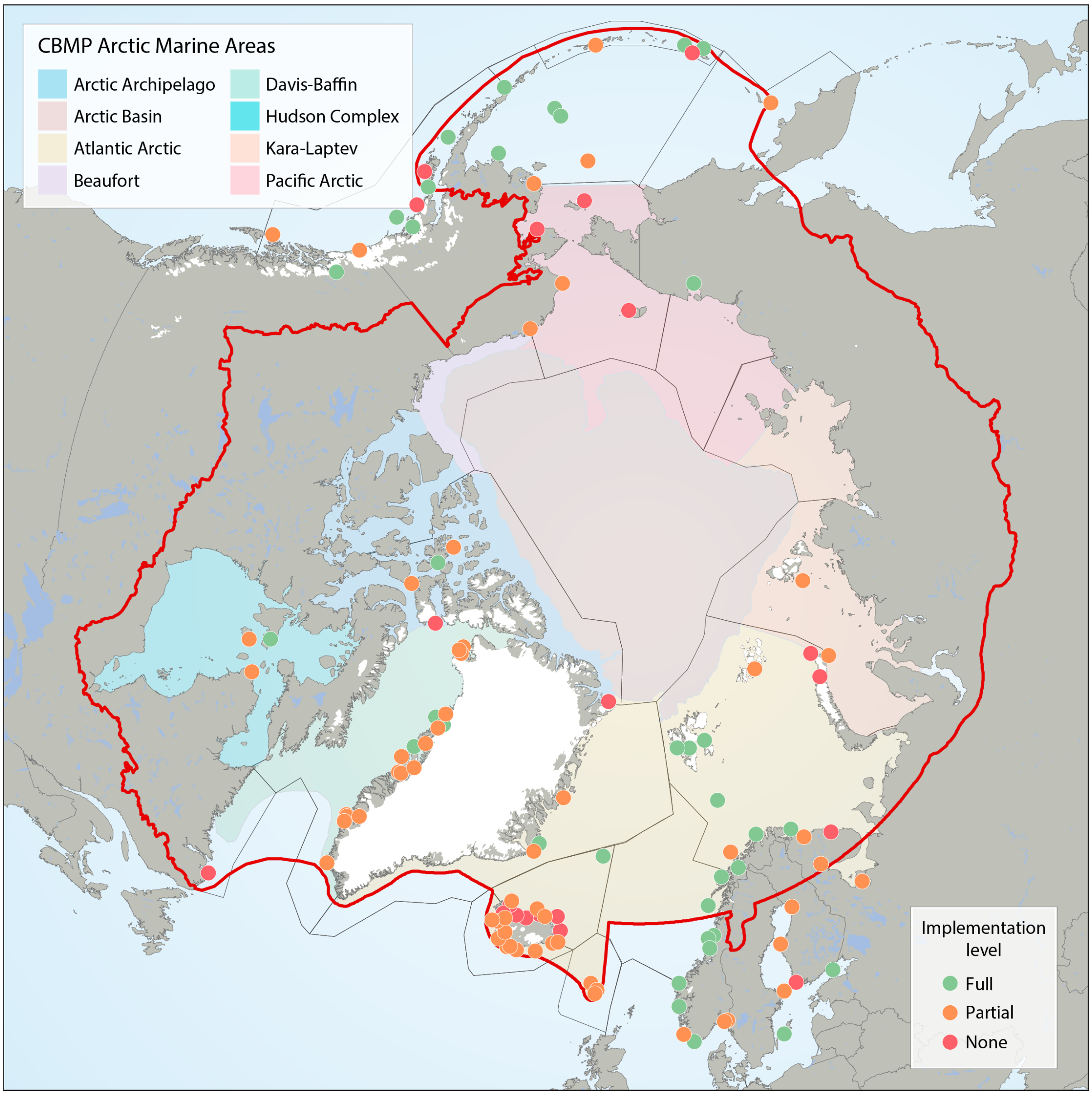


Figure 3.5.1. Boundaries of the 22 ecoregions (grey lines) as defined in the CSMP (Irons et al. 2015) and the Arctic Marine Areas (colored polygons with names in legend). Filled circles show locations of seabird colony sites recommended for monitoring ('key sites'). The current level of monitoring plan implementation are green = fully implemented, amber = partially implemented, red = not implemented. The CSMP provides implementation maps for each forage guild.

The following is a summary of monitoring activities of FECs by country, starting with the Canadian Arctic Archipelago and working clockwise around the Arctic. Because the efforts and responsibilities for historic data sets have been specific to national objectives and vary among countries, the Circumpolar Seabird Expert Group focused on each country's history and status. In addition, the long-term and current knowledge of local, Indigenous communities might be integrated with current scientific efforts to expand our temporal scale of knowledge.

Canada maintains historical colony-based monitoring at several locations (Prince Leopold Island, Digges Sound, Coats Island, East Bay, Gannet Islands, Hudson Strait Archipelagos) in the Canadian Arctic, dating back to 1975 (e.g., Gaston et al. 2012). Additionally, at-sea monitoring dates to the early 1970s, and has been revitalized as the Environment Canada Seabirds at Sea program, which continues (Wong et al. 2014). Another focus of monitoring efforts is the annual assessment of murre harvest in eastern Canada (Gaston and Robertson 2010). However, Indigenous harvest of marine birds is poorly monitored. Canada has initiated a community-based, seabird-health monitoring program in Nunavut and Nunavik, in collaboration with the Canadian Co-operative Wildlife Health Centre.

In Alaska, trends in colony status and reproductive or diet parameters are summarized in the annual Status and Trends of Breeding Seabirds in Alaska series (Dragoo et al. 2015), which summarizes results from the monitoring program of the Alaska Maritime National Wildlife Refuge (AMNWR) and others at 17 colonies throughout Alaska, which dates to the 1970s at some sites. Only two of those monitored colonies are in the Pacific Arctic AMA, yet some of the largest colonies in the Pacific are located on islands of the northern Bering Sea (Diomede, King, St. Lawrence) and central Bering Sea (St. Matthew and Pribilof Islands), which together host millions of nesting seabirds. The trends at colonies south of the Pacific Arctic may also be relevant to the AMA due to late summer and autumn use of the Chukchi Sea by birds that breed in the Bering Sea (Kuletz et al. 2015).

At-sea survey data for the Pacific Arctic is archived in the North Pacific Pelagic Seabird database (NPPSD); this database has > 300,000 km of effort and includes survey data from 1975-2015 (ongoing), albeit often opportunistically in accordance with broader ecosystem objectives. In the Pacific Arctic waters of Alaska, ~80,000 km of survey effort has been archived, primarily from 2006 to 2015. While most effort has been opportunistic or focused on federal oil lease sale areas of the Chukchi Sea, during which time frame seabird surveys within the internationally monitored areas of the Distributed Biological Observatory have been conducted at least annually and this effort is anticipated to continue. The NPPSD has been used to examine hotspots of seabird activity in the Chukchi Sea (Kuletz et al. 2015) and long-term trends in the seabird community (Gall et al. 2017). Biologging has been used to monitor changes in seasonal movements across vast oceanic regions that include areas outside the AMA (e.g., Orben et al. 2014, 2015). Scientific monitoring of seabird harvest, which occurs at many Alaska Indigenous communities, has been sporadic, with intermittent surveys occurring since the 1980s (Naves 2015).

Colony-based monitoring in Russia is traditionally based on its Specially Protected Areas (Strict Nature Reserves (SNR), and more recently, National Parks), but very few of them currently maintain seabird monitoring. The longest historical datasets (late 1920s to 1990s) were obtained in Kandalaksha SNR (Barents Sea and White Sea, CSMP region 19; Krasnov et al. 1995) and Wrangel Island SNR (Chukchi Sea, region 5) from the 1970s to 1990s.

These long-term datasets were disrupted in the 1990s and are not currently maintained on a full scale in Kandalaksha SNR. During past two decades monitoring has been initiated by Murmansk Marine Biological Institution on the Kola Peninsula and in Franz-Josef Land by the National Park Russian Arctic (NPRA, region 19). Since 2006, ivory gull monitoring in the Russian part of the species breeding range (regions 19, 20) is conducted by the NPRA on an opportunistic basis (Gavrilo 2015). Except for work on the spectacled eider (*Somateria fischeri*) in west Chukotka and ivory gull monitoring as mentioned above, seabird monitoring has not been conducted in the central Russian Arctic (AMAs Kara-Laptev and eastern Pacific Arctic). The recently established Beringia National Park in east Chukotka is hoped to fill this gap in the future.

Norway maintains colony-based monitoring for a variety of species and has the most fully implemented monitoring program in the Arctic (Fig. 3.5.2). Its comprehensive program collectively called 'SEAbird POPulation,' (SEAPOP) is a long-term monitoring and mapping program established in 2005. The most extensive monitoring, which includes population size, reproduction rates, survival rates and diets, is concentrated on 17 key sites evenly distributed along the borders of marine areas surrounding Norway, Svalbard and adjacent seas. Many of the key sites in Norway have been monitored annually since the 1980s, with a few series dating back to the 1960s (Fauchald et al. 2015). At-sea monitoring surveys in the Barents Sea in the autumn have been conducted since 2004.

Another program, SEATRACK (SEAbird TRACKing) is underway in the Atlantic AMAs and involves Norway, Russia, Iceland, the Faroe Islands and (outside the AMAs) Great Britain. The program uses geolocators to describe migratory routes, wintering areas and the variation in these between years, with the goal to link these with population dynamics, migration routes and wintering areas with marine environmental and anthropomorphic factors. Two FEC species, black-legged kittiwake and thick-billed murre, were the subjects of projects that used geolocator data loggers on birds from multiple colony sites to track breeding and post-breeding movements at a regional scale (Frederiksen et al. 2012, 2016). Nine other species at more than 30 colonies have been tagged and tracked during 2014-2016.

In Iceland, 28 key sites have been identified, most of which have population trends monitored (some since the 1980s) and some of which have productivity monitored (Fig. 3.5.2). Additionally, for several non-FEC species, colonies are monitored in aerial surveys and survival is monitored at colonies (Frederiksen and Petersen 1999, Garðarsson and Petersen 2009, Garðarsson and Jónsson 2011). Recommended and currently monitored parameters for Icelandic seabirds, revised in 2015, are provided in Irons et al. (2015). Annual seabird harvest information since 1995 is available online at the Environment Agency of Iceland and has been published during the period 1898-1942. Harvest of Atlantic puffin (*Fratercula arctica*) in the Westman Islands has been compiled for 1840-2015 (E.S. Hansen et al., unpubl. data).

The Kingdom of Denmark includes two countries with seabird monitoring activity in the Atlantic Arctic AMA. In the Faroe Islands, common murres and black-legged kittiwake colonies have been counted at about 10 year intervals since 1972 and 1987, respectively. Annual monitoring has occurred at one murre colony since 1972 and one kittiwake colony since 2001. Other non-FEC species are also monitored (Appendix 3.5.1). Greenland identified 24 key sites, with fully implemented population trends and productivity studies at three eider and one little auk colony, and partial implementation in 19 colonies with a variety of species (see Appendix 3.5.1). Since 1998, a monitoring program for thick-billed murre and black-legged kittiwake has been implemented, and a community-based program for common eider was initiated in 2001. In addition to the key sites, intermittent surveys are conducted at eider, murre, kittiwake and little auk colonies. The oldest colony surveys in Greenland go back to the early 20th Century, but in general, historical survey activity has been limited and non-systematic.

At-sea surveys (mainly ship-based, but also aerial surveys) near Greenland go back to 1988 and cover most waters of the Davis Strait-Baffin Bay and Atlantic Arctic adjacent to Greenland. Since the mid-2000s, it has been mandatory for ships conducting seismic surveys in Greenland waters to have seabird and marine mammal observers onboard and observations made from seismic vessels make up a large proportion of the data. Thus, survey effort is concentrated in areas with oil exploration activities, e.g., Disko Bay, Eastern Baffin Bay, Davis Strait-Baffin Bay and NE Greenland waters. In general, at-sea surveys (approximately 80,000 km of effort) have mainly been conducted in summer and autumn, corresponding to the open water season. Seabird harvest statistics have been compiled systematically in Greenland since 1993, using annual reports from hunters; statistics quantify the taking of birds (and mammals) on a monthly basis and since 2002, have included bycatch of seabirds in fishing gear and harvested eggs.

3.5.3 Status and trends of FECs

At a circumpolar scale, several studies have been implemented that relied on collaborative efforts and technological innovations to examine trends of focal seabird species. The two most widely studied species groups in circumpolar regions are the murres (common murre and thick-billed murre), which are diving foragers, and the black-legged kittiwake, a surface forager; these two species groups thus form the nexus of comparative studies across circumpolar regions. The benthic-feeding common eider has also been widely monitored (Table 3.5.2).

Recent population trends of thick-billed murres are mostly stable (or even increasing) in the Arctic, but declining in most of the Atlantic Arctic (Table 3.5.2). Common murres increase in the Pacific Arctic and CSMP region 19 of the Atlantic Arctic, but decrease in Davis Strait-Baffin Bay and other sites in the Atlantic Arctic.

Population trends of black-legged kittiwakes are being examined at the circumpolar scale in Descamps et al. (in prep.; Fig. 3.5.3). Overall, trends from 2001 to 2010 indicate kittiwake population declines, particularly in the Atlantic Arctic and Davis Strait-Baffin Bay AMAs (Fig. 3.5.3). Stable or increasing colonies occurred primarily in the eastern Bering Sea and Chukchi Sea of the Pacific Arctic, and to some degree in the Arctic Archipelago. More recently, key sites in

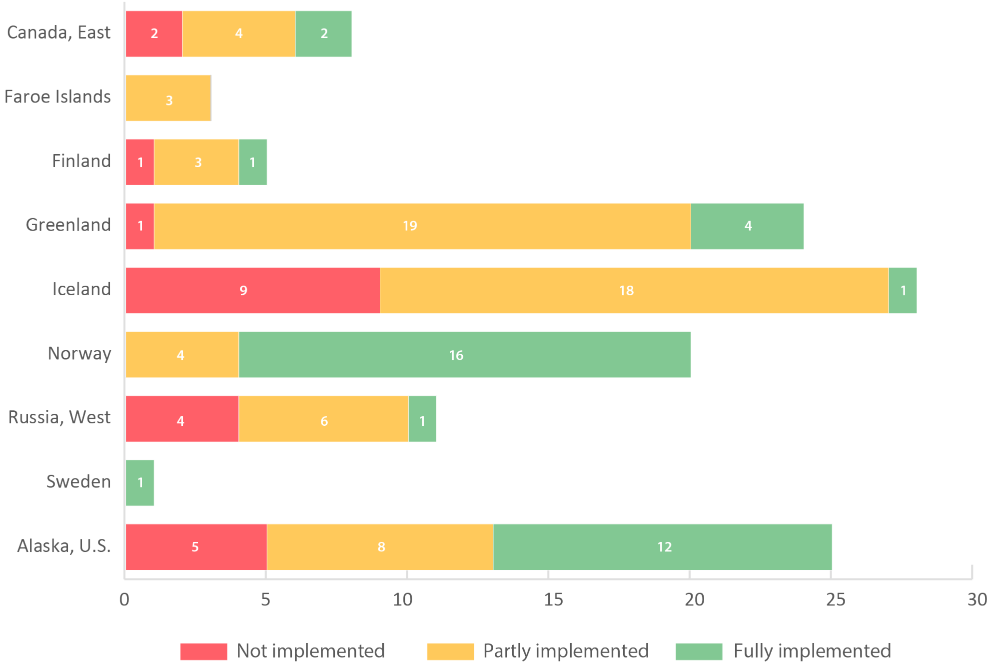


Fig. 3.5.2. The number of key sites (monitored colonies) for seabirds (in 22 CSMP ecoregions) by country (a total of 125 sites). Sites are categorized as having fully, partially, or not met the CSMP criteria for parameters monitored. Data were from Appendix 3 of the CSMP (Irons et al. 2015); the degree of implementation may have changed at some sites since this summary was compiled.

the Pacific Arctic, Arctic Archipelago and Davis Strait-Baffin Bay AMA do not indicate declines in kittiwake populations (Table 3.5.2). Colonies have also declined outside the AMAs, in the northern Gulf of Alaska (CSMP ecoregion 4). Tracking studies have shown that kittiwakes breeding at colonies spread throughout the Atlantic Arctic AMA may face similar threats because they overlap in winter distribution, thus stressors may not simply be occurring at the breeding sites (Frederiksen et al. 2012).

The glaucous gull is widely distributed across the Arctic in 2,768 colonies, but systematic long-term monitoring is rare (Petersen et al. 2015). Nonetheless, there is reported evidence of population declines at sites throughout the Arctic Archipelago and Atlantic Arctic, whereas populations appear to be stable or increasing in the Davis Strait-Baffin Bay region and the Bering as well as in the Russian part of the Atlantic Arctic (eastern portion of region 19) and the Chukchi Seas of the Pacific Arctic and the Kara-Laptev. In the recent summary of key sites (Table 3.5.2), population trends are mostly unknown, with mixed results in Davis Strait-Baffin Bay and regions of the Atlantic Arctic. A similar circumpolar examination is underway for the other omnivore priority species, ivory gull, which have declined in the Arctic Archipelago (Table 3.5.2) by an estimated 80-90% over the past 20 years (Gilchrist and Mallory 2005).

Figure 3.5.3. Trends in kittiwake colonies 2001-2010, based on linear regression with year as the explanatory variable. Slope of the regression is red = negative trend, blue = positive trend; shaded circle = significant trend (at p<0.05), open circle = non-significant trend. Non-significant deviation from zero could imply a stable population, but in some cases was due to low sample size and low power. Provided with permission from Descamps et al. (in prep).

Table 3.5.2. Population trends through 2015 for priority and FEC (*) species at key sites. CSMP Region is the ecoregion used by the Circumpolar Seabird Monitoring Plan, and regions that do not fall in the CBMP AMAs are not included here. Trend categories are increasing (i; green), stable (s; yellow), decreasing (d; red) or unknown (u) or rare (r; breeding status unknown); a dash indicates the species does not occur in that region. Population estimates and trends are from recent country reports, otherwise reported by members of the Circumpolar Seabird Expert Group.

CBMP Arctic Marine Area	CSMP region	Country	Ivory gull		Glaucous gull		Black-legged kittiwake		Thick-billed murre		Common murre		Common eider		Least auklet		Little auk	
			Total pop.	Trend	Total pop.	Trend	Total pop.	Trend	Total pop.	Trend	Total pop.	Trend	Total pop.	Trend	Total pop.	Trend	Total pop.	Trend
Pacific Arctic	5	Russia	-	-	U	S	U	U	U	U	U	U	U	U	U	U	-	-
	5	USA	-	-	843	-	57,047	I	125,880	I	147,722	I	173	U	972,500	U	R	-
Beaufort	6	USA	-	-	426	U	-	-	-	-	-	-	346	I	-	-	-	-
	6	Canada	0	-	U	U	-	-	400	S	-	-	45,000	D	-	-	-	-
Arctic Archipelago	7	Canada	100	D	U	U	-	-	-	-	-	-	-	I	-	-	-	-
	7	Greenland	200	D	500	U	-	-	-	-	-	-	-	-	-	-	-	-
	8	Canada	600	D	U	U	116,000	I	540,000	S	-	-	U	I	-	-	-	-
Davis-Baffin	8	Greenland	-	-	25,000	S	42,628	I	212,160	S	-		65,000	I	-		33 mil	U
	10	Canada	-	-	U	U	7,000	U	50,000	S	-	-	U	U	-	-	-	-
	10	Greenland	-	-	15,000	S	60,720	I	13,325	D	390	D	22,000	I	-		100	U
	11	Canada			1,800	D	2,000	S	4,500	S	33,600	D	17,374	D				
Hudson Complex	9	Canada	-	-	U	U	-	-	950,000	S	-	-	>200,000	I	-	-	-	-
Atlantic Arctic	12	Greenland	1,500	D	20,000	S	3,700	U	4,225	D			13,000	U	-		5 mil	U
	13	Iceland	-	-	800	D	407,200	D	205,000	D	405,600	D	300,000	I	-	-	-	-
	14	Iceland	-	-	1,600	D	173,700	D	121,800	D	292,500	D	U	I	-	-	-	-
	15	Faroe Islands					200,000	D			180,000	D	10,000	S				
	18	Norway	-	-	-	-	81,000	D	100	D	17,000	S	50,000	D	-	-	-	-
	19	Norway	2,000	S	4,200	U	255,000	D	725,000	D	133,000	I	17,000	U	-	-	>1 mil	U
	19	Russia	<3,000	U	>5,000	I	<500,000	D	<700,000	U	>10,000	U	<50,000	U	-	-	>500,000	U
Kara Laptev	20-21	Russia	<10,000	U	U	U	<50,000	U	<20,000	U	-	-	U	U	-	-	<100,000	U

Common eider populations show variable trends across the Arctic, with recent summaries of key sites (Table 3.5.2) showing mixed results in the Beaufort, mostly increasing populations in the Arctic Archipelago and Davis Strait-Baffin Bay regions, as well as Iceland in the Atlantic Arctic (Jónsson et al. 2013), a stable population in the Faroes, and decreases or unknown trends elsewhere. Since the early 2000s, populations in West Greenland have increased dramatically (Merkel 2010, Burnham et al. 2012), apparently in response to stricter harvest regulations in wintering areas. Populations have also increased in the southern end of Davis Strait-Baffin Bay AMA, Labrador (Chaulk et al. 2005), although recent studies indicate declines there (Table 3.5.2). Wintering population of the common eiders in the White Sea and Russian part of the Barents Sea (region 19) has been estimated in 2009 the largest ever recorded for this area (Krasnov et al. 2016).

While seabird trends in general are variable, many species have declined within the Atlantic Arctic, including seabird colonies in Norway, Iceland, and the Faroe Islands. For example, in Norway the estimated population of breeding seabirds was 30% lower (at 5.5 million pairs) in 2013 than the previous estimate made in 2003, consistent with declines extending over decades; the strongest negative trends were for pelagic foraging species. Concurrently, coastal seabirds have declined (Anker-Nilssen et al. 2015; Fauchald et al. 2015). Similar or greater declines have been detected in non-FEC species breeding in Iceland (Garðarsson et al. in press, Hansen and Sigurðsson submitted). In the Norwegian Sea (Faroe Islands), four piscivorous species, including surface-feeding black-legged kittiwakes and diving common murres, have declined over decades, resulting in hunting restrictions in the Faroe Islands (B. Olsen, unpubl. data.).

3.5.4. Drivers of observed trends

As the Arctic has longer seasonal ice-free periods due to ***climate change***, seabird communities are likely to change. In the Chukchi Sea of the Pacific Arctic, decadal shifts in seabird species composition and abundance at-sea have been documented (Box 3.5.1). Intensive studies in the Atlantic Arctic on little auk have found low survival rates of breeding adults, with potential population-level effects related to the impacts of climate warming on their main prey, large Arctic copepods (Hovinen et al. 2014). Because most seabird species migrate among breeding, staging (i.e., for molting), and overwintering sites, conditions south of the AMAs can have implications for Arctic breeding populations (Frederiksen et al. 2012, 2016, Orben et al. 2015). Outside of the AMAs, in the Baltic Sea, numbers of over-wintering waterbirds have responded to climate change over decades, and the numbers have correlated with early-winter temperature and open water (Fraixedas et al. 2015).

Changing ice conditions affect the diet of seabirds and reveal species plasticity in response to climate change and sea ice conditions (Grémillet et al. 2012, 2015). Changes in ice coverage might have positive or negative impacts on seabirds. For example, planktivorous seabirds appear to have increased at sea in the Chukchi Sea of the Pacific Arctic (Box 3.5.1), whereas a Beaufort population of black guillemot (*Cepphus grylle*), which generally feed close to their colonies, experienced increased breeding failures as sea ice coverage declined between 1975 and 2012. Guillemots feeding their chicks had to switch from ice-associated polar cod to prey of lower quality (e.g., sculpins), and subsequently had lower breeding success (Divoky et al. 2015). Ivory gulls have also shown negative trends during past decades expressed in deacreasing colony size and mismatch breeding events throughout their breeding range in Russia, which correlates with the northward shift of the summer ice edge (M. Gavrilo 2011 and unpubl. data). In spring and early summer, Arctic seabirds rely on open leads and polynyas, which may provide good foraging conditions combined with resting areas (Lovvorn et al. 2015). Early ice reduction may degrade or eliminate these protected and important feeding areas.

Indirectly, changes in sea ice affects the physical characteristics of habitats for seabird and coastal birds; less sea ice leads to coastlines being more exposed to erosion from wave impacts, and compounded by sea level rise. In the Arctic Archipelago/Hudson Bay Complex, annual variation in sea ice extent plays a dominant role in the timing of reproduction, reproductive effort and success for most marine bird species (Gaston et al. 2005, Mallory and Forbes 2007, Love et al. 2010). Reduced ice cover has also led to increased bear predation on ground-nesting common eiders, ivory gulls, as well as little auks and cliff-nesting murres (Box 3.5.2), potentially leading to local population declines (Gaston and Elliott 2013, Iverson et al. 2014, Prop et al. 2015, M. Gavrilo, unpubl. data).

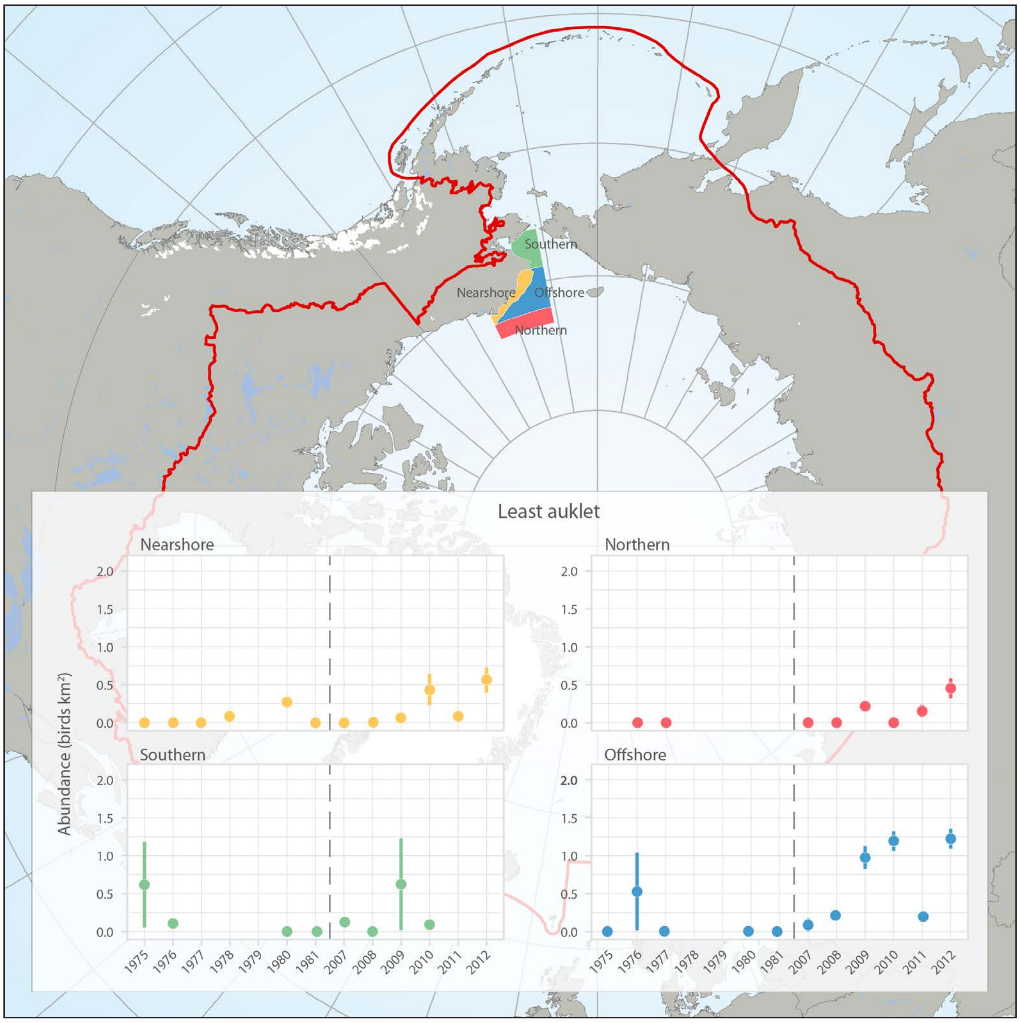
The longer ice-free period in the Arctic also increases ***vessel traffic (e.g., shipping and tourism) and opportunities for mineral (e.g., oil and gas) and biological (e.g., fisheries) resource extraction,*** which may eventually impact seabirds. Where water, wildlife, and humans must pass through 'choke points' between the Arctic and adjoining seas, overlapping activities put seabirds at risk (Humphries and Huettmann 2014). The Bering Strait is one such narrow passage between the Bering and Chukchi Seas. During summer and autumn, the Bering Strait is rich in nutrients and prey, and birds foraging and moving through the strait result in consistently high seabird densities there (Wong et al. 2014, Kuletz et al. 2015). The increase in Arctic vessel traffic has potential to displace foraging birds, which could be particularly important near nesting colonies in summer.

The circumpolar regions may offer a unique opportunity to examine the impacts of broad-scale shifts in ***ocean temperatures*** on upper trophic levels. For example, a circumpolar-level analysis of the impacts of climate on murre populations showed that murres respond negatively to large (0.5-1°C) changes in sea surface temperature, in either direction, resulting from large-scale climatic shifts (Irons et al. 2008). Sea surface temperatures and climate can also affect species that nest on tundra, such as common eiders (Jónsson et al. 2013).

Warmer ocean temperatures have been associated with more frequent ***blooms of harmful algae*** and ***coccolithophore plankton blooms***, which in turn could change the distribution and abundance of seabird prey (NOAA 2015). In the southern Bering Sea (south of the Pacific Arctic AMA), a conservative estimate of 32,000 seabirds (primarily thick-billed or common murres) died offshore in August 2014, in association with warmer than normal sea surface temperature and

Box 3.5.1. Seabird community changes in the Chukchi Sea

The impacts from changes occurring in the Arctic marine environment vary among different types of seabirds. In the Chukchi Sea of the Pacific Arctic, the community of seabirds observed during ship-based surveys has changed over the last 40 years, with sub-Arctic species, especially planktivores (seabirds that eat zooplankton) increasing as the number of ice-free days has increased there. Based on at-sea surveys spanning 1975-2012, Gall et al. (2017) compared two time periods, 1975-1981 versus 2007-2012. They found that in early years, fish-eating (piscivorous) birds predominated, primarily black-legged kittiwakes, thick-billed murres and common murres. In the last decade, however, planktivores have become more abundant in the at-sea surveys. Currently, one of the most abundant species is the least auklet (Box fig. 3.5.1), which eats copepods. The other super-abundant species is the short-tailed shearwater (*Ardenna tenuirostris*), which eats mostly euphausiids (the northern 'krill') and does not breed in Alaska. Over decades, the longer ice-free season has created conditions that lead to greater northward transport of nutrients (and perhaps zooplankton) through the Bering Strait in summer (Woodgate et al. 2012), more wind-driven mixing of the water column (Carmack and Chapman 2003), and subsequent increases in stocks of copepods and euphausiids (Ershova et al. 2015), which are important prey for planktivorous seabirds. Physical barriers (e.g. water temperature) likely prevent the expansion of fish stocks into the Chukchi Sea (Sigler et al. 2011). There are few seabird colonies on the eastern Chukchi coast, which has little appropriate nesting habitat (i.e., rocky, steep cliffs and islands) and the few existing colonies consist of fish-eating species such as murres, puffins and kittiwakes. Land-based counts indicate that murre and kittiwake populations have increased since the 1980s at Cape Lisburne, Alaska, one of the major seabird colonies in the eastern Chukchi Sea (Dragoo et al. 2016). Nonetheless, as the ice retreats throughout summer and autumn, post-breeding or non-breeding seabirds arrive to take advantage of abundant zooplankton, with their numbers at sea surpassing those of locally breeding birds. These visitors come from colonies in the Bering Sea or, in the case of shearwaters, from breeding sites in the southern hemisphere. Combined, the planktivorous seabird species have altered the offshore seabird community, perhaps signaling major changes in the marine food web.



Box figure 3.5.1. Abundance (birds/km^2) of least auklets in four regions (see map) of the eastern Chukchi Sea, 1975-1981 and 2007-2012, based on at-sea surveys (archived in the North Pacific Pelagic Seabird Database). Figures provided by Adrian Gall, ABR, Inc. and reprinted with permission.

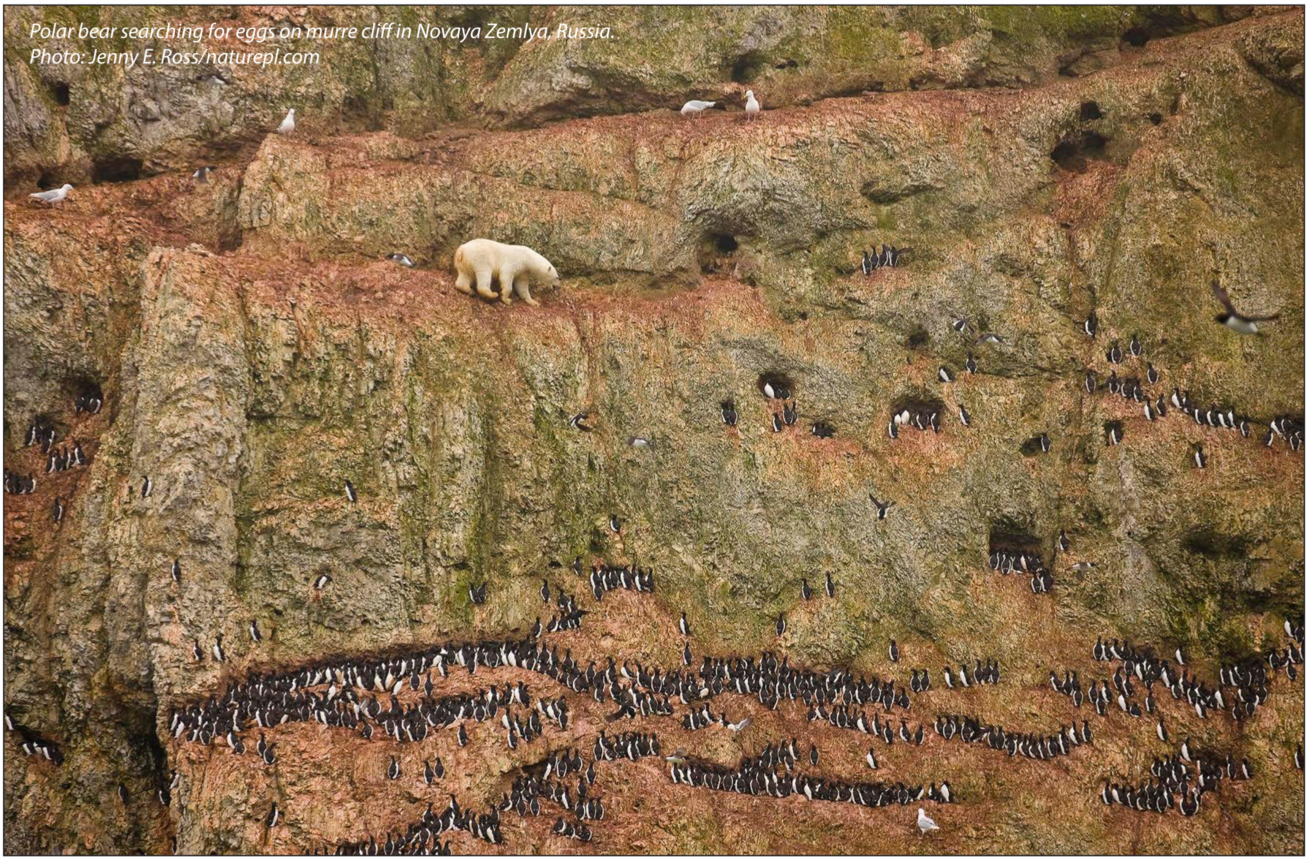
a large coccolithophore bloom (NOAA 2015). While a coccolithophore bloom is not toxic, it is associated with opaque blue water that may affect seabird foraging or prey distribution (Bauduini et al. 2001). This late summer die-off was followed in 2015 with high ocean temperatures that extended into the northern Bering and Chukchi Seas (Pacific Arctic). Murres and kittiwakes exhibited widespread reproductive failures in the eastern Bering Sea and northern Gulf of Alaska (H. Renner, unpubl. data), and murre die-offs were unprecedented in numbers and duration in 2015-2016 (K. Kuletz, unpubl. data). However, inadequate monitoring made it impossible to determine if the impact extended into the Arctic.

In the Atlantic Arctic, the weakening of the sub-polar gyre in the mid-1990s was associated with a basin-scale regime shift in the Northeast Atlantic and a warming of the sea. Changes in oceanographic conditions in this area affected many components of the North Atlantic marine fauna (Hatun et al. 2009), and similar conditions may have been a key driver of the decline in Svalbard's thick-billed murre population (Descamps et al. 2013). The warming of the Atlantic has led to a shift in copepod prey species, with the larger, lipid-rich *Calanus glacialis* and *C. hyperboreus* being replaced by smaller, less energy-rich *C. finmarchicus* (Welcker et al. 2009). During this time period, the planktivorous little auk has demonstrated changes in diet and foraging distances while raising chicks, which suggests adaptability to changes in prey and foraging grounds (Gremillet et al. 2012). However, continued warming could lead to negative trends in some populations (Karnovsky et al. 2010, Hovinen et al. 2014).

Shifts in prey distribution can affect seabirds. Some species, not always Arctic breeders, may be increasing their presence

Box 3.5.2. Increased polar bear predation on seabirds

One of the unexpected effects of reduced sea ice in the Arctic has been an increase in polar bear predation on seabird nests. Affected birds include ground-nesting seabirds such as glaucous gulls and common eiders, and even cliff-nesting murres. Since the 1970s, ice has left coastal areas earlier in summer, which has made it difficult for bears to hunt seals. As a result, bears prowl coastal beaches in early summer and have been observed inland with greater frequency. The bears prey on seabird eggs and chicks, or their presence near the colonies disturbs the adult birds, which subsequently abandon their nests. Local populations of eiders have lost up to 90% of nests (Prop et al. 2015) and murres have lost up to 30% (Gaston and Elliott 2013). Polar bear predation on seabird nests was rarely observed in the past, but is increasingly observed in the Hudson Strait area of the Canadian Arctic (Iverson et al. 2014), and in Svalbard and east and west Greenland of the Atlantic Arctic (Prop et al. 2015). Models indicate that, for ground-nesting birds, the increased rate of predation and nest abandonment could result in population declines, or force birds to move to new areas. However, in Canada the loss of seabird nests to bears was lower at colonies closer to Inuit villages, presumably because bears avoid people. Thus, a warming climate affects polar bear hunting behaviour, which then results in predation pressure on local seabirds during the nesting season. The impact to affected seabirds could result in lower reproductive success and eventual population decline, as well as changes in the bird's choice of nesting sites.



Polar bear searching for eggs on murre cliff in Novaya Zemlya, Russia. Photo: Jenny E. Ross/naturepl.com in Arctic or sub-Arctic seas, presumably because suitable prey has become more available. Historically, it was noted by Fisher (1952) that northern fulmar (*Fulmarus glacialis*) increased in abundance and range over 200 years throughout the Atlantic Arctic, perhaps in response to availability of offal from commercial fisheries and whaling ships. Changes in forage fish stocks have also affected seabird populations, in some cases abetted by commercial fisheries on these prey. For example, while sandeels (*Ammodytes* spp.) are not fished in Iceland, the Icelandic sandeel stock crashed in 2003-2005 (Lilliendahl et al. 2013). During the same time period capelin (*Mallotus villosus*), which is fished, shifted in distribution of its nursery grounds from north of Iceland to southeast Greenland (Pálsson et al. 2012); both events negatively impacted seabirds in the Atlantic Arctic (e.g., colonies in Iceland; Lilliendahl et al. 2013, Garðarsson et al. in press).

Recent examples of shifts in seabird distributions have been documented in the Pacific Arctic. Based on 40 years of data in the NPPSD, three albatross species (*Phoebastria* spp.) have become more abundant with a more northerly distribution in the Bering Sea than in past decades (Kuletz et al. 2014). Changes in abundance and distribution of albatross's primary prey, squid, could be a likely factor. New species have been observed in the Chukchi Sea in recent years, including the first Arctic record of an albatross in 2011 (short-tailed albatross). Other species that were rarely observed there historically, such as ancient murrelet (*Synthliboramphus antiquus*), are now regularly recorded during surveys in late summer and autumn, thousands of kilometres from breeding sites (Day et al. 2013). In addition, open water in the Arctic's Northwest Passage may be allowing Atlantic species to follow prevailing currents into the Pacific Arctic, indicated by recent sightings of northern gannets in the North Pacific (Day et al. 2013). Presumably, Pacific species could also follow open water to the Atlantic side.

Despite their breeding areas being far from large sources of human-caused pollution, Arctic seabirds are exposed to ***contaminants*** that might affect their populations or the people that rely on seabirds for subsistence. Ivory gull eggs collected in Canada, Greenland, Svalbard, and Russia had high levels of Persistent Organic Pollutants (POPs), including the insecticide DDT (Miljeteig et al. 2009, Lucia et al. 2015), and the high levels of DDT may have caused reduced eggshell thickness (Miljeteig et al. 2012). Glaucous gulls may also show population-level impacts from persistent organic pollution at colonies in the Atlantic Arctic (Erikstad et al. 2013). Point et al. (2011) suggested that loss of sea ice could accelerate the amount of biologically accessible methylmercury throughout the food chain, and they found that the deposition of mercury in murre eggs increased with latitude. Arctic seabirds benefit the land via transport of nutrients from the sea, but they might also transport contaminants; for example, Arctic ponds near large colonies of northern fulmars had higher levels of POPs and mercury (Blais et al. 2005). The accumulation and transport of contaminants might be a concern to indigenous peoples that rely on seabirds and adjacent colony sites for subsistence.

A possible indirect effect of climate change is the increased prevalence of ***diseases*** in Arctic regions that can affect seabird populations. Avian cholera, a fatal disease associated with waterfowl in temperate climes, was first detected in common eiders in the Canadian Arctic Archipelago in 2004, and in 2006 led to a 75% reduction in the largest eider colony in eastern Canada over six years (Descamps et al. 2012). Although still present in the region and monitored by local communities (Box 3.5.3; Iverson et al. 2016), population level effects of cholera have abated. In the Pacific Arctic, avian cholera was first detected in the northern Bering Sea during a seabird die-off in November 2013 in nearshore waters of St. Lawrence Island, Alaska (Bodenstein et al. 2015). A conservative estimate of 36,000 birds died in this event – primarily common murre and crested auklet (*Aethia cristatella*).

Seabird mortality imposed directly by ***human use*** (e.g., hunting or egg collection), and potentially indirectly (e.g., displacement of foraging birds), occurs throughout most of the circumpolar nations and may represent an important driver for some species (Merkel and Barry 2008). Where programs are in place to monitor subsistence use of seabirds, indigenous communities are important allies in providing harvest data to assist monitoring and management of birds. Overharvesting may contribute to substantial decrease in breeding populations, such as occurred for common eiders in Greenland and Canada (Gilliland et al. 2009) and thick-billed murres in Greenland (Merkel et al. 2014). The reverse has also been documented, i.e., rapid population recovery of common eider in Greenland following a large reduction in hunting pressure (Merkel 2010). However, in most countries, hunting levels are declining (Merkel and Barry 2008), so the future impact of this driver may also be declining.
Incidental catch of seabirds (***bycatch***) in commercial fisheries remains a potential anthropogenic driver worldwide (Zydelis et al. 2013) and long-line and gillnet fisheries in the Atlantic Arctic kill tens of thousands of birds annually (Fangel et al. 2015, Hedd et al. 2016). Overall, seabird bycatch is widespread, but not well monitored (Chardine et al. 2000, Hedd et al. 2016). Species taken as bycatch varies by fishing method (i.e., gillnets take diving birds and long-lines take surface-plungers), location and season. For example, Hedd et al. (2016) found highest seabird bycatch in summer and autumn, with waters near breeding colonies in the Davis Strait-Baffin Bay region having particularly high bycatch rates. Murres are often the most common bycatch in gillnets of Pacific and Atlantic fisheries, although bycatch in the North Pacific occurs south of the AMAs (Chardine et al. 2000, NOAA 2015). Even fisheries with relatively low bycatch rates can have significant bycatch if they are extensive temporally and spatially, such as the Atlantic cod fisheries of Norway (Fangel et al. 2015). In Icelandic waters, bycatch by cod gillnets has decreased by approximately 80% since the peak fishing effort in 2001, to about 6,100 birds (primarily common murres) in 2013 (Pálsson et al. 2015). The lower bycatch may be partially due to reduced gillnet use (in favour of long-lines), but could also be a consequence of the general seabird population decline over the same period (Garðarsson et al. in press). Current long-line annual bycatch in Iceland is estimated to be around 5,000 birds (G. Sigurðsson pers. comm.) Bycatch in the lumpsucker fishery was estimated to take about 5,300 birds and could have a large impact on seabirds in the Atlantic Arctic, particularly for black guillemots, with small, coastal populations (Fangel et al. 2015, Pálsson et al. 2015).

Despite a generally small human population in the Arctic, seabirds are subject to ***indirect mortality from human***

Box 3.5.3. Tracking infectious disease emergence in Arctic seabirds using Inuit community-based surveillance

Community-based research team investigates common eider nesting colony. Photo: Samuel Iverson

A poleward expansion of infectious diseases appears to be occurring in association with the effects of economic globalization and climate change. This expansion may threaten the viability of wildlife populations that are important for ecosystem function and human subsistence. However, disease surveillance in remote, sparsely settled regions like the Arctic is a tremendous logistic, financial, and safety challenge. In the Canadian Arctic, Inuit participation in ecological monitoring and the inclusion of indigenous ecological knowledge in decision making have become fundamental components of wildlife co-management. Inuit have increasingly contributed to wildlife disease surveillance and control efforts. A recent example involves the sudden appearance of avian cholera at common eider nesting colonies located on offshore islands in the Hudson Strait region.

Avian cholera is a virulent disease of birds that has long circulated in temperate regions of North America. Its appearance at Arctic common eider nesting colonies is a new phenomenon. Inuit harvesters are very familiar with the location and status of common eider colonies near their communities because they regularly visit them during summer to collect feather down for use in clothing and blankets. Indeed, Inuit eider down harvesters were the first to notice avian cholera outbreak events in the ecosystem and report them to conservation authorities.

A collaborative research initiative is now underway that integrates scientific expertise with Inuit local ecological knowledge (Iverson et al. 2016). The objectives of the initiative are to collect samples for laboratory testing, map disease-distribution patterns, and determine the host species range and extent of mortality. These data are fundamental to determining conservation threat and predicting the risk of further spread of disease. Inuit participation as sentinels on the land, experts helping in the development of a study plan, and as guides leading research teams into the field have been integral to project success.

activity. Fishing and other vessel traffic can result in light-induced bird strikes; these events typically occur during darkness or poor visibility due to weather (Merkel and Johansen 2011). In southwest Greenland, common eider accounted for 95% of seabird mortality from vessel strikes over three winters (Merkel and Johansen 2011). Plastic ingestion, which has long been documented in the world's oceans, has been documented in northern fulmars in the Arctic for >15 years (e.g., Mallory 2008, Provencher et al. 2014), and now has also been found in thick-billed murres in the Arctic Archipelago and Hudson Complex of eastern Canada (Provencher et al. 2010). However, models suggest that in general, seabirds face lower risk of plastic ingestion in high northern latitudes than they do in southern latitudes (Wilcox et al. 2015).

Mammalian predators introduced by humans into Arctic regions, intentionally or not, include red fox (*Vulpes vulpes*), rats (i.e., *Rattus norvegicus*) and American mink (*Neovison vison*). Introduced predators have had negative impacts on seabird populations south of the AMAs (e.g., Aleutian Islands; Byrd et al. 2005), but there is less evidence for population-level effects in the AMAs. Two exceptions may be American mink in the Atlantic Arctic (reviewed in NDNM 2011) and historically, rats in the Faroes (Bengtson and Bloch 1983). Mink were introduced to Norway and Russia in the 1920s and recent increases in mink at some common eider breeding sites have been coincident with high predation of eider nests and population declines (NDNM 2011).

Oil spills and chronic oil pollution also affect Arctic seabirds. A series of major oil spills likely contributed to low over-winter survival of common murres in the North Atlantic (Votier et al. 2005). Population modelling indicated that chronic oil pollution, combined with the hunting of thick-billed murres in the eastern Canadian Arctic, could reduce the population growth rate by 0.047 per year (Wiese et al. 2004). Determining the population-level impacts from such catastrophic events, or chronic levels of pollution, highlight the need for regional data on survival and demography for affected species. Impacts to specific colonies may be difficult to detect, partly because accidents often occur in winter, and multiple breeding populations intermingle in wintering areas (Votier et al. 2005, Frederiksen et al. 2012, 2016).

3.5.5 Knowledge and monitoring gaps

Throughout the circumpolar regions, the enormous geographic scale and lack of infrastructure constrain the scope and frequency of monitoring efforts to adequately address the priorities of the CSMP. Most of the circumpolar regions are lacking in consistently funded seabird monitoring efforts, but efforts and results are foremost missing from AMAs adjacent to Russia (Table 3.5.2), which spans the Atlantic Arctic, Kara-Laptev and Pacific Arctic (Fig. 3.5.1). Equally problematic is the lack of any monitoring at large colonies in the Pacific Arctic, St. Lawrence Island in the north Bering Sea, and the Diomede islands in Bering Strait. In both Russia and Alaska, local communities could efficiently assist monitoring efforts. They also serve as first responders to report unusual events and can conduct surveys to estimate mortality, such as occurred with the seabird die-off from avian cholera on St. Lawrence Island in 2013 (Bodenstein et al. 2015). In addition to the benefit of local residents being able to provide *in situ* observations and collect data (e.g., Box 3.5.3; Iverson et al. 2016), they also hold a wealth of current and historical Traditional Knowledge (TK) that is needed to better understand trends.

Among the priority species selected in the CSMP, it was not possible to determine population trends for roughly a third of the region-species, as sampled data could not be used to determine trends. The two priority species representing diving planktivores were notably lacking useful data on population trends. In the Atlantic, the little auk is well studied in terms of diet, foraging behaviour, productivity and survival (e.g., Karnovsky et al. 2010, Gremillet et al. 2012, 2015, Hovinen et al. 2014), but detecting population trends for this abundant, crevice-nesting seabird is challenging. The least auklet, also a crevice nester, may be the most abundant seabird in the Pacific Arctic, but it is difficult to monitor and only a few sites in the southern Bering Sea and Aleutian Islands have been studied over time (Dragoo et al. 2015), south of the AMA.

Data gaps exist on the distribution of seabirds during non-breeding season, including migratory paths and staging areas (Ganter and Gaston 2013). For example, at-sea surveys in the Chukchi Sea since 2007 identified new hotspots for post-breeding least and crested auklets, with auklets taking advantage of late summer peaks in zooplankton abundance far from breeding areas, when many birds molt and are flightless (Kuletz et al. 2015, Gall et al. 2017). Applications of biologgers and satellite tags have made it possible to identify the distribution of birds during seasonal periods when they are not at their breeding sites. Recent findings highlight the need to expand conservation efforts for circumpolar species beyond AMA boundaries; examples include the post-breeding migration of black-legged kittiwakes from the Bering Sea to the central Pacific (Orben et al. 2015) and murres, kittiwakes and other species that nest in the Atlantic Arctic moving south to the Newfoundland banks (Frederiksen et al. 2012, 2016).

Two additional major gaps in monitoring efforts are the lack of current information on seabird diets and insufficient demographic data. Collection of birds for dietary samples has not been used frequently over the last two decades and methods such as stable isotope analysis, while useful for basic information, does not provide data on specific dietary items at a given location. New methods for assessing diet will be required to follow changes in the ecosystem. Concurrently, data on survival is essential to make the link between diet, environmental and human stressors, and how they affect seabird populations.

Beyond monitoring, there is only localized or opportunistic and sporadic data relative to known sources of seabird mortality, particularly the true mortality level caused by chronic oiling, predation by introduced mammals, and incidental take in fisheries; this lack of information is especially true for Russian waters. Finally, improved data on prey species and the impact that climate warming will have on them will require multi-disciplinary research and management efforts.

Little auks.
Photo: Incredible Arctic/Shutterstock.com

3.5.6 Conclusions and key findings

To summarize by AMA ecoregions, based on recent trends at CSMP key sites (Table 3.5.2), the Pacific Arctic and Beaufort have shown increasing or stable populations of six of eight priority (including FEC) species (with exception of common eiders in the Canadian Beaufort). However, these regions have few sites with available data relative to other AMAs. Most species in the Arctic Archipelago and Hudson Complex are also increasing or stable, except for the ivory gull, which shows declines throughout most of its breeding range (the exception being in CSMP region 19 in Norway). Davis Strait-Baffin Bay AMA shows mixed results, and indeed appears to be a zone of transition between Pacific/Arctic Archipelago regions and the Atlantic Arctic, with the latter showing primarily population decreases. Nearly 70% of the region-species samples in the Atlantic Arctic show declines and this pattern cuts across foraging guilds (omnivores, piscivores, benthivores).

An avenue to explore is whether the Atlantic Arctic population declines are linked to the cumulative impact of stressors, including commercial fisheries of forage fish species (i.e., sandeels and capelin), incidental take in commercial fisheries, introduced predators, harvest, contaminant load, and oil extraction and transport. Alternatively, this ecoregion simply has more complete data, which allows us to detect seabird trends, compared to other Arctic regions. There is a notable lack of population trend data for diving planktivores (least auklet in the Pacific and in the Atlantic) and for all species in Russia, which crosses three AMAs.

Optimally, national monitoring efforts should be combined with collaborative approaches, i.e., integrated and standardized sufficiently to allow synthesis across the circumpolar regions. Collaborative efforts from the Circumpolar Seabird Expert Group include: 1) the circumpolar population trends of murres relative to sea surface temperatures (Irons et al. 2008); 2) differing trends in eastern versus western Atlantic populations (Frederiksen et al. 2016); 3) black-legged kittiwake trends driven by oceanographic factors linked to climate patterns (Descamps et al. in prep); 4) documentation of genetically indistinguishable ivory gull populations, which has implication for its conservation (Yannic et al. 2016); 5) a conservation plan for ivory gulls (Gilchrist et al. 2008); 6) circumpolar status and trends of glaucous gulls (Petersen et al. 2015); 7) CAFF strategy and conservation plans for murres and eiders (CAFF 1996, CBird 1997) and the Circumpolar Seabird Monitoring Plan (Irons et al. 2015).

For most Arctic ecoregions, additional monitoring is recommended and should strive to include a more complete array of parameters, in particular, diet and measures of survival, as well as higher frequency of monitoring. In most cases, the current frequency of monitoring makes it difficult to identify mechanisms or causes of changes in populations. At-sea surveys will continue to be conducted mainly on a ship-of-opportunity basis, particularly during seismic survey activity, but targeted surveys and individual tracking studies would improve our understanding of seabird interactions at sea, where seabirds spend most of their time.

- Most circumpolar nations have at least one source of long-term seabird monitoring datasets, but efforts vary across regions. These long-term monitoring efforts are crucial to examining the effects of environmental drivers to changes in seabird populations.
- Some of the most widely studied species groups in circumpolar regions include the FECs, i.e. common and thick-billed murres (diving piscivores), black-legged kittiwakes (surface piscivores), and common eider (benthivores); these species groups make it possible to conduct comparative studies across circumpolar regions.
- To better represent all foraging guilds, which sample different components of the marine ecosystem, additional species (priority species) have been selected for monitoring at a circumpolar or regional scale: glaucous gull and ivory gull (omnivores), and least auklet and little auk (diving planktivores).
- Population trends for seabirds vary within and among regions, making it difficult to assess circumpolar trends. Nonetheless, among key sites, current trends indicate that most of the stable or increasing populations are in the Pacific Arctic and Arctic Archipelago, while most of the declining populations are in the Atlantic Arctic.
- The declines in seabird populations in the Atlantic Arctic cut across foraging guilds, including the three FEC species/groups (kittiwakes, murres, common eider); of these, murres have shown the greatest declines. The ivory gull is declining throughout its range; notably, this species is one of the more ice-associated species.
- Important drivers for seabird population changes include climate change, reduced sea-ice, changes in sea temperatures, changes in food webs and species interactions, disease outbreaks, hunting, fisheries bycatch, and pollution (contaminants and oil pollution).
- National monitoring efforts combined with collaborative approaches, when integrated and standardized sufficiently to allow synthesis across the circumpolar regions, would be optimal.
- Most of the circumpolar regions are lacking in consistently funded seabird monitoring efforts, but seas near Russia, spanning three ecoregions, are particularly lacking in seabird monitoring efforts and represent a clear data gap.
- Demographic data are lacking for most species and colony sites.
- New methods for assessing diet will be required to follow changes in the ecosystem and how they affect seabird populations. Most dietary data are not current or rely on what adults feed their chicks (which can be different from what the adults themselves eat).
- Recent findings about migration routes and over-wintering areas highlight the need to expand conservation efforts for circumpolar species beyond the AMA boundaries.
- People from local communities are important ‘first responders’ to catastrophic events. In addition, we should continue or increase community engagement in monitoring of seabird populations in order to connect monitoring initiatives across spatial scales.

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Appendix 3.5.1.

Seabird species monitored at one or more key monitoring sites for each Arctic country. Seabird species names in bold are FECs. Asterisks indicate the species is one of eight priority species identified in the Circumpolar Seabird Monitoring Plan (Irons et al. 2015).

Species	Canada	Alaska, U.S.	Russian Federation	Finland	Norway	Iceland	Faroe Islands	Greenland
Northern gannet					x	x	x	
Fork-tailed storm-petrel		x						
Leach's storm petrel		x				x		
Northern fulmar	x	x			x	x		
Great skua					x		x	
European shag					x	x		
Great cormorant			x	x	x	x		
Pelagic cormorant		x	x					
Common eider*	x	x	x	x	x	x		x
King eider		X						
Arctic tern		x	x	x		x	x	x
Common gull					x	x		
Black-legged kittiwake*	x	x	x		x	x	x	x
Ivory gull*	x		x		x			x
Glaucous gull*	x	x	x		x			
Glaucous-winged gull		x						
Great black-backed gull			x	x	x	x		
Herring gull	x		x	x	x			
Lesser black-backed gull					x			
Least auklet*		x						
Little auk*					x			x
Black guillemot				x	x	x		
Pigeon guillemot		x	x					
Atlantic puffin	x				x	x		
Tufted puffin		x						
Common murre*		x	x		x	x	x	
Thick billed murre*	x	x	x		x	x		x
Razorbill					x	x		

Bowhead whale.
Photo: Vicki Beaver, Alaska Fisheries Science Center, NOAA

3.6 Marine Mammals

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[1] ArcticTurn Consulting, U.S., [2] All Russian Research Institute for Nature Protection, Russia,[3] Marine Mammal Commission, U.S., [4] Fisheries and Oceans Canada, Canada, [5] Norwegian Polar Institute, Norway, [6] Greenland Institute of Natural Resources, Greenland

Snapshot

- Marine mammals are top predators in Arctic marine ecosystems.
- Many Arctic marine mammal species are important resources and hold special cultural significance for traditional and local communities
- In a warmer Arctic, endemic marine mammal species face extreme levels of habitat change, which is expected to result in dramatic reductions in sea ice dependent species.
- Extirpations of some marine mammal stocks are likely.
- The effects of climate change are expected to be exacerbated by increasing oil and gas exploration and production, marine mining, commercial fisheries, tourism, pollution, noise and shipping, which in combination can profoundly impact marine mammal populations and disrupt complex ecological relationships.
- Changes underway are affecting marine mammal behaviour, abundance, growth rates, body condition and reproduction, impacting the resilience of marine mammal populations with concomitant effects on the people who rely on them for subsistence, economic and cultural purposes.
- Interpretation of current population dynamics and trends has to take into account historical overharvest, which can mask the potential effects of climate change.
- Marine mammals are harvested in many regions, mostly under sustainable management regimes.
- Changing environmental conditions present new challenges to managing marine mammal populations.
- Effective marine mammal population monitoring will need improved techniques at appropriate geographic scales and detail to measure trends that can be evaluated relative to changes in climate (e.g., sea-ice cover) and human activities (e.g., hunting, shipping, mineral exploration)

3.6.1 Introduction

Sea ice declines across the circumpolar Arctic are the most visible and dramatic impact of climate change. Changes to this defining aspect of the environment will have transformative impacts on ice-associated Arctic marine mammals through direct habitat loss; and indirectly through 1) changes in prey species abundance and distribution; 2) increased levels of ocean noise due to increased ship traffic and industrial activities; 3) increased risks of disease; and, 4) alteration of predator-prey relationships (Kovacs et al. 2011, Laidre et al. 2015). Initially, five marine mammal species (walrus (*Odobenus rosmarus*), ringed seal (*Pusa hispida*) , beluga (*Delphinapterus leucas*), bowhead whale (*Balaena mysticetus*) and polar bear (*Ursus maritimus*)) were identified as Focal Ecosystem Components (FECs) in the Circumpolar Biodiversity Monitoring Program's (CBMP) *Arctic Marine Biodiversity Monitoring Plan* (*CBMP Marine Plan*; Gill et al. 2011) as they are of substantial value to Arctic residents. In further evaluating Arctic marine mammals that require sea ice for part, or all, of their life histories, the CBMP Marine Mammal Expert Network included an additional six species for a total of 11 species considered useful for evaluating changes in Arctic biodiversity (Moore and Huntington 2008, Gill et al. 2011, Kovacs et al. 2011, Laidre et al. 2015). These species are highly visible components of the Arctic ecosystems and also an integral part of Arctic subsistence culture. The seven selected species are: beluga, narwhal (*Monodon monoceros*), bowhead whale, the ice seals—ringed and bearded (*Erignathus barbatus*)—, walrus, and polar bear. Four of the selected species are sub-Arctic seals that breed on sea ice and spend part of the year deep into the Arctic: spotted seal (*Phoca largha*) and ribbon seal (*Phoca fasciata*) in the Bering Sea area (Burns 1981), and harp (*Phoca groenlandica*) and hooded seals (*Cystophora cristata*) in the North Atlantic area. These species are associated with sea ice and will be affected by sea ice loss to various degrees depending on regional conditions, individual species ecological requirements, and individual species or stocks historic status. These 11 species, and the aspects related to them, are discussed in this chapter. Marine mammals that are present in the Arctic, but not endemic, are not considered here.

Marine mammals associated with sea ice in the Arctic use all types of ice: glacier ice, multi-year ice, landfast ice and free-floating pack ice. Of all ice types, loose seasonal pack ice is the most important as it serves as habitat for all 11 species (Laidre et al. 2008, Eamer et al. 2013). Seasonally formed annual ice provides breeding habitat for pinnipeds, serving as an essential platform for birthing and pup rearing activities as well as a substrate for energy-efficient moulting platform (Feltz and Fay 1966). Most Arctic and sub-Arctic pinnipeds use sea ice (when available) throughout the year. Polar bear depend upon sea ice for travel and access to ice-associated seals, and generally fast when on land during ice-free periods. Polar bear mainly den on land but also den on sea ice in the Southern Beaufort Sea. Sea ice denning has decreased, however, as ice cover has seasonally diminished (Fishbach et al. 2007, Durner 2015). Sea ice provides a sheltered environment for whales and their calves, which is likely important protection against storms. Sea ice also provides protection from predators (killer whale (*Orcinus orca*)) and competitors of Arctic whales.

Ice seals and whales forage in ice-covered waters, as do polar bear, and are part of an ice-linked food web (Eamer et al. 2013). Seals and whales consume both fish and invertebrate prey, often focusing on Arctic endemic species such as polar

Beluga.
Photo: Vicki Beaver, NOAA

Narwhal.
Photo: Magnus Andersen, Norwegian Polar Institute

Bowhead whale.
Photo: Vicki Beaver, NOAA

Ringed seal.
Photo: Fernando Ugarte

Bearded Seal.
Photo: Allan Hopkins/Flickr.com

Ribbon seal.
Photo: Michael Cameron, NOAA

Harp seal.
Photo: Vladimir Melnik/Shutterstock.com

Hooded seal.
Photo: Aqqa Rosing-Asvid/ILoveGreenland.com

Spotted seal.
Photo: Jay Verhoef, NOAA

Walrus.
Photo: Vladimir Melnik/Shutterstock.com

Polar bear.
Photo: Kit M. Kovacs and Christian Lydersen, Norwegian Polar Institute

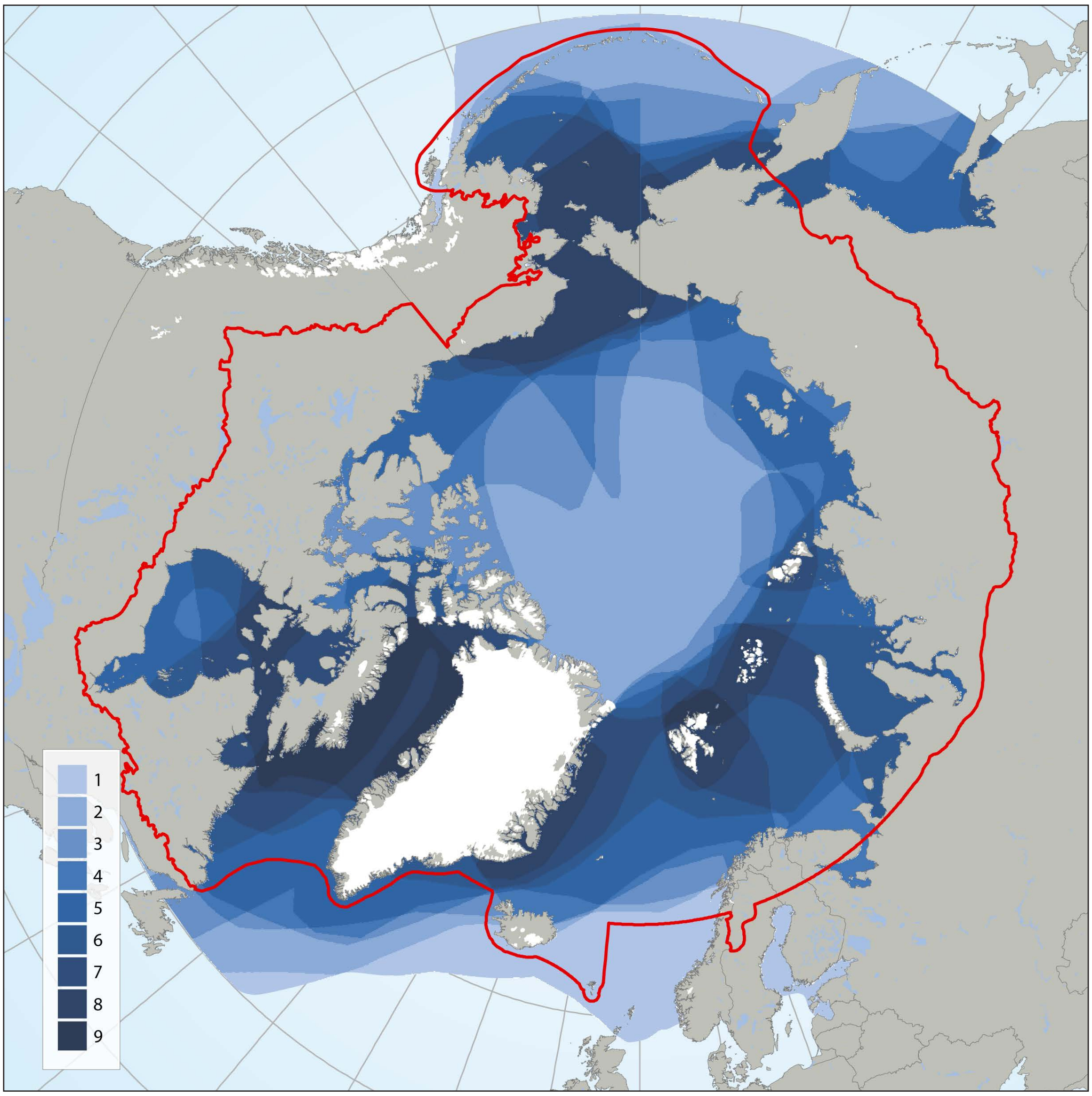


Figure 3.6.1. Circumpolar depiction of species richness based on the distributions of the 11 ice-associated Focal Ecosystem Components (according to the distributions reported in IUCN Red List species accounts). A maximum of nine species occur in any one geographic location. The Arctic gateways in both the Atlantic and Pacific regions have the highest species diversity.

cod (*Boreogadus saida*) and Arctic cod (*Arctogadus glacialis*) and fat-rich *Calanus* copepods and krill (euphausiids), while polar bear feed primarily on seals. Changes in sea ice dynamics affect distribution and timing of primary production, with subsequent effects throughout the food web (Eamer et al. 2013). Changes documented on a regional basis include increased benthic productivity in the Barents Sea (Cochrane et al. 2009) and a complex suite of changes in the northern Bering and Chukchi Seas highlighted by northward shifts in primary productivity and changes in benthic species composition (Grebmeier 2012). Marine mammal responses to changing ice conditions similarly differ by region. Ringed seal body condition and reproductive rate has declined in Hudson Bay and in the Eastern Beaufort Sea (Chambellant et al. 2012, Harwood et al. 2012). In contrast, analyses of ringed and bearded seals off Alaska (Chukchi and western Beaufort Seas), taken in subsistence harvests (2003-2012 compared with 1975-84), documented dietary changes along with increased blubber thickness and earlier female maturation indicating a positive effect to the population (Crawford et al. 2015). Ringed seal are foraging generalists and may be able to adapt to a changing suite of prey, but may be affected by other factors. Understanding characteristics of sea ice use by individual species and populations and tracking responses to changes in ice conditions will be important in determining the significance of environmental changes to ice-affiliated marine mammals and to the human communities.

Population dynamics of many Arctic marine mammal species are also driven by past and present harvests (Laidre et al. 2015). Such dynamics can mask the potential effects of climate change; therefore, it is important to understand the history of exploitation. High historic levels of take depleted a number of marine mammal populations. For some species, such as bowhead whale (George et al. 2015), harp seal (Stenson et al. 2016), and Atlantic walrus (Kovacs et al. 2015), reductions in harvest levels have allowed populations to increase. In other cases, such as the Greenland Sea hooded seal, there is no sign of recovery from a severe harvest-induced decline even decades after catch levels have been reduced (Øigård et al. 2014). Harvest history must therefore be considered in analyses of population trends and effects of various drivers including climate change.

Box 3.6.1 Greenland hooded seals

Greenland Sea hooded seal has been commercially exploited for centuries (ICES 2016). Catches increased substantially after the 1920s and following World War Two to such a high level that regulatory measures were brought in to reduce effort. Eventually, catches declined and quotas were imposed beginning in 1971. It was assumed that with reduced catches, the population would increase. No successful surveys were conducted until 2005, at which time the population was much lower than expected. Consequently, the population has been fully protected from commercial harvesting since 2007. A recent assessment estimates that Greenland Sea hooded seal decreased from approximately one million seals in the late 1940s to approximately 84,000 in 2013 (Øigård et al. 2014). The main decline occurred before 1980 and is thought to have been driven primarily by harvest (Øigård et al. 2014). No statistically significant change in abundance has occurred between aerial surveys conducted in 2005 and 2012, but modelling suggests that the population may still be decreasing slightly even in the absence of hunting (Øigård et al. 2014). Only small scientific catches have been allowed from the population since 2007 (a total of 515 pups and 268 adults over the period 2007-2014) and Greenland hunters take few hooded seals from this population. Hooded seal are not exhibiting the expected density dependent compensation (e.g. increased reproductive rates, lower mortality) that normally occurs when populations are low compared to available resources. Clearly, some other factors such as food shortages, predation levels or disease, have become important in controlling the population's trajectory. Recent studies document increased predation on harp and hooded seals by East Greenland polar bear, which may be mediated by the reduced distance from the Greenlandic coast to the pack ice edge (McKinney et al. 2013). This has likely affected survival rates of both harp and hooded seals in the area. Morphometric data collected over the period from the 1950s through to the present show reduced length-at-age and body condition of female hooded seals from the Greenland Sea compared to the highest levels observed for Northwest Atlantic hooded seals. Particularly poor conditions seem to have prevailed in the 1980s and 1990s, prior to the recent severe decline in ice cover in the Greenland Sea, and may be more related to competition with commercial fisheries (Anne Kirstine Frie, Institute of Marine Research, Norway, unpubl. data.).

Marine mammal biodiversity— if described as a simple tally of species present—masks the impact of climate driven changes on endemic Arctic species. Using a simple tally, biodiversity in the Arctic may increase as temperate species move into the area with shifting ice and warming conditions. Their arrival may further stress Arctic endemic species already faced with changing physical and ecological conditions. The cumulative and synergistic effects of multiple stressors associated with the changing environment and additional competition as temperate species move northward may become significant challenges for ice-dependent marine mammal species (Moore et al. 2014). The selection of ice-dependent and ice-adapted species as a focal group in CBMP reflects the importance of evaluating changes in biodiversity of Arctic marine ecosystems.

The efforts to track and understand trends in population status in each of the marine mammal FECs will provide insights into their responses to ecosystem changes and, ultimately changes in Arctic biodiversity. Population status may be defined as both population abundance measured by counts, or as population level relative to carrying capacity inferred from demographic parameters and/or condition indices (Gill et al. 2011). Responses will vary by species, population and region (Moore and Huntington 2008). Endemic Arctic species range across jurisdictional boundaries and their responses to environmental change, whether in distribution, behaviour, abundance, or other factors, will result in new conservation and management challenges. To address these challenges, current population and distribution information is essential, and represents basic information needed by those charged with marine mammal management. It is essential to provide the resources for such monitoring and that management-relevant information be collected and disseminated widely.

3.6.2. Current monitoring

Monitoring is necessary to assess population trends and status and the effect of environmental changes and anthropogenic activities, to support informed management. Assessing trends, which are important indicators of population status, requires knowledge of stock structure, abundance data over many years or demographic analysis of vital rates (e.g., reproduction and survival) and statistics of direct and indirect human-caused mortality (e.g., catch, bycatch, ship strikes). These parameters are available for relatively few populations of marine mammals (Laidre et al. 2015).

Tracking animals in space and time provides data on connectivity among groups and populations as well as raw distributional information. Photographic ID catalogues are useful for species with individual markings and are maintained for several whale species. The purpose of identity catalogues is to track individuals and provide information on movements and abundance; examples include bowhead whales in the Bering-Chukchi-Beaufort Seas, killer whales in Canada, humpback whales (*Megaptera novaeangliae*) in the North Atlantic and in the North Pacific. Satellite telemetry is broadly applicable and used on a variety of species. Telemetry studies can provide vital information about stock structure and seasonal movements as well as baseline data useful for comparisons of changes in distribution over time and for comparisons of changes in activity budgets and other parameters with changing environmental situations. An example is the telemetry studies of ringed seals in Svalbard, which show how changes in ice conditions have influenced foraging behaviour of a strongly ice-associated seal (Hamilton et al. 2015, 2016). Further examples include studies that used telemetry linked changes in ice conditions to observed reductions in reproductive rates of Northwest

Atlantic harp seals (Stenson et al. 2016) and body condition declines of Barents Sea harp seals (Bogstad et al. 2015).

Similar to mammalian status assessments elsewhere (e.g. IUCN Red List for Mammals), a key parameter used for determining the status of marine mammals in the Arctic is the estimate of abundance. The most common abundance estimation method for marine mammals is visual and/or photographic aerial surveys of the entire population or the visible component (e.g., pups). Generally, survey estimates must be corrected for animals missed by the observer (perception bias) or animals that may not be present to be counted (availability bias, e.g., whales that are below the surface). If only a component of the population is surveyed, total abundance is estimated using a population model that incorporates additional data such as reproductive rates and/or survival rates, pregnancy rates or other population parameters. Mark-recapture studies use individual identification (appearance, tags, or genetic sequencing) to mark part of the population and then the proportion of marked animals subsequently re-sighted is used to estimate the total population. Passive acoustic monitoring devices are increasingly in use, often within area-based arrays to get an index of abundance. These devices also permit the assessment of changes in phenology (timing of events), such as breeding or migration, if the devices are maintained over periods of decades and in some cases can identify potential sub-stock structure in whale populations (e.g., Delarue et al. 2009).

To determine population trends, surveys must be repeated over time, though the level of variation around estimates often precludes trend estimation. Multiple estimates can be used to evaluate trends in the whole population using a population model, or used simply as an index of change in abundance. Given the large ranges of many species, expense of ships and aircraft, and challenging climatic conditions in the Arctic, surveys of most stocks are only carried out sporadically and time-series data for most stocks are limited (Laidre et al. 2015).

Population surveys for the 11 FECs are generally conducted by or for resource management agencies at the national level or as a cooperative effort between jurisdictions (e.g., North Atlantic Sightings Survey (NASS)). In Canada, Fisheries and Oceans Canada is responsible for assessing stock status for whales and seals in the Arctic while Environment and Climate Change Canada and provincial and territorial and provincial governments conduct surveys and research on polar bears. In the U.S., the U.S. Fish and Wildlife Service (USFWS; walrus and polar bear) and the National Marine Fisheries Service (ice seals and whales) are responsible for monitoring the status of marine mammals. In Greenland, the Institute of Natural Resources (GINR) oversees marine mammal stock monitoring. GINR provides the Greenland Self Rule with advice on sustainable exploitation of living resources and safeguarding of the environment and biodiversity. In Norway, the Norwegian Polar Institute (NPI) is responsible for monitoring most Arctic endemic marine mammals, except for harp and hooded seal, which are the responsibility of the Institute of Marine Research. NPI acts as scientific and strategic adviser to the Norwegian government in polar issues. Marine mammal monitoring in Russia is conducted by regional research and management agencies and studies on protected areas (parks and nature reserves) are the responsibility of the protected area managers.

Stock assessments are carried out at national, bilateral (Inuvialuit/Inupiat Agreement; Canada/U.S. Agreement; and Canada-Nunavut-Greenland Memorandum of Understanding for polar bear; Joint Commission on Narwhal and Beluga between Canada and Greenland; U.S.-Russia assessment of shared populations of walrus, ice seals and polar bears in the Bering/Chukchi Sea region; Norway and Russia cooperation to assess status of shared marine mammal populations, such as polar bear), regional (i.e., North Atlantic Marine Mammal Commission (NAMMCO), or international levels (International Whaling Commission (IWC), International Union for the Conservation of Nature (IUCN) Polar Bear Specialist Group (PBSG)). These international efforts are key in setting management parameters ultimately implemented by individual jurisdictions.

International cooperative efforts are critical for tracking scientific research and identifying issues of concern for shared stocks. NAMMCO consists of representatives from the Faroe Islands, Greenland, Iceland and Norway and was formed to cooperate on the conservation, management and study of marine mammals in the North Atlantic. Under the *1973 Agreement on the Conservation of Polar Bears* the Polar Bear Range States are implementing a Circumpolar Action Plan for Polar Bear (Polar Bear Range States 2015). One focus of this work is to help coordinate and improve monitoring and research efforts for polar bear. Under the umbrella of the IUCN PBSG tracks and evaluates polar bear population status and trends throughout the circumpolar region. The IWC evaluates whale populations and is responsible for setting harvest limits for bowhead whales. These international efforts are key in setting management parameters and identifying information needs that are ultimately implemented by individual jurisdictions.

Harvested animals are another important data source (Harwood et al. 2015). Arctic and sub-Arctic marine mammals, which are an important resource for northern people (Hovelsrud et al. 2008), are harvested for both subsistence and commercial purposes. Most harvests are monitored and some operate with allocated quotas. The availability of subsistence harvest samples provides an opportunity, in collaboration with communities, to obtain a suite of metrics (e.g., age at maturity, pregnancy rate, growth rate, body condition, pollution and contaminant loads) that could serve as broader ecological indicators.

Monitoring of community subsistence hunts of marine mammals is conducted throughout the Canadian Arctic sporadically, with about one-third of the communities participating in general, and the extent of sampling varies with the region (Inuvialuit settlement region, Nunavut, Nunavik, Nunatsiavut). Monitoring of polar bear subsistence harvest is conducted through the whole Canadian Arctic with the exception of Quebec where a monitoring program is being developed through a co-management process. For all marine mammal subsistence harvest monitoring, tissue samples and harvest information are collected for genetics, disease, body condition, contaminants, reproduction, feeding ecology, and stress with collaborations at a number of universities. The longest monitoring programs exist for ringed seal, beluga, and polar bear. Fisheries and Oceans Canada, in partnership with regional Inuit co-management groups, collects national harvest statistics for walrus, whales, and seals. The provincial and territorial governments collect harvest information for polar bears in collaboration with Inuit. In the U.S., harvest information is collected by the USFWS and through collaborative efforts with marine mammal co-management groups, communities, and the Alaska Department of Fish and Game, U.S. In Greenland, catch data are collected and administrated by the Ministry of Fisheries and Hunting. Catches of species not regulated by quotas, including seals, are reported on a form that hunters have to send to the government in order to renew their hunting permit. Catches of species harvested according to quotas (narwhal, beluga, walrus, polar bear and large whales) are reported in more detailed special forms, which include, for each catch, date and position, information about the hunting method and time to death and biological data such as age class, gender, size, reproductive state and stomach contents.

Marine mammal studies can benefit from Traditional Knowledge (TK), which provides a long-term and detailed wealth of information and understanding of wildlife and resources upon which communities depend. Sources are not necessarily marine mammal specific, such as a general overview of TK possessed by the Chukotkan peoples (Bogoslovskaya and Krupnik 2014) that provides insights on local patterns and environmental changes over time. Another localized study around Diomede Island in the Bering Straits region details currents and regional anomalies around the island that affect, among other things, marine mammal distribution (Social Science Program 2014). Other studies are species specific, such as the Final Report of the Inuit Bowhead Knowledge Study (Hay 2000). Studies repeated over time, such as polar bear habitat use studies in the Chukchi and Bering Straits region (Kalxdorff 1997, Kochnev et al. 2003, Voorhees et al. 2014) document local knowledge in a changing environment. Community based sampling programs provide biological parameters for ringed and bearded seal research in the Canadian Arctic (Harwood et al. 2012). Subsistence harvests provide another important source of information, both from hunters' knowledge of the animals and their environment and from samples taken from harvested animals (e.g., Laidre et al. 2015). Community participation in conservation efforts, co-management of harvest monitoring, inclusion of TK in identification of research priorities, and direct local involvement in scientific sampling are ways to continue access to this important source of information and expertise.

In some cases, TK holders provide important insights on data utility and limitations. For example, in Alaska, the Ice Seal Committee, a co-management group supported by the National Marine Fisheries Service, supported a compilation of historic ice seal harvest information and identified both the strengths and limitations of the information. Data on harvest by village from 1960-2012 demonstrate the importance of seal harvest as a subsistence resource throughout the region. Extrapolation of the data is limited, however, as most information was collected as part of household surveys conducted intermittently in different villages. As a result, the data are insufficient to measure changes in harvest patterns across villages, regions or years (Ice Seal Committee 2014)

Monitoring polar bear in Greenland.
Photo: Fernando Ugarte

3.6.3. Status and trends of FECs

The CBMP Marine Mammals Expert Network updated the estimates and abundance table developed in Laidre et al. (2015) and new information on status and harvest was added. The table includes the initial five FECs (beluga, bowhead whale, walrus, ringed seal and polar bear), as well as an additional six species we identified as important for tracking ecosystem changes (narwhal and bearded, spotted, ribbon, harp and hooded seals). The eight Arctic Marine Areas (AMAs) referred to in our table are as defined by the CBMP (Gill et al. 2011). These areas differ slightly from those used in Laidre et al. (2015), who described 12 geographic regions that extend further south in the Pacific (including the southern Bering Sea and the Sea of Okhotsk) and identified the Chukchi Sea, Baffin Bay, Labrador Sea, Greenland Sea and Barents Seas as distinct regions and did not include the central Arctic Basin. Notable population updates include new estimates for narwhal, beluga, walrus and polar bear in some regions.

Nearly all stocks are harvested, primarily for subsistence. One stock, belugas in Southwest Greenland, was extirpated in the first half of the twentieth century (Heide-Jørgensen and Laidre 2006). Of the 83 remaining stocks, only 11 are not subject to harvest, and six of these are in the Atlantic Arctic. Many harvests are managed within a quota system; of the 73 harvested populations, 39 (or 54%) are harvested with quotas throughout their entire range. The majority of harvested populations in Canadian and Greenlandic waters are taken under a quota system. In Canada, most hunts are by quotas (beluga, narwhal, bowhead whale, walrus and polar bear) and more detailed harvest information is collected periodically. In Greenland harp, hooded, ringed, and bearded seals are not under quotas, while walrus, beluga, narwhal, bowhead, and polar bear are. All the protected stocks are in Norway, Russia or the Arctic Basin, while all stocks in Alaska, Arctic Canada and Greenland are harvested.

With the exception of bowhead whale and polar bear, formal quotas do not limit marine mammal harvest in the U.S.; however, the harvest must be non-wasteful and it must be conducted for subsistence and cultural purposes. Harvesting occurs across the Arctic although to a lesser extent along the coastline of northern Russia (Kara and Laptev Seas) and off Norway. The majority of the protected (not harvested) stocks are in the Barents Sea region, off the coast of Norway.

Trend information remains elusive for the ringed, bearded, ribbon and spotted seals and some polar bear populations, and is limited for beluga subpopulations outside the Atlantic Arctic region. More is known about other cetaceans, with a majority of narwhal subpopulations considered stable and most bowhead subpopulations considered to be increasing. The status and trends of harp and hooded seal populations are regularly documented (Hammill et al. 2015, Stenson et al. 2016). The status column in Table 3.6.1 incorporates information on exploitation history to facilitate the interpretation of temporal trends. Specifically, an increasing population may be the result of a positive reaction by the species to changing ecological conditions, e.g., increasing primary production resulting in increased prey abundance. Alternatively, and most commonly among Arctic marine mammals, a species that has been overharvested in the past may simply be increasing due to a cessation or regulation of harvest. While not definitive in sorting out details, the status information provides important context for evaluating trend information.

From a regional perspective, little abundance and trend information is available for the many populations that

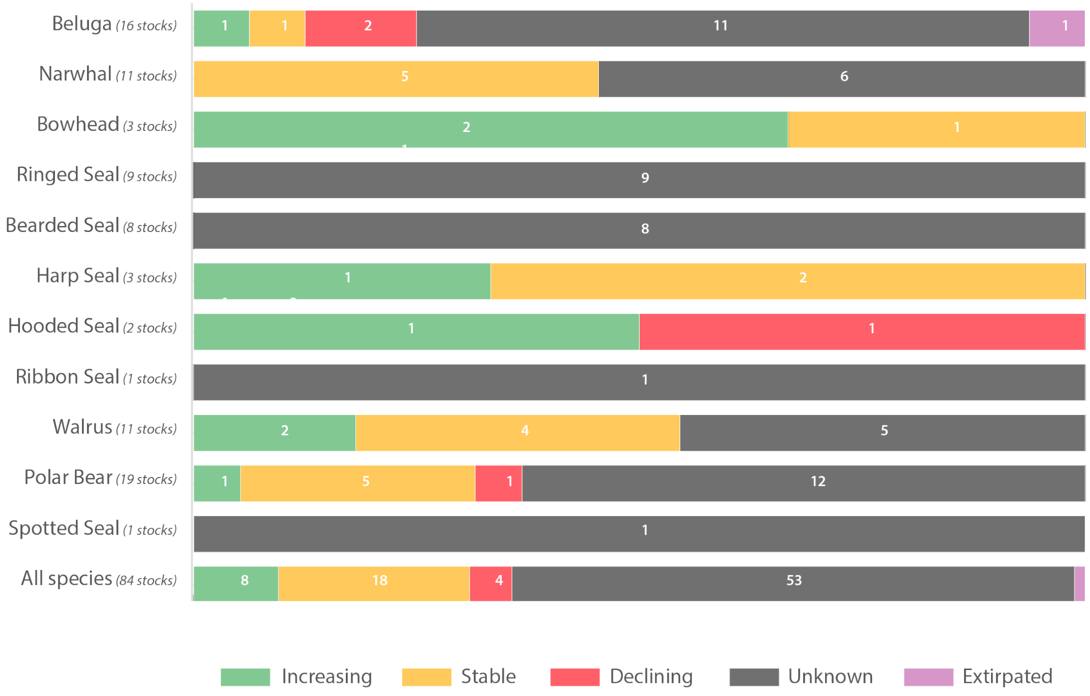


Figure 3.6.2. Trends in abundance of Arctic marine mammal Focal Ecosystem Components based on the most recent assessment for each recognized subpopulation of a species (red, declining trend; yellow, stable trend; green, increasing trend; grey, unknown trend). Number of subpopulations is given after species name. Each column is divided into equal segments, the sizes of which are not proportional to the size of the subpopulation. Ringed seal and bearded seal segments represent subspecies. Walrus segments represent subpopulations within subspecies. See Table 3.6.1 for details on abundance.

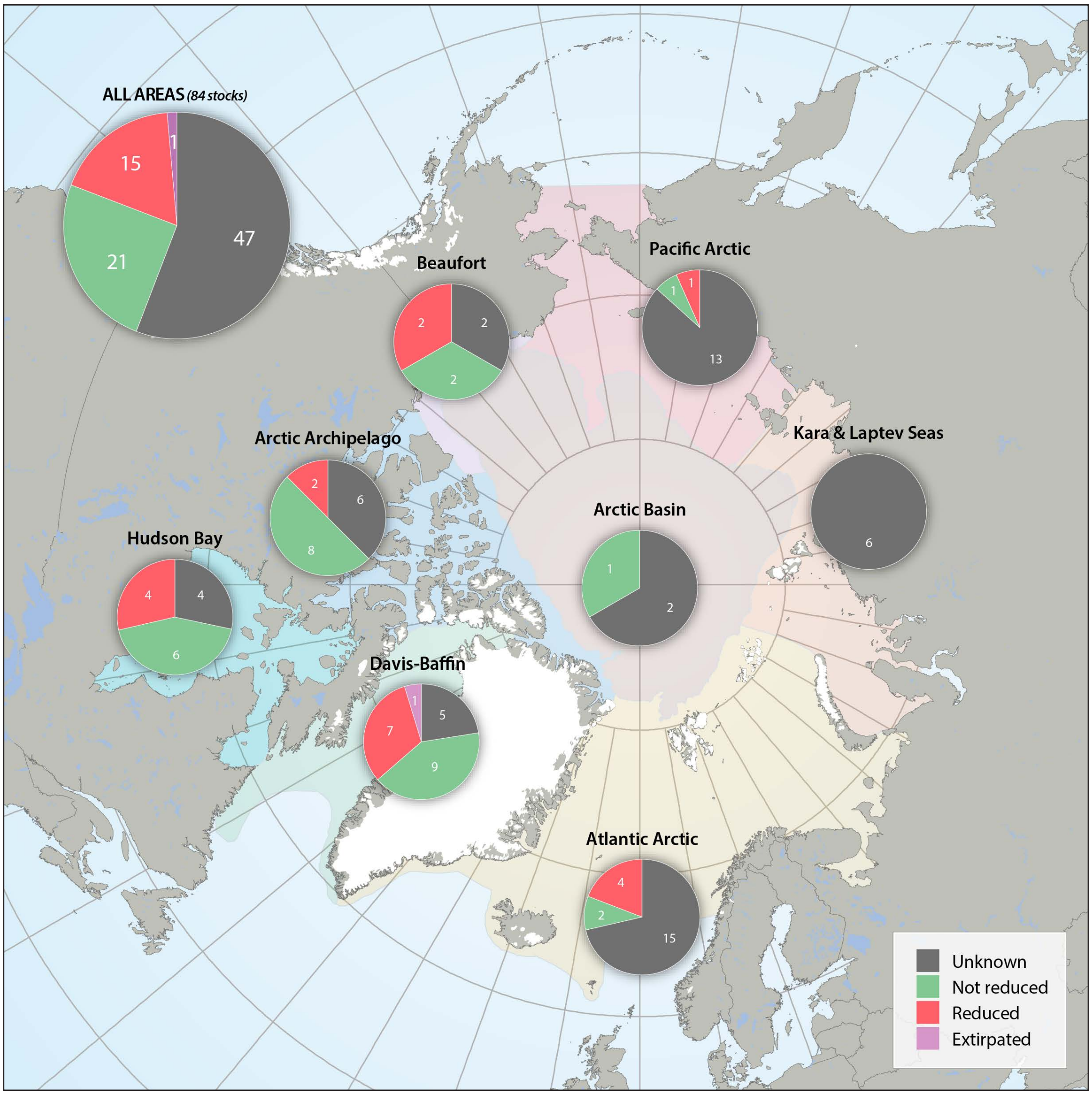


Figure 3.6.3 Status of marine mammal Focal Ecosystem Component stocks by Arctic Marine Area.

occupy the Pacific Arctic and Atlantic Arctic regions. Both areas include extensive open-ocean as compared with other regions that are comparatively more defined seas over continental shelves or within archipelagos. The Arctic Basin and adjacent Beaufort and Kara-Laptev regions have the lowest number of marine mammal populations and trend information is also limited in these regions.

Long-term population monitoring is important for the ability to detect changes in vital rates that can influence population dynamics and in some cases point to the main drivers of population change. For example, changes in harp seal abundance, growth rates, body condition and reproductive rates in Labrador and Newfoundland since the 1950s have been linked to changes in harvest levels and ice conditions (Stenson et al. 2016). Situated at the southern edge of the seasonal pack ice, the pupping areas of Northwest Atlantic harp (and hooded) seals have undergone significant warming, with concomitant sea ice losses, over the past four decades (Stenson and Hammill 2014). During the same period, the population has recovered from a low level due to management actions and reduced harvests (Hammill et al. 2015). Monitoring of reproductive rates since the 1950s has shown that pregnancy rates of mature females have declined while the interannual variability in the proportion of seals that are pregnant has increased (Stenson et al. 2016). These changes are associated with increased population size, and annual changes in mid-winter ice extent and prey abundance. The changes in ice extent likely reflect or even cause many concurrent ecosystem changes, including changes in food availability, notably for capelin the main forage fish in the area (Buren et al. 2014). In Barents Sea harp seals, body condition has declined during the past 10 years, when Barents Sea ice cover has been lower than in the late 1990s. This could be related to longer travel distances to the ice edge or changes in prey availability (Øigård et ak 2013). The latter may be partly due to increased competition from a historically large Atlantic cod stock, which has profited from the warming trend (Bogstad et al. 2015). Comparisons of swimming distances and dive behaviour in ringed seals off Svalbard before and after a major retreat of summer ice showed an increased foraging effort suggesting increased energetic costs of finding food associated with changes in ice conditions (Hamilton et al. 2015, 2016). The complexity inherent in interpreting Arctic marine mammal population status underscores the need for long-term monitoring as carrying capacity changes due to changing climatic conditions.

Distributional changes within polar bear populations have led to differing perceptions of population trends. Increasing interactions with polar bears in northern communities can

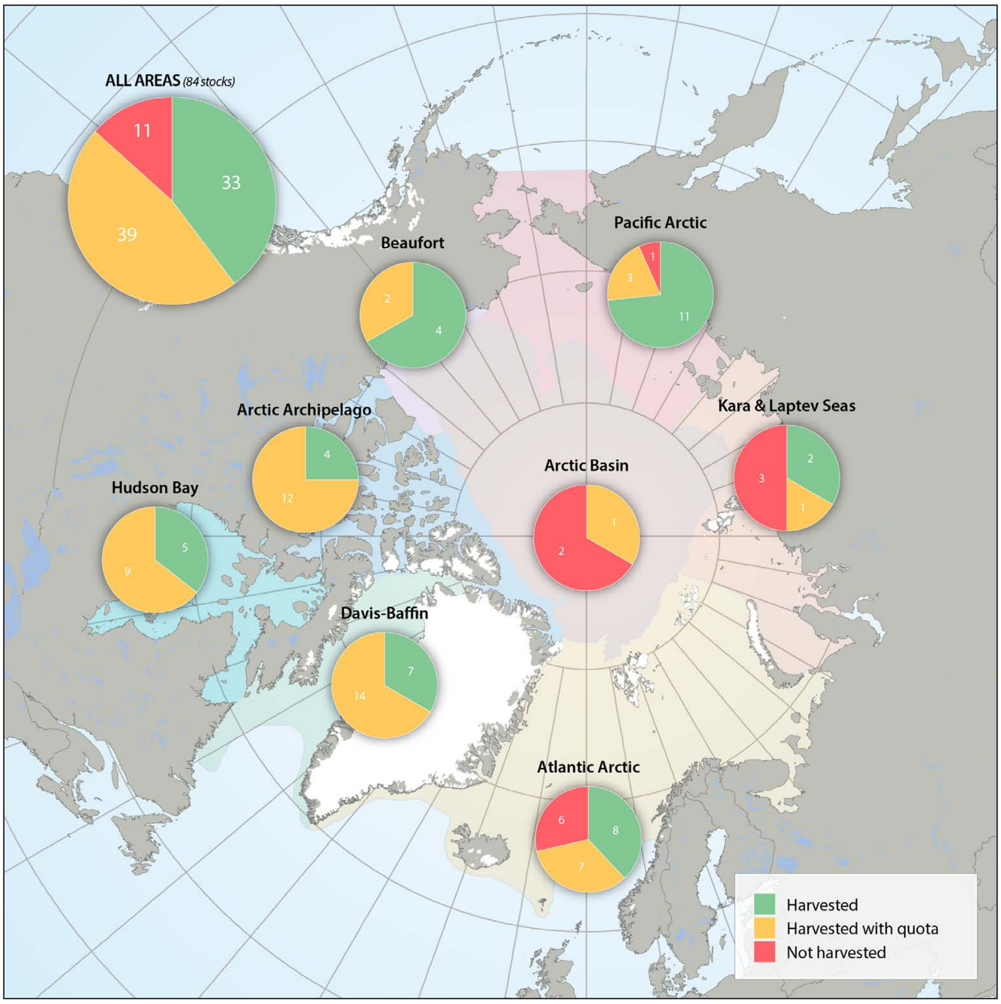


Figure 3.6.4. Harvest marine mammal Focal Ecosystem Component stocks in Arctic Marine Areas. Harvested without quotas, with quotas or not harvested.

be due to changes in population, but they may also be because of changes in distribution due to loss of sea ice. Understanding both the reality and perception of population status is critical to developing effective management strategies. While humans and polar bear have existed side by side in the Arctic for centuries, the frequency of conflicts between bears and humans has increased in parallel with sea ice reduction and increasing numbers of people residing in and visiting the Arctic (Derocher et al. 2004, Stirling and Parkinson 2006, Hovelsrud et al. 2008, Towns et al. 2009). The Polar Bear Range States have given this issue high priority, and began developing a database tool in 2009 to document interaction events throughout the range of polar bears and develop appropriate mitigation strategies (Polar Bear Range States 2015). However, this tool is not fully implemented. In Alaska, local residents and management agencies are working collaboratively to minimize human/polar bear conflicts. In oilfield developments along the Beaufort coast, industry activities are required to have formal polar bear management plans that include site design features that minimize polar bear attraction, polar bear guards, and spring den site surveys. In the Indigenous village of Kaktovik, where bears congregate in the autumn to feed on whale bones from the subsistence harvest, the village and the USFWS in collaboration with numerous partners implements and updates as needed comprehensive strategies to manage polar bear viewing opportunities, food storage, and village safety. As with other marine mammal's subject to subsistence hunt, a co-management group comprised of coastal village representatives in the range of polar bears was used to support ongoing partnerships to develop local management plans for villages along the Chukchi Sea coast.

In partnership with the World Wildlife Fund-Canada, the town of Arviat in Nunavut participated in a Human-Polar Bear Conflict Reduction Project. A polar bear guard was trained in deterrence techniques (spotlights and bear bangers) and in identifying and reducing bear attractants in the community (like garbage and poorly protected meat storage). In addition, electric fences were installed and steel bins were provided for meat storage. Over the three-year project the number of bears killed per year in Defense of Life and Property in Arviat dropped from eight to zero. In addition, the Polar Bear Alert Program (PBAP) in Churchill, Manitoba is well known for its effective approach to protect polar bears and humans. The town of Churchill lies on the western coast of Hudson Bay and is in the path of an annual travel route for polar bears that are traveling north to reach ice as it re-forms for the season. The PBAP has two tiers for protecting the bears and humans. When bears first approach the Churchill area they are chased away by Conservation Officers using a variety of deterrence techniques. If they return they are captured and put in a holding facility until the ice re-forms in the fall and they are released. This prevents bears from entering the city and becoming problem animals that need to be killed and protects residents from possible encounters.

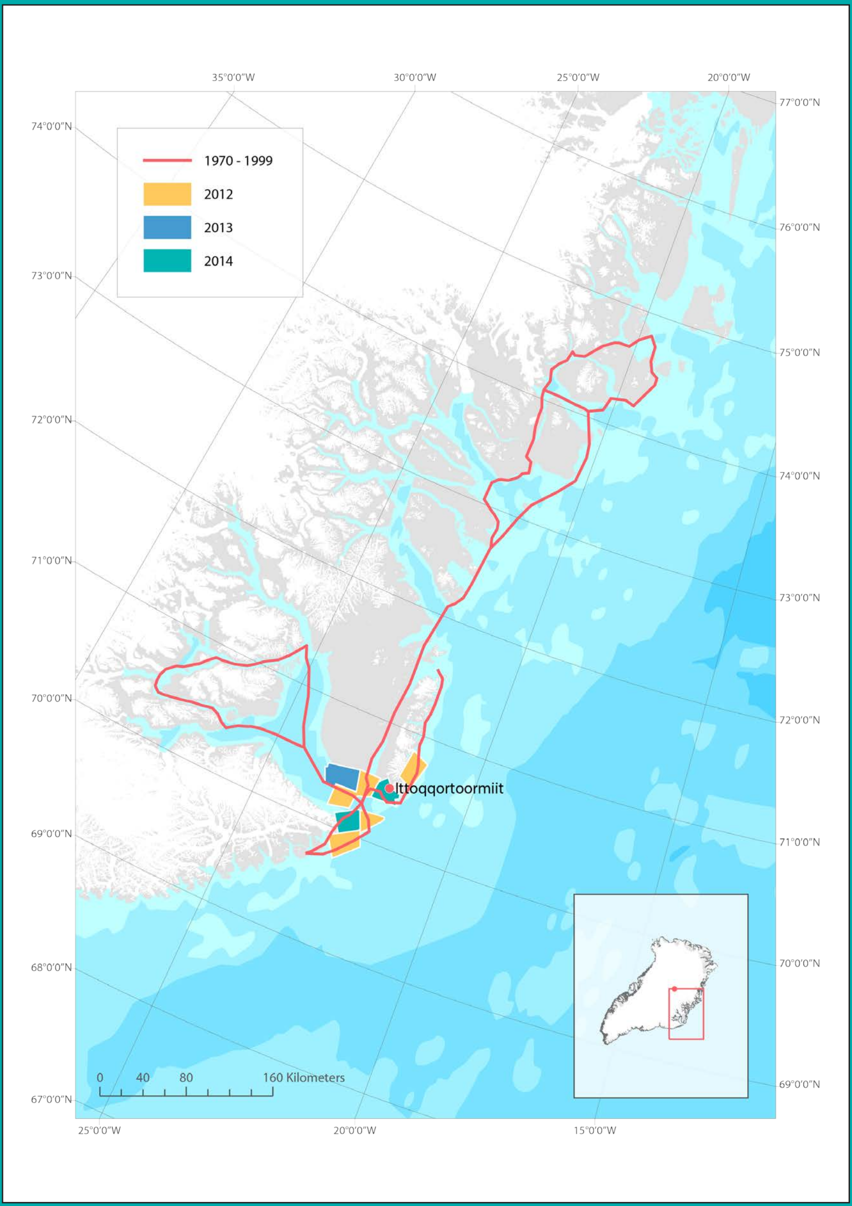
Box 3.6.2: Polar bear Traditional Knowledge

Traditional Knowledge (TK) contributes insights into polar bear condition and abundance, particularly in the face of rapidly changing sea ice environments. Extensive hunter interviews in the 1990s and early 2000s in the Chukchi and northern Bering Sea regions documented polar bear seasonal use and distribution around villages, and the importance of polar bears in Indigenous culture (Kalxdorff 1997, Kochnev et al. 2003). Since then, subsequent studies provide insight about how polar bears are faring in the face of rapid environmental changes, notably the loss of summer sea ice. The value of the information is in part due to the technical challenges of collecting baseline and updated information on polar bear, and in large part on the insights provided by hunters that live in and depend upon the same environment as polar bear. Similar studies to connect past and present knowledge to add insights to the effects of climate change on polar bear have been conducted in Canada (Kotierk 2010, Slavik 2012) and Greenland (Sandell et al. 2001, Born et al. 2010).

Hunters in all villages observed changes in distribution and timing of seasonal movements and in local abundance in recent years. Other important conclusions from these studies include observations on polar bear condition and diets. In general, bears were considered to be in good condition, even when stranded on land during the summer or late autumn. Bears were observed eating a variety of terrestrial foods indicating flexibility to deal with changing conditions. Despite this, hunters cautioned that the ultimate effect of sea ice loss is not clear and speculation on the future is avoided in St. Lawrence Island Yupik and Inupiaq cultures (Voorhees and Sparks 2012, Voorhees et al. 2014).

Inuit hunters from Greenland have experienced profound changes in their subsistence harvest of polar bear (Born et al. 2010). In the 1990s and before, sea ice conditions allowed for hunting trips in dog sledges over very long distances. It took several days to hunt a few polar bear, as bear densities were low. Since the 2000s, the season when the sea ice is safe for sledge travel is increasingly shorter, and the areas where transport over the ice is possible have been greatly reduced. As consequence, the number of polar bear harvested from skiffs, instead of dog sledges has increased. In addition, polar bears are now found closer to settlements. As a result, trips for hunting polar bear are much shorter than before. This change, coupled with the introduction of quotas in 2006, result in an increased presence of polar bear in areas inhabited by people and more bears killed to protect human lives.

TK and science are knowledge systems that for the most part complement each other, however, there are instances in which their conclusions differ. For example, information on polar bear population status and trends can be particularly difficult to reconcile due to variability in scope and methods (e.g., IUCN Polar Bear Specialist Group 2017, Polar Bear Technical Committee 2013). Progress has been made in the utilization of both knowledge systems in assessments, and efforts continue to determine the best path forward in using TK effectively in decision making.



Box figure 3.6.1. Routes used for hunting polar bear in Ittoqqortoormiit, East Greenland before 1999 (red line), and in 2012 (yellow), 2013 (blue) and 2014 (green).

Table 3.6.1. Estimates of abundance (with associated estimate of uncertainty, if available), status - reduced versus not reduced, trend - increasing, stable, decreasing, and harvest regime – harvested (H), harvested with quotas (HQ) or protected (P) for subpopulations of Arctic marine mammals. The table is an update of table 1 in Laidre et al. (2015). Sources included dedicated surveys, population viability analyses, expert opinion.

Species	**Subpopulation/ Stock**	**CBMP Arctic Marine Area**	**Abundance** (with 95% confidence interval (CI) or coefficient of variation (CV) if available)	**Year**	**Status:** Unknown (U), Reduced (R) or Not Reduced (N)	**Trend:** Unknown(U), Increasing(I), Stable (S), Declining (D)	**Harvest:** harvested without quota (H), harvested with quota (HQ), currently protected (P)	**Survey/trend reference from Laidre et al. unless noted**
Beluga	East Siberian and West Chukchi Seas	Pacific Arctic	Unknown		Unknown	Unknown	HQ	
	Eastern Chukchi Sea	Pacific Arctic	3,700	1992	Unknown	Unknown	H	Frost et al 1993
	Eastern Beaufort Sea	Beaufort Sea	41,800	1999	Not Reduced	Unknown	H	Allen et al 2011
	Eastern Bering Sea	Pacific Arctic	18,000	1989-1991	Unknown	Unknown	H	Allen et al 2011
	Bristol Bay	Pacific Arctic	2,877	2005	Not Reduced	Increasing	H	Lowry et al 2008
	Western Hudson Bay	Hudson Bay	57,300 (95% CI 37,700-87,100)	2004	Not Reduced	Unknown	H	Richard 2005
	James Bay	Hudson Bay	14,967 (95% CI 8,316-26,939)	2011	Not Reduced	Unknown	H	Gosselin et al 2013
	Eastern Hudson Bay	Hudson Bay	3,351 (95% CI 1,552-7,855)	2011	Reduced	Stable	HQ	Gosselin et al 2013
	Ungava Bay	Hudson Bay	32 (95% CI 0 – 94)	2012	Reduced	Unknown	HQ	Doniol-Valcroze and Hammill 2012
	Cumberland Sound	Davis-Baffin	1,150 (CV = 0.214, 95% CI = 761–1744)	2014	Reduced	Declining	HQ	Marcoux et al. 2016
	East high Arctic and Baffin Bay	Arctic Archipelago	21,200 (CV 0.25)	1996	Reduced	Unknown	H (Canada), HQ (Greenland)	Innes et al 2002
	"- West Greenland Winter component"	*Davis-Baffin*	*9,072 (95% CI 4,895 - 16,450)*	*2012*	*Reduced*	*Stable*	*HQ*	*NAMMCO/JCNB 2015*
	"- NOW Polynya Winter component"	*Davis-Baffin*	*2,324 (95 % CI 1,786 - 2,820)*	*2014*	*Reduced*	*Unknown*	*HQ*	*NAMMCO / JCNB 2015*
	White Sea	Atlantic Arctic	6,498 (95% CI 4,664-8,818)	2008	Unknown	Declining	HQ	Glazov et al 2010
	Southwest Greenland winter	Davis-Baffin	0	ca 1930	Extirpated	Extirpated	Extirpated	Heide-Jørgenen and Laidre 2006
	Svalbard	Atlantic Arctic	Unknown		Unknown	Unknown	P	Gjertz and Wiig 1994
	Kara and Laptev Seas	Kara -Laptev Seas	Unknown		Unknown	Unknown	HQ	
	Gulf of Anadyr	Pacific Arctic	15,127 (95% CI 7447 -30741)	2006	Unknown	Unknown	HQ	Litovka 2013

Species	**Subpopulation/ Stock**	**CBMP Arctic Marine Area**	**Abundance** (with 95% confidence interval (CI) or coefficient of variation (CV) if available)	**Year**	**Status:** Unknown (U), Reduced (R) or Not Reduced (N)	**Trend:** Unknown(U), Increasing(I), Stable (S), Declining (D)	**Harvest:** harvested without quota (H), harvested with quota (HQ), currently protected (P)	**Survey/trend reference from Laidre et al. unless noted**
Narwhal	Eclipse Sound	Arctic Archipelago, Davis-Baffin	10,489 (CV 0.24)	2013	Unknown	Unknown	HQ	NAMMCO/JCNB 2015
	Admiralty Inlet	Arctic Archipelago, Davis-Baffin	35,043 (CV 0.42)	2013	Not Reduced	Stable	HQ	NAMMCO/JCNB 2015
	Somerset Island	Arctic Archipelago, Davis-Baffin	49,758 (CV 0.20)	2013	Not Reduced	Stable	HQ	NAMMCO/JCNB 2015
	Jones Sound	Arctic Archipelago, Davis-Baffin	12,694 (CV 0.33)	2013	Not Reduced	Unknown	HQ	NAMMCO/JCNB 2015
	Smith Sound	Arctic Archipelago, Davis-Baffin	16,360 (CV 0.65)	2013	Not Reduced	Unknown	HQ	NAMMCO/JCNB 2015
	East Baffin Island fjords	Davis-Baffin	17,555 (CV 0.35)	2013	Not Reduced	Stable	HQ	NAMMCO/JCNB 2015
	Northern Hudson Bay	Hudson Bay	12,485 (CV 0.26)	2011	Not Reduced	Unknown	HQ	Asselin et al 2012
	Inglefield Bredning, West Greenland	Davis-Baffin	8,368 (95% CI 5209-13,442)	2007	Reduced	Stable	HQ	NAMMCO/JCNB 2015
	Melville Bay, West Greenland	Davis-Baffin	3,091 (95% CI 1,228-7,783)	2014	Reduced	Stable	HQ	NAMMCO / JCNB 2015
	"- West Greenland winter aggregation"	*Davis-Baffin*	*18,583 (95% CI 7,308-47,254)*	*2006*	*Reduced*	*Stable*	*HQ*	*NAMMCO / JCNB 2015*
	East Greenland	Atlantic Arctic	6,444 (95% CI 2505-16,575)	2008	Unknown	Unknown	HQ	Heide-Jørgensen et al 2010
	Svalbard / Franz Josef Land	Atlantic Arctic	Unknown		Unknown	Unknown	P	
Bowhead whale	Bering-Chukchi-Beaufort Seas (BCB)	Pacific Arctic, Beaufort	16,892 (95% CI 15,704– 18,928)	2011	Reduced	Increasing	HQ	Givens et al 2013
	East Canada-West Greenland (BBDS and FBHB)	Arctic Archipelago, Davis Baffin, Hudson Bay	6,745 (CV 0.22)	2013	Reduced	Increasing	HQ	Wiig et al 2011
	"-West Greenland winter component"	*Davis Baffin*	*1,538 (95% CI 827 - 2,249)*	*2012*	*Reduced*	*Stable*	*HQ*	*Rekdal et al 2014*
	Svalbard-Barents Sea	Atlantic Arctic			Reduced	Unknown	P	Wiig et al 2010
	"- NE Greenland summer component"	*Atlantic Arctic*	*102 (95% CI 32 - 329)*	*2009*	*Reduced*	*Unknown*	*P*	*Boertmann et al 2014*
Ringed seal	Beaufort and Chukchi Seas	Beaufort	1,000,000	Unspecified	Unknown	Unknown	HQ (Russia), H (USA)	Kelly et al 2010
	Bering Sea	Pacific Arctic	340,000	1976-2012	Unknown	Unknown	HQ (Russia), H (USA)	Conn et al 2014
	Hudson and James Bays	Hudson Bay	516,000	1974	Unknown	Unknown	H	Smith 1975
	Baffin Bay	Davis-Baffin, Arctic Archipelago	1,200,000	1990s	Unknown	Unknown	H	Kingsley 1998
	Greenland Sea & Southeast Greenland	Atlantic Arctic	Unknown		Unknown	Unknown	H	
	Svalbard & Barents sea	Atlantic Arctic	Unknown		Unknown	Unknown	H	
	"-Svalbard only, partial"	*Atlantic Arctic*	*7,585 (95% CI 6332-9085)*	*2002-2003*	*Unknown*	*Unknown*	*H*	*Krafft et al 2006*
	White, Barents, Kara & East Siberian seas	Atlantic Arctic, Kara & Laptev	220,000	Unspecified	Unknown	Unknown	HQ (Russia), H (Norway)	Kelly et al 2010
	Labrador	Davis-Baffin	Unknown		Unknown	Unknown	H	
	Arctic Basin	Arctic Basin	Unknown		Unknown	Unknown	P	

Species	**Subpopulation/ Stock**	**CBMP Arctic Marine Area**	**Abundance** (with 95% confidence interval (CI) or coefficient of variation (CV) if available)	**Year**	**Status:** Unknown (U), Reduced (R) or Not Reduced (N)	**Trend:** Unknown(U), Increasing(I), Stable (S), Declining (D)	**Harvest:** harvested without quota (H), harvested with quota (HQ), currently protected (P)	**Survey/trend reference from Laidre et al. unless noted**
Bearded seal	*E. nauticus* subspecies		Unknown total					
	Bering Sea	Pacific Arctic	>299,000	2012	Unknown	Unknown	HQ (Russia), H (USA)	Conn et al 2014
	Chukchi Sea	Pacific Arctic	27,000	2000	Unknown	Unknown	HQ (Russia), H (USA)	Cameron et al 2010
	Beaufort Sea	Beaufort	Unknown		Unknown	Unknown	H	
	East Siberian Sea	Pacific Arctic	Unknown		Unknown	Unknown	HQ (Russia), H (USA)	
	E. barbatus subspecies		Unknown total				H	
	Eastern Canada and West Greenland	Arctic Archipelago, Davis-Baffin, Hudson Bay			Unknown	Unknown	H	
	"-Canadian waters component"	*Arctic Archipelago, Davis-Baffin, Hudson Bay*	*190,000*	*1958-1979*	*Unknown*	*Unknown*	*H*	*Cleator 1996*
	East Greenland	Atlantic Arctic	Unknown		Unknown	Unknown	H	
	Svalbard & Barents Sea	Atlantic Arctic	Unknown		Unknown	Unknown	H	
	White, Kara & Laptev Seas	Atlantic Arctic, Kara & Laptev	Unknown		Unknown	Unknown	HQ (Russia), H (Norway)	
Ribbon seal	Bering Sea	Pacific Arctic	143,000	2007	Unknown	Unknown	HQ (Russia), H (USA)	Boveng et al. 2013
Harp seal	Northwest Atlantic	Davis-Baffin, Atlantic Arctic	7,420,000 (95% CI 6,360,000 - 8,360,000)	2012	Not Reduced	Stable	H (Greenland), HQ (Canada)	Hammill et al. 2015
	Greenland Sea	Atlantic Arctic	627,410 (95% CI 470,540 – 784,280)	2012	Not Reduced	Increasing	H (Greenland), HQ (Norway)	ICES 2013
	White Sea	Atlantic Arctic	1,419,800 (95% CI 1,266,910-1,572,690)	2013	Reduced	Stable	HQ (Norway) P (Russia)	ICES 2013
Hooded seal	Northwest Atlantic	Davis-Baffin, Atlantic Arctic	593,500 (95% CI 404,400-728,300)	2005	Reduced	Increasing	H (Greenland), HQ (Canada)	Hammil and Stenson 2006
	Greenland Sea	Atlantic Arctic	84,020 (95% CI 68,060–99,980)	2013	Reduced	Decreasing	H (Greenland), P (Norway)	Øigård et al. 2014
Spotted seal	Bering sea	Pacific Arctic	>460,000	2012	Unknown	Unknown	H	Han et al. 2010

Species	**Subpopulation/ Stock**	**CBMP Arctic Marine Area**	**Abundance** (with 95% confidence interval (CI) or coefficient of variation (CV) if available)	**Year**	**Status:** Unknown (U), Reduced (R) or Not Reduced (N)	**Trend:** Unknown(U), Increasing(I), Stable (S), Declining (D)	**Harvest:** harvested without quota (H), harvested with quota (HQ), currently protected (P)	**Survey/trend reference from Laidre et al. unless noted**
Walrus	*O. r. divergens* subspecies (Pacific)							
	Bering-Chukchi Seas	Pacific Arctic	~129,000 (95% CI 55,000–507,000)	2006	Unknown	Unknown	HQ (Russia), H (USA)	Speckman et al. 2011
	Laptev Sea	Kara-Laptev	3,000-5,000	1992	Unknown	Unknown	P	Belikov and Boltunov 2005
	O. r. rosmarus subspecies (Atlantic)							
	North and Central Foxe Basin	Hudson Bay	13,452 (CV=0.43)	2011	Not Reduced	Stable	HQ	Stewart et al. 2013d
	South and East Hudson Bay	Hudson Bay	Low hundreds	2006	Unknown	Unknown	HQ	COSEWIC 2006
	North Hudson Bay-Hudson Strait-Southeast Baffin Island-North Labrador	Hudson Bay, Davis Baffin	Unknown		Unknown	Unknown	H (Canada) or HQ (Greenland)	
	"- Southeast Baffin Island summer aggregation"	*Davis-Baffin*	*2,502 (95% CI 1,660-3,345)*	*2007*	*Unknown*	*Unknown*	*H*	*Stewart et al. 2013b*
	"-North Hudson Bay summer aggregation"	*Hudson Bay*	*1,376*	*1990*	*Unknown*	*Unknown*	*H*	*COSEWIC 2006*
	"-Hudson Strait winter aggregation"	*Hudson Bay*	*6,020 (95% CI 2,485-14,585)*	*2012*	*Unknown*	*Unknown*	*H*	*Elliott et al. 2013*
	"-West Greenland winter aggregation"	*Davis-Baffin*	*1,408 (95% CI 922-2,150)*	*2012*	*Reduced*	*Increasing*	*HQ*	*Heide-Jørgensen et al. 2013*
	West Jones Sound	Arctic Archipelago	503 (95% CI 473-534)	2008	Not Reduced	Stable	HQ	Stewart et al. 2013a
	Penny Strait/Lancaster Sound	Arctic Archipelago	727 (95% CI 623-831)	2009	Not Reduced	Stable	H	Stewart et al. 2013a
	Baffin Bay	Davis-Baffin			Reduced	Increasing	HQ	
	"-Winter (Greenland)"	*Davis-Baffin*	*2,544 (95% CI 1,513-4,279)*	*2014*	*Reduced*	*Increasing*	*HQ*	*Heide-Jørgensen et al. 2016*
	"-Summer (Canada)"	*Davis-Baffin*	*1,251 (95% CL 571-2,477)*	*2009*	*Reduced*	*Increasing*	*H*	*Stewart et al. 2013c*
	East Greenland	Atlantic Arctic	1,429 (95% CI 705-2,896)	2009	Unknown	Stable	HQ	NAMMCO 2015
	Svalbard/Franz Josef Land	Atlantic Arctic			Unknown	Increasing	P	
	"-Svalbard only"	*Atlantic Arctic*	*3,886 (95% CI 3553-4262)*	*2012*	*Unknown*	*Increasing*	*P*	*Kovacs et al. 2014*
	Novaya Zemlya-Eastern Barents-Pechora-White Seas	Atlantic Arctic	3,943 (95% CI 3,605-4,325)	2010	Unknown	Unknown	P	Lydersen et al 2012

Species	**Subpopulation/ Stock**	**CBMP Arctic Marine Area**	**Abundance** (with 95% confidence interval (CI) or coefficient of variation (CV) if available)	**Year**	**Status:** Unknown (U), Reduced (R) or Not Reduced (N)	**Trend:** Unknown(U), Increasing(I), Stable (S), Declining (D)	**Harvest:** harvested without quota (H), harvested with quota (HQ), currently protected (P)	**Survey/trend reference from Laidre et al. unless noted**
Polar bear	Arctic Basin	Arctic Basin	Unknown	-	Unknown	Unknown	P	PBSG 2017
	Baffin Bay	Davis-Baffin	2,826 (95% CI 2,059-3,593)	2013	Not Reduced	Unknown	HQ	PBSG 2017
	Barents Sea	Atlantic Arctic	2,644 (95% CI 1899-3592)	2004	Unknown	Unknown	P	PBSG 2017
	Chukchi Sea	Pacific Arctic	Unknown	-	Unknown	Unknown	H	PBSG 2017
	Davis Strait	Davis-Baffin	2,158 (95% CI 1833-2542)	2007	Not Reduced	Stable	HQ	PBSG 2017
	East Greenland	Atlantic Arctic	Unknown	-	Unknown	Unknown	HQ	PBSG 2017
	Foxe Basin	Hudson Bay	2,580 (95% CI 2093-3180)	2010	Not reduced	Stable	HQ	PBSG 2017
	Gulf of Boothia	Arctic Archipelago	1,592 (95% CI 870-2314)	2000	Unknown	Unknown	HQ	PBSG 2017
	Kane Basin	Davis-Baffin	357 (95% CI 221-493)	2014	Not Reduced	Increasing	HQ	PBSG 2017
	Kara Sea	Kara and Laptev Seas	Unknown	-	Unknown	Unknown	P	
	Lancaster Sound	Arctic Archipelago	2,541 (95% CI 1759-3323)	1997	Unknown	Unknown	HQ	PBSG 2017
	Laptev Sea	Kara and Laptev Seas, Pacific Arctic			Unknown	Unknown	P	PBSG 2017
	M'Clintock Channel	Arctic Archipelago	284 (95% CI 166-402)	2000	Unknown	Unknown	HQ	PBSG 2017
	Northern Beaufort Sea	Arctic Basin-Beaufort-Arctic Archipelago	980 (95% CI 825-1135)	2006	Not reduced	Stable	HQ	PBSG 2017
	Norwegian Bay	Arctic Archipelago	203 (95% CI 115-291)	1997	Unknown	Unknown	HQ	PBSG 2017
	Southern Beaufort Sea	Beaufort	907 (95% CI 548-1270)	2010	Reduced	Declining	HQ (Canada), H (USA)	PBSG 2017
	Southern Hudson Bay	Hudson Bay	951 (95% CI 662-1366)	2012	Not reduced	Stable	HQ	PBSG 2017
	Viscount Melville	Arctic Archipelago	161 (95% CI 121-201)	1992	Unknown	Unknown	HQ	PBSG 2017
	Western Hudson Bay	Hudson Bay	1,030 (95% CI 754-1406)	2011	Reduced	Stable	HQ	PBSG 2017

3.6.4 Drivers of observed trends

In a warmer Arctic, endemic marine mammal species are already facing and will continue to face extreme levels of ***habitat change***, most notably a dramatic reduction in sea ice (Laidre et al. 2015, Stern and Laidre 2016). The pattern and timing of sea ice loss is important and will likely result in varied impacts by region and by species. For example, early spring sea ice retreat reduces suitable breeding and pup rearing habitat for ringed seals. Polar bear breeding precedes the ringed seal pupping season and bears depend on hunting seal pups to rebuild energy stores after fasting during their own breeding period. Reduced availability of seal pups will detrimentally affect the polar bear (Bromaghin et al. 2015, Stirling et al. 2016). In Svalbard, changes in ice conditions have been observed to lead to changes in prey composition of bearded seal as estimated by stable isotope signatures (Hindell et al. 2012). Late summer open water (due to seasonal ice retreat north of the continental shelf) limits offshore foraging habitat for Pacific walrus and increases their use of coastal haulouts. Historically, Pacific walrus rested on sea ice located directly over prime feeding areas; use of coastal haulouts results in increased travel time and energy expenditure to access feeding areas and also increased potential of calf mortality due to stampede events (panic exodus of haulouts) (Udevitz et al. 2013). Walrus also depend on winter sea ice adjacent to key feeding areas, notably the St. Lawrence Island polynya, which has high bivalve productivity (primary forage species) and broken ice of sufficient size to provide resting places along with sufficient open water (Jay et al. 2014). Seasonal changes to the polynya may detrimentally affect walrus and in general, changes in the seasonal occurrence and the quality of sea ice in key feeding habitats reduce foraging efficiency of walrus.

In addition to habitat loss, ***physical environmental changes*** (e.g., increased water and air temperatures) alter the forage base of Arctic marine mammals. Such changes may appear as shifts in the density and distribution of prey species, and potentially loss of some fat-rich prey species (Moore et al. 2014). ***Reductions in sea ice*** is already allowing northward movement of temperate species with the possibility of increased competition for food and increased predation by species (i.e., killer whale) formerly unable to access them in areas of extensive sea ice (Laidre et al. 2015). Warmer waters may also bring increased disease risk and increased risks from contaminants (Lefebvre et al. 2016). For some species, notably ice-associated cetaceans, predictions are difficult because the nature of their affiliation with sea ice is not clearly understood. In fact, bowhead whale are doing well, both at the population and individual level, in the increased open-water conditions of the Beaufort and Chukchi Seas (George et al. 2015). In contrast, ice-breeding seals will have marked, or total, breeding-habitat loss in their traditional breeding areas and will certainly undergo distributional changes and likely abundance reductions (Cameron et al. 2010, Kelly et al. 2010). In general, species with fixed traditional spatial and temporal cycles that track historic sea ice and climatic patterns are expected to decline in abundance. It is not certain to what, if any extent such species will be able to adapt their patterns of breeding and habitat use on decadal time scales. Extirpation of some stocks is likely.

Anthropogenic activities that may affect marine mammals in the Arctic are increasing concomitantly with loss of sea ice habitat. The longer and more widespread open water season has already stimulated increases in ship traffic and resource development in the Arctic (Reeves et al. 2014, Laidre et al. 2015). Major shipping routes into the Arctic include the Bering Sea from the Pacific Ocean, Baffin Bay-Davis Strait and Barents Sea from the North Atlantic. Impacts from increased shipping on marine mammal species and the people who depend upon them can come from the direct impact of ship strikes on whales, the loss or disruption of habitat from activities such as icebreaking to clear shipping channels, disturbance from noise generated by ships, and from contamination. The potential for impact will vary by season, dependent in large part on ice conditions.

Noise associated with increasing ship traffic and resource development is also of concern for marine mammal populations. Marine mammals communicate via underwater vocalizations and can be negatively affected by underwater noise from shipping and other industrial activities (Reeves et al. 2014). Bowhead whale, for example, respond to anthropogenic sound in their environment (Southall et al. 2007) and concern that bowhead whale will avoid areas with industrial noise has been the subject of ongoing regulatory discussions of oil and gas operations in the Arctic (NOAA Fisheries 2013). The degree to which bowhead whale respond to noise depends on the activity of the whales; they generally respond less when involved in feeding or social behaviour and more when resting or migrating (Richardson et al. 1999, Richardson 2004). Shipping noise is not anticipated to cause acute physical harm, although many species will likely move away from noise and constant noise may effectively result in habitat loss. In Canada, belugas were observed avoiding ice-breaking vessels at great distances and altering their behaviour for days following the event (Finley et al. 1990). Based on acoustic modelling, noise from an icebreaker is audible to beluga from 35–78 km away, depending upon water depth, and can mask vocalizations over most of that range (Erbe and Farmer 2000). The possibility of noise disturbance is a particular concern to communities and local residents, concerned that key subsistence species may be deflected away from traditional hunting areas (Huntington et al. 2016).

Pollution and the presence of ***toxic chemicals and heavy metals*** are of concern for the health of marine mammals and for the food safety of subsistence communities that depend upon them (Huntington et al. 2016). With increased Arctic oil exploration and shipping, the risk of oil spills from tanker or other shipping accidents has increased. Fuel and heating oil are regularly carried through the region on both destination, and increasingly, inter-ocean voyages. The risk of oil spills to Arctic marine mammals is exacerbated by the lack of effective clean-up techniques and lack of response equipment and capability in remote Arctic regions. Discharge of bilge water, oily sludge, garbage and other materials may be of greater chronic widespread impact than acute accidental spills and as difficult or impossible to clean up.

In addition to the ice-dependent species considered here, under the influence of a warming climate a number of temperate species have extended their distribution range northward and increased the amount of time they spend

Box 3.6.3: Pacific Arctic pinnipeds unusual mortality event

Monitoring seals.
Photo: Josh London, NOAA

In 2011, the emergence of skin lesions and mortality in Arctic seals and walrus on the U.S. Arctic Slope, Pacific Western Arctic, and Bering Strait led to the declaration of an Unusual Mortality Event (UME) by NOAA and the USFWS (NOAA, 2011). In response, a trans-boundary interdisciplinary disease investigative team was assembled to join Indigenous hunters from Alaska, Chukotka, Russia, and the Northwest Territories (NWT) of Canada. No specific cause has been identified, but investigations have ruled out numerous bacteria, viruses, contaminants and algae toxins known to affect marine mammals. Advanced testing for unidentified infectious agents continues as well as testing for other potential causes.

Ice seals and Pacific walrus are key species essential to the Arctic ecosystem and food security for Indigenous subsistence communities (ICC-Alaska, 2015, Raymond-Yakoubian et al., 2014, Gadmus, 2013). At least 60 coastal communities in Alaska, Chukotka and Canada's Northwest Territories are reliant on the non-commercial harvest of local marine wildlife for their nutritional, cultural, and economic well-being. The UME initially identified in northern Alaska ultimately extended to impact communities both westward across the Bering Strait in Chukotka and eastward into the NWT. Thus, food safety and food security aspects are integral components of the response. Disease surveillance continues, including follow-up with surviving animals. NOAA conducted an ice-associated seal research survey in the central Bering Sea in April 2016; nine of the 10 ribbon seals captured had extensive bald patches and are thought to be survivors of the initial disease outbreak. Similar findings of an increased incidence of "black skin" (hairloss patches) and or delayed/incomplete molt have been observed among subsistence harvested ice seal species including, ringed, bearded and spotted seals since 2011. While the outbreak has subsided, such unusual events present food security and public health concern in a region currently experiencing significant environmental and industrial maritime change (Ice Seal Committee 2012).

This was the first UME to be designated in the U.S. Arctic and the first to involve marine mammal species commonly utilized as essential food resources. As such, the event has resulted in important lessons learned to address public health and food security concerns:

Future marine wildlife responses (e.g., for disease outbreaks or contaminant spills) must consider regional public health and food security concerns.

1. Wildlife disease detection in remote coastal areas is likely to be made by people actively engaged in the utilization of resources.
2. Agencies and organizations located in urban centres should successfully integrate with existing regional communication networks (i.e. regional hub organizations, institutions, and Indigenous organisations) to build efficient and comprehensive communications and response capacity.
3. Trans-boundary communication is critical to understanding the status and spread of a disease event occurring in shared wildlife populations.
4. Agencies and communities need wildlife health response networks and response plans with mechanisms to review plans and update contact information on an annual basis.

in the Arctic. Some species that may become important components of the Arctic ecosystem in the future include sperm whales (*Physeter macrocephalus*), northern bottlenose whale (*Hyperoodon ampullatus*), minke whale (*Balaenoptera acutorostrata*), humpback whale, gray whale (*Eschrichtius robustus*), killer whale, pilot whale (*Globicephala melas*), white beaked dolphin (*Lagenorhynchus albirostris*) and harbour porpoise (*Phocoena phocoena*) as well as harbour seal (*Phoca vitulina*) and possibly grey seals (*Halichoerus grypus*). Notably, killer whales have been identified as an increasingly important predator in the Arctic (Ferguson et al. 2010). It is important to monitor temporal and spatial changes in the distribution and seasonal abundance of these species to determine how these changes might impact Arctic ecosystems.

3.6.5 Knowledge and monitoring gaps

The Conservation of Arctic Flora and Fauna (CAFF) has well-developed, basic plans to conduct circumpolar marine biodiversity monitoring (Gill et al. 2011). These plans have not been fully implemented for marine mammals, leaving large knowledge gaps. The first priority for monitoring is therefore to implement the *CBMP Marine Plan* in all Arctic countries.

Specifically, broadly scoped plans have been proposed and circumpolar monitoring plans include those for beluga, ringed seal, and polar bear (e.g., Kovacs (ed) 2014, Simpkins et al. 2009), but the level of implementation of such plans is inadequate (Table 3.6.2). For example, the need for circumpolar monitoring of ringed seal has been recognized as an essential component of any Arctic-monitoring plan. This is the most numerous of the endemic Arctic pinnipeds and a key food resource for polar bear and people in many northern communities. As an ice dependent species, ringed seal are threatened by global warming. Specifically, loss of and changes to sea ice have caused structural changes in their habitat linked to key life history events (Kovacs et al. 2011, 2012). The species is already experiencing serious reductions of breeding habitat; in 2012 a circumpolar CAFF Ringed Seal Network group met in Tromsø, Norway to further develop an initial plan developed in Valencia, Spain in 2008. The primary goals of this workshop were to review current research and monitoring activity, and to select key monitoring parameters that could be consistently collected at key sites across the ringed seal's range. To date, this plan has not been fully implemented.

The cumulative effect of changes in Arctic ecosystems on marine mammals is a key knowledge gap. Arctic ecosystems are undergoing increasing pressure from a variety of major anthropogenic stressors, including increasing shipping activity and resource development, continued increases in human populations, and climate change. By integrating long-term monitoring studies of Arctic marine mammals into research on Arctic change, there is an opportunity to gain a large spatial-scale perspective of ecosystem functioning. Historically, species information has been collected for specific regional concerns or research interests and seldom coordinated across jurisdictions. A notable regional example of coordinated work is the Atlantic Arctic region under the umbrella of NAMMCO and its collaboration with the Canada-Greenland Joint Commission on Narwhal and Beluga. Compiled datasets often provide emergent properties and conclusions that are unanticipated, and consequently can have greater impact on policy decisions and interest to an informed public (Ferguson et al. 2012).

The remote nature of Arctic systems also leads to knowledge gaps, which can be addressed in part through monitoring efforts that engage communities. A successful localized marine mammal monitoring approach, developed independently by a number of circumpolar countries to collect time-series data on Arctic marine mammal health and stock assessment, is community-based monitoring. Long-term monitoring from such programs has provided valuable information for managers and conservation efforts

Box 3.6.4: Local monitoring

Sanikiluaq residents assist research scientists project exploring the effects of climate change on Arctic marine mammals. Photo: Fisheries and Oceans Canada

Fisheries and Oceans, Canada and the Arviat and Sanikiluaq Hunters and Trappers Organization/ Association in Hudson Bay, Canada have developed a cooperative community-based monitoring program. Local Inuit hunters have been provided with sampling equipment and trained to collect biological data from the ringed, bearded, harp, and harbour seals that they harvest. The hunters record the species, sex, date and time, hunter's name, location of harvest and habitat type. They also provide data on total length, axillary girth, hip girth, fat depth at sternum, fat depth at hips, total body weight, and skull weight. Tissues collected by the hunters generally included lower jaw, muscle, blubber, liver, kidney, hair, whiskers, flipper with claws, blood, and reproductive tract. Samples are frozen and shipped to the Fisheries and Oceans Canada at the end of the season. The age of the seal is determined by counting growth layer rings in the teeth and the morphometric measurements are included in various analyses as important indicators of seal health and to determine trends in growth rates and condition over time.

Table 3.6.2. Assessment of monitoring implementation

Focal Ecosystem Components Key parameters

Symbol	Meaning
🟩	Parameter is routinely (and well) collected based on a financed (secure) on-going monitoring programme.
🟦	Some coverage through routine monitoring – but it is not considered complete
🟧	Coverage through research programmes gathering data – based on irregular or insecure funding.
🟨	Some coverage through research programmes gathering data – based on irregular or insecure funding.
🟥	Unknown
⬛	Not applicable - no harvest.

** Russian polar bear monitoring assessment refers only to a single site - Wrangel Island*

Polar bear

	United States	Canada	Greenland	Norway	Russia*
Distribution *(seasonal)*	🟧	🟦	🟧	🟨	🟨
Abundance *(number per sq km)*	🟨	🟦	🟧	🟦	🟨
Habitat selection	🟧	🟦	🟧	🟨	🟨
Stock structure *(genetics/telemetry)*	🟧	🟦	🟧	🟦	🟨
Body condition	🟦	🟦	🟧	🟩	🟨
Contaminants	🟧	🟧	🟩	🟦	🟨
Harvest statistics	🟩	🟩	🟩	⬛	⬛

Walrus

	United States	Canada	Greenland	Norway	Russia
Distribution *(seasonal)*	🟨	🟨	🟨	🟨	🟨
Abundance *(number per sq km)*	🟨	🟦	🟦	🟩	🟨
Habitat selection	🟨	🟧	🟧	🟨	🟨
Stock structure *(genetics/telemetry)*	🟧	🟦	🟧	🟧	🟨
Body condition	🟨	🟨	🟨	⬛	🟨
Contaminants	🟨	🟧	🟨	🟦	🟨
Harvest statistics	🟩	🟩	🟩	⬛	🟦

Ringed seal

	United States	Canada	Greenland	Norway	Russia
Distribution *(seasonal)*	🟦	🟦	🟨	🟨	🟥
Abundance *(number per sq km)*	🟧	🟨	🟨	🟥	🟥
Habitat selection	🟨	🟦	🟨	🟨	🟥
Stock structure *(genetics/telemetry)*	🟨	🟧	🟨	🟥	🟥
Body condition	🟦	🟩	🟨	🟨	🟥
Contaminants	🟦	🟩	🟨	🟦	🟥
Harvest statistics	🟨	🟧	🟦	🟩	🟥

Beluga

	United States	Canada	Greenland	Norway	Russia
Distribution *(seasonal)*	🟦	🟦	🟩	🟦	🟦
Abundance *(number per sq km)*	🟧	🟦	🟩	🟥	🟦
Habitat selection	🟧	🟦	🟨	🟨	🟦
Stock structure *(genetics/telemetry)*	🟩	🟩	🟨	🟨	🟥
Body condition	🟩	🟦	🟨	🟥	🟨
Contaminants	🟦	🟩	🟨	🟨	🟨
Harvest statistics	🟩	🟩	🟩	⬛	🟦

Bowhead whale

	United States	Canada	Greenland	Norway	Russia
Distribution *(seasonal)*	🟧	🟦	🟦	🟥	🟥
Abundance *(number per sq km)*	🟦	🟩	🟦	🟥	🟥
Habitat selection	🟧	🟦	🟦	🟥	🟥
Stock structure *(genetics/telemetry)*	🟦	🟩	🟦	🟥	🟥
Body condition	🟩	🟨	🟨	⬛	🟦
Contaminants	🟨	🟧	🟥	🟥	🟨
Harvest statistics	🟩	🟩	🟩	⬛	🟦

on several species, including polar bear (e.g., Western Hudson Bay and Southern Beaufort Sea [Stirling et al. 1999, Regehr et al. 2010]), ringed seal (Harwood et al. 2012, 2015), bowhead whale (George et al. 2015), and harp seal (Sjare and Stenson 2010, Stenson et al. 2016). In many of these programs, local peoples assist with collection of data such as tissue samples from hunts or changes in timing or distributions of animals. Ideally, Indigenous and local peoples should be integrally involved in the design and implementation of monitoring programs so that scientific knowledge and TK holders are working collaboratively.

3.6.6 Conclusions and key findings

Climate-induced changes are amplified in the Arctic compared to other areas of the globe. As a result, Arctic marine ecosystems are rapidly changing due to atmospheric and oceanic warming and its impacts on sea ice and associated marine biota, including marine mammals. Other types of anthropogenic activity that exacerbate climate impacts on marine mammal populations include oil and gas exploration and production, commercial fisheries, and both local and global shipping. Marine mammals are highly visible components of Arctic ecosystems, often identified as sentinels of change in the Arctic ecosystem. The prominent use of Arctic marine mammals in generalized descriptions of the changing Arctic is due in part to the great cultural and subsistence value to local peoples and iconic species status at a global level.

Regional differences in our level of understanding of the status of different marine mammal species, populations and stocks compromise our ability to evaluate regional variability in species response to climate warming across the Arctic. To guide data collection and address regional disparities, much effort has gone into developing detailed monitoring plans for the ringed seal, beluga and polar bear, but these plans have not been implemented uniformly across the Arctic. As a result, the level of investment by Arctic governments in monitoring and assessment, and our level of knowledge remain inadequate to understanding impacts of climate and ecosystem change. Communities should be integrally involved in the design and implementation of monitoring programs so that scientific knowledge and TK holders are working collaboratively.

Historically, several marine mammal populations were heavily exploited and reduced to low numbers. Some populations now facing the impacts of Arctic change are still recovering from over-harvest, complicating the interpretation of climate-change effects on population trends. Harvest continues, with many species still an important subsistence resource for indigenous and local peoples across the Arctic. In general, subsistence hunts are managed based on abundance assessments and monitoring of population status, but there are some populations where harvest levels are of concern, for example, narwhal in Melville Bay and East Greenland and walrus in northern Baffin Bay (GINR 2016). Information on harvest levels and status is important to evaluating overall population status and managing hunts. Long-term data sets based on data collected from hunted animals can be an important information source, as they constitute base-line information on demographic parameters during different ecological regimes. The value of collected tissues can be increased even more by subjecting them to modern techniques such as analyses of stable isotopes, providing links to trophic structure of the ecosystem at the time of collection. Similar data series are often collected in different areas/countries and comparative studies across regions further increase the value of individual data sets; provided that approaches for sampling and analyses are comparable.

In summary, Arctic marine ecosystems are under immense cumulative pressure from a variety of factors including climate change, global pollution, shipping, gas-oil exploration and production, and in some areas, hunting and commercial fisheries. Synergistic impacts from the collective pressures can be expressed on individual animals as well as at stock and population levels and are likely to increase the impacts of individual drivers. Major shipping routes are expanding into the Arctic, including the Bering Strait from the Pacific Ocean, Baffin Bay-Davis Strait and Fram Strait/Barents Sea in the North Atlantic, which are also the key areas of marine mammal biodiversity. Ongoing complex spatial-temporal shifts in ecological, and subsequently animal health, suggest that Arctic marine ecosystems are undergoing change. The trends will continue and become more exacerbated with future Arctic climatic warming, particularly with the continued and increasing presence of anthropogenic activities in the Arctic. Reaching an adequate understanding of the responses of marine mammal population to the ongoing environmental changes in Arctic marine ecosystems requires a multidisciplinary and multi-knowledge approach and a high degree of collaboration across borders and between researchers, communities and Arctic governments.

Future indicators that the CBMP Marine Mammal Expert Network plans to collate include health parameters, passive acoustics, habitat changes, and telemetry tracking studies. It is also vital to obtain more knowledge about population sizes, densities, and distributions of marine mammal populations in order to understand the relationships between sea ice loss and climate change and to manage Arctic marine mammal populations in an appropriate manner.

Finally, Laidre et al (2015) identified six recommendations for conservation of Arctic marine mammals in the 21st Century:

1. maintaining and increasing co-management by local, governmental and international entities,
2. understanding that species and populations exhibit variable responses to climate change over time and space,
3. improving monitoring,
4. understanding and mitigating cumulative impacts from industrial activities,
5. recognizing the utility and limitations of protected species legislation in a changing Arctic, and;
6. practicing forward-looking conservation that incorporates scientific evidence on species status with value based-conservation, including the communication of accurate information to the public.

These recommendations are still valid.

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Tagging narwhal in Greenland.
Photo: Carsten Egevang/ARC-PIC.com

4. Synthesis: Status and trends of Arctic marine biodiversity and monitoring

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Arctic marine ecosystems are highly dynamic and affected by a wide variety of human activities and their consequences, not least climate change. Arctic marine ecosystems are warming twice as fast as the global average (Hoegh-Guldberg and Bruno 2010). Monitoring the status and trends of Arctic biodiversity and attributing causes of change is thus challenging. Complexity, logistics, funding, international coordination, and availability of expertise and technology combine to limit the available knowledge. These limitations affect biotic groups unevenly, with some groups better studied than others, and the information presented in Chapter 3 reflects this. Thus, while some Circumpolar Biodiversity Monitoring Program (CBMP) Marine Expert Networks have many years of more or less standardised monitoring to draw on (i.e., seabirds, marine mammals), others are still at the stage of mapping biodiversity and identifying new taxa, and have very little information on time series (i.e., sea ice biota and plankton). Synthesizing the information from all CBMP Marine Expert Networks into a coherent picture of status and trends of Arctic marine biodiversity is therefore difficult, and the present treatment is inevitably incomplete.

Several recent publications have reviewed the state of Arctic marine ecosystems and their biodiversity (Meltofte 2013, Jørgensen et al. 2016). The release of the *Arctic Biodiversity Assessment* (ABA) provided the baseline against which to identify emerging trends and conduct targeted assessments. The aim of this chapter is not to replicate these efforts, but rather to summarise the limited information available on status and trends in biodiversity and the drivers of these changes, as well as provide an overview of the current state of Arctic marine biodiversity monitoring. The SAMBR provides the first of a series of targeted assessments helping to build upon and further develop our knowledge and understanding of the status and trends in Arctic marine biodiversity, and to examine how to improve biodiversity monitoring efforts.

The outcomes of the report, including the cooperation to date and the data generated, represent an important step towards improving coordination of marine monitoring across the circumpolar Arctic. Its outcomes will feed into and inform other Arctic Council and circumpolar initiatives e.g., the implementation of the Arctic Council's Framework for a Pan-Arctic Network of Marine Protected Areas (PAME 2015), the Adaptation Actions for a Changing Arctic (AACA) and the planned Integrated Ecosystem Assessment for the Central Arctic Ocean being conducted by the International Council for the Exploration of the Seas (ICES), Arctic Monitoring and Assessment Programme (AMAP), Protection of the Arctic Marine Environment (PAME) and CAFF.

4.1 Status and trends in Arctic marine biodiversity

This section summarizes the available information from the CBMP Marine Expert Networks on recent status and trends in biodiversity (e.g., numbers of species, absolute or relative abundance of particular species). For several Expert Networks, the available information is quite limited, and it is therefore difficult to draw general conclusions. In particular, information on spatial variation in trends is limited for most groups, and thus general trends in the Arctic marine region often remain obscure. This section describes the actual changes and trends identified by the Expert Networks; a discussion of the wider implications of these trends can be found in Chapter 4.2.

Scientists lower containers through a hole in the ice to collect water samples from different depths.
Photo: The Hidden Ocean, NOAA

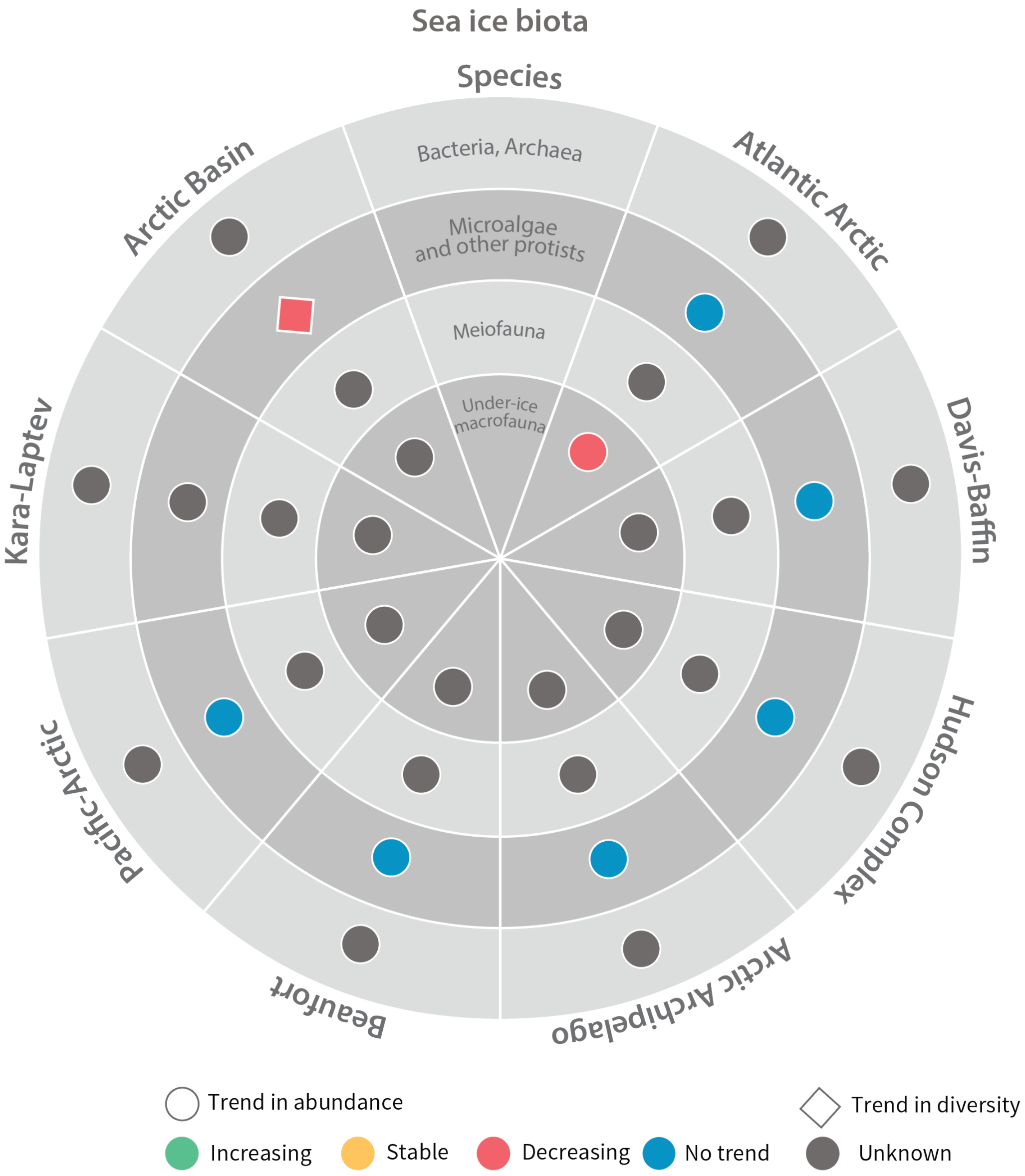

Figure 4.1: Trends in abundance or diversity of sea ice biota Focal Ecosystem Components across each Arctic Marine Area.

4.1.1 Sea ice biota

Many different organisms live in and under sea ice, including microbes, single-celled algae, and small multicellular animals. The status of sea ice biota is generally poorly known due to logistical difficulties, and new species are still being described and their distribution documented. Many species present in sea ice are specialists that only occur in this habitat, whereas others also occur in the water column or sediment. Most ice algae documented in sea ice are large diatoms and dinoflagellates, but this may reflect current knowledge more than real patterns. Meiofauna (animals < 0.5 mm) belong to many different taxonomic groups, and are typically more abundant near land because larvae of benthic organisms also occur in ice. The composition of meiofauna communities appears to vary geographically. The most well-known larger animals living below sea ice are amphipods belonging to the family Gammaridae, which also appear to show large spatial and temporal variations in abundance.

Few time series are available for sea ice biota, which limits our understanding of how these species have changed over time (Fig. 4.1). Studies in the central Arctic Basin have demonstrated a change in community structure of ice algae, with fewer pennate diatoms and more dinoflagellates in recent years (Fig. 3.1.8). This change may be related to the reduction in sea ice thickness. Around Svalbard, a large decline in sympagic amphipods has been observed since the mid-1990s (Fig. 3.1.7) and this has been linked to the decline in multi-year ice. Amphipod abundance is now so low that quantitative sampling by previous quantitative collection techniques is impossible. This may reflect a change towards a seasonal ice community, with greater dependence on recruitment from the sea floor in shallow area and/or the water column and thus favouring planktonic or benthic forms over sea ice specialists.

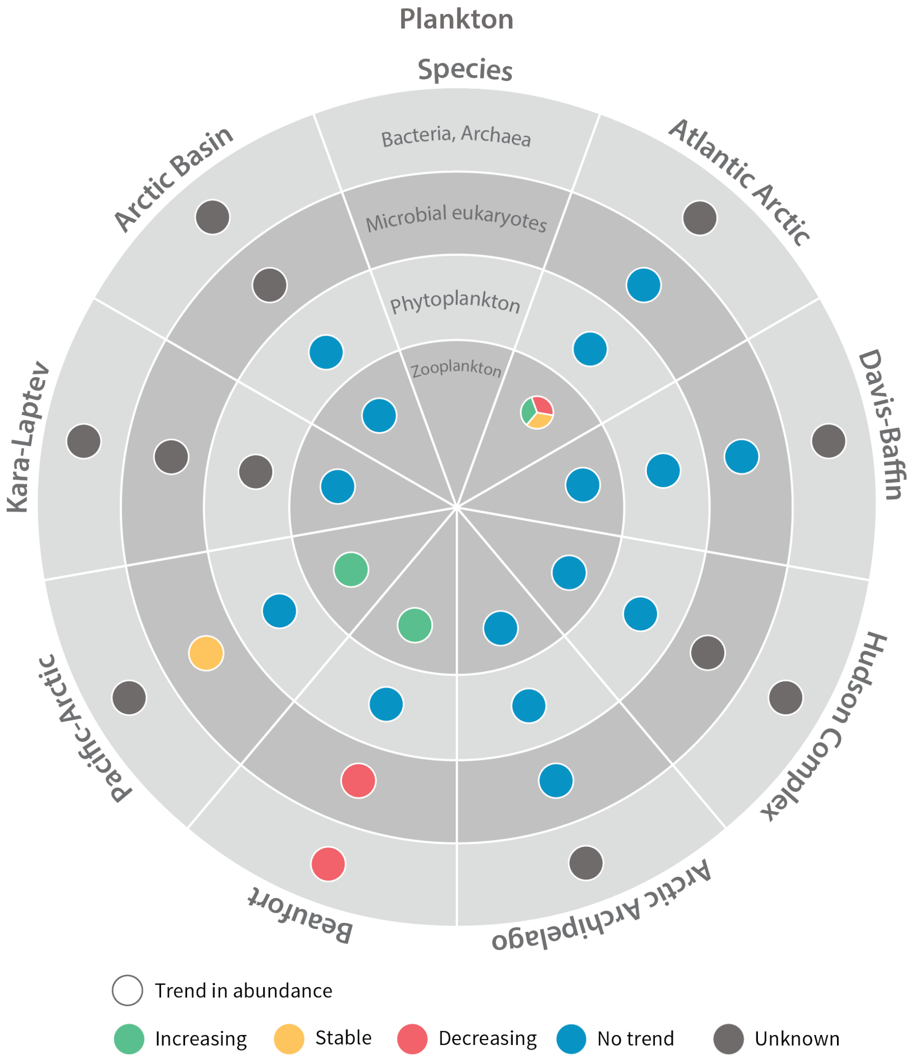

Figure 4.2: Trends in abundance of plankton Focal Ecosystem Components across each Arctic Marine Area.

4.1.2 Plankton

The status of planktonic biodiversity in the Arctic is insufficiently known, particularly for the microbial forms (Bacteria, Archaea and small eukaryotes) where distribution and relative abundance are still being documented through molecular techniques. Arctic phytoplankton is highly diverse, with many species and groups represented; many of these species are mixotrophic and can also act as consumers. Diatoms often dominate the spring bloom, whereas chlorophytes are common during summer, including the ubiquitous *Micromonas*. In the zooplankton, large copepods of the genus *Calanus* and its relatives are specifically important for energy transfer to higher trophic levels, due to their abundance and high energy content in the form of stored lipids.

The available information on trends for plankton differs substantially between species groups (Fig. 4.2). For microbial plankton, the use of molecular techniques is generally so recent that no time series exist. One study from the Beaufort Sea showed large differences in species composition before and after the 2007 sea ice minimum (Comeau et al. 2011).

More time series are available for groups that can be studied using traditional techniques. Short time series show complex inter-annual variation in phytoplankton composition in two fjords in Svalbard (Kongsfjorden and Rijpfjorden), and this is likely linked to variation in Atlantic water inflow (Fig. 3.2.5). The best data exist for the larger copepods (genus *Calanus* and relatives). In the Chukchi Sea, increases have been documented of four species of large copepods, including the high Arctic *Calanus glacialis*, concurrent with increasing ocean temperature (Fig. 3.2.6). Detailed studies in Young Sund in the Greenland Sea show a change in dominant copepods from the near-shore *Pseudocalanus* to the oceanic *Microcalanus*, probably caused by increased flushing of the fjord due to less sea ice (Fig. 3.2.7). The ratio between the high Arctic *Calanus glacialis* and the boreal *C. finmarchicus* has varied in Kongsfjorden in Svalbard, linked to annual differences in temperature (Fig. 3.2.9). In the Barents Sea, there has been a decrease in *C. glacialis*, as well as changes in the species composition of amphipods and krill towards more southern species.

Overall, these results confirm that plankton communities are highly sensitive to climatic forcing and that further rapid changes in species composition can be expected (cf. Hays et al. 2005). Such changes potentially have wide-ranging implications for higher trophic levels, as the plankton community varies seasonally with species of different sizes and nutritional values for predators.

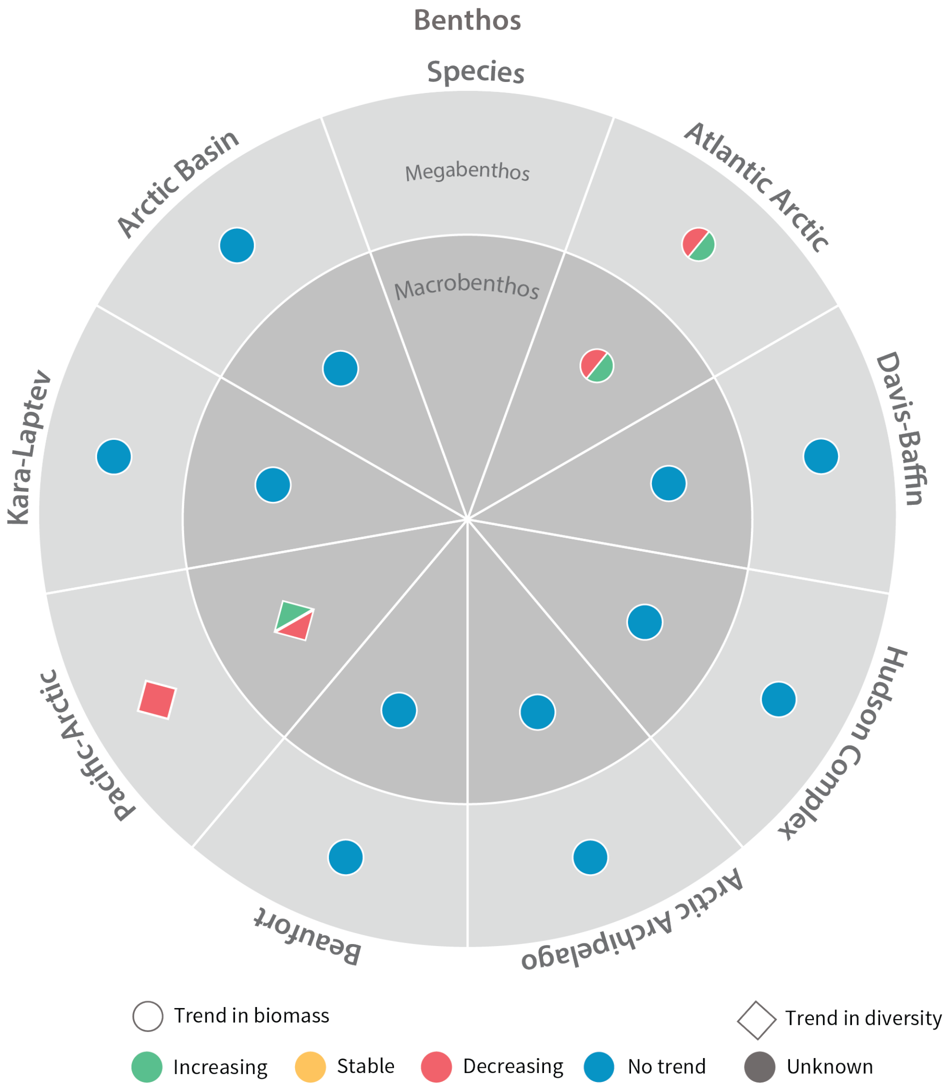

Figure 4.3: Trends in biomass or diversity of benthic Focal Ecosystem Components across each Arctic Marine Area.

4.1.3 Benthos

The ocean floor is inhabited by many different organisms from microbes to large invertebrates. All these organisms depend on food supply derived from planktonic (or sea ice) communities in the overlying water column. Tiny animals (meiofauna) and microbes consume the organic material (detritus) and release nutrients, and at the same time serve as food for larger animals, such as worms, bivalves and crustaceans. However, sufficient survey data only exist to assess status and trends for the larger animals, macro- and megabenthos, and even for these groups biodiversity is incompletely known and species lists are still expanding.

Few time series exist of benthos species composition or abundance, despite significant levels of research (Fig. 4.3). Many benthic organisms are long-lived (up to > 500 years for the bivalve ocean quahog (*Arctica islandica*), Butler et al. 2013) and sessile (e.g. corals), while others are mobile (e.g., crabs). These species integrate long-term variation in conditions in the water column over long time spans. Permanent changes (i.e., not seasonal) in benthic communities can therefore be quite slow.

The best-studied region of the Arctic in terms of benthos is the Barents Sea. The extensive time series concern, among others, macrobenthos biomass, which has shown complex spatial patterns of change over shorter and longer time spans (Figs. 3.3.2, 3.3.3). This is probably due to new species entering the Barents Sea (snow crab (*Chionoecetes opilio*), king crab (*Paralithodes camtschaticus*)) or Arctic species generally being replaced by more boreal species. Similarly, there are complex long-term changes in benthos biomass in the Chukchi and northern Bering Seas that may have implications for the food availability for sea ducks and walrus (Fig. 3.3.6).

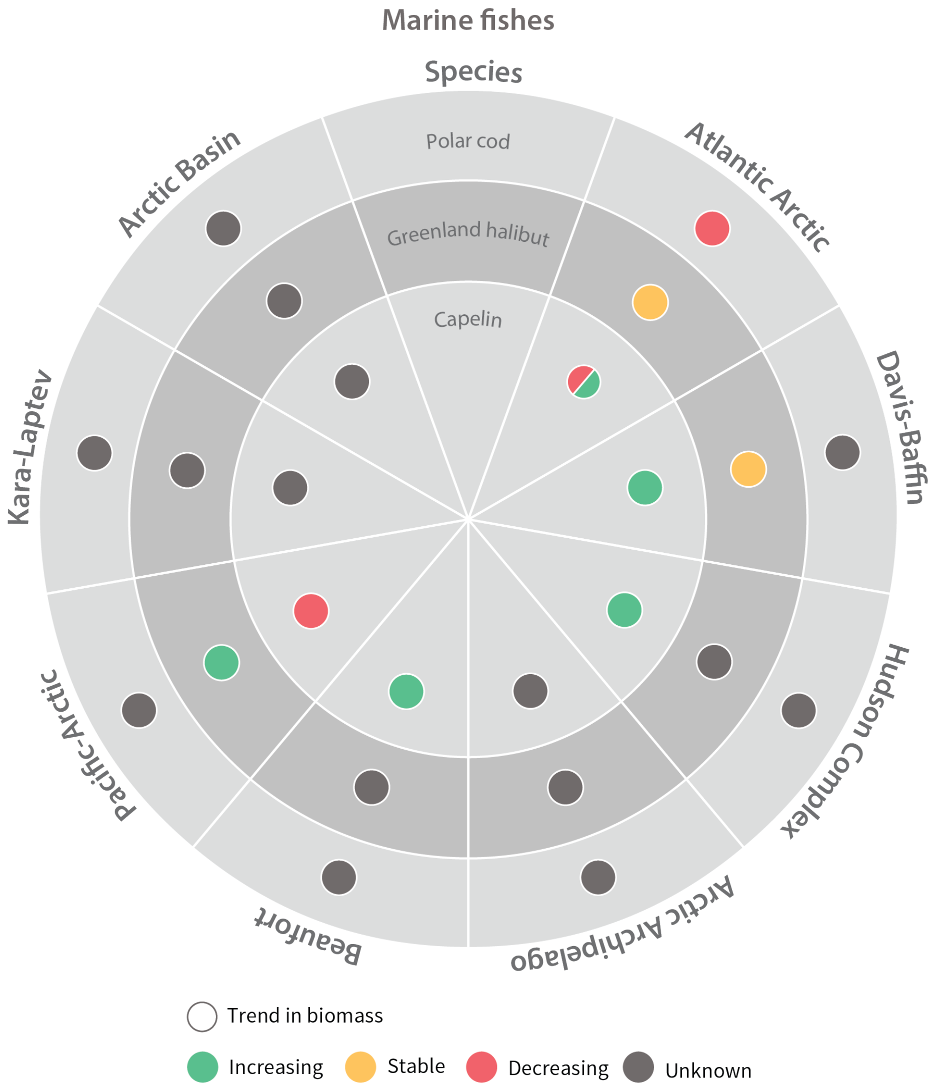

Figure 4.4: Trends in biomass of marine fish Focal Ecosystem Components across each Arctic Marine Area.

4.1.4 Fishes

Fish biodiversity in the marine Arctic is surprisingly poorly known. A large number of species have been documented, but in many cases their distribution, abundance and relationships are largely unknown. Only the few species of commercial interest have been studied extensively. The most important of these in the area covered by this report are capelin (*Mallotus villosus*), polar cod (*Boreogadus saida*) and Greenland halibut (*Reinhardtius hippoglossoides*).

There are few fishery-independent long-term studies of fish abundance or biomass in the Arctic (Fig. 4.4). Monitoring in the Barents Sea has shown a large decline in polar cod since 2005 (Fig. 3.4.3), probably due to poor recruitment related to decline in sea ice, predation from Atlantic cod (*Gadus morhua*), and competition from capelin. On the other hand, capelin increases in recent years throughout the high Arctic have been associated with warming trends, although the capelin stocks typically vary periodically from high abundance to very low (references in Chapter 3.4). Capelin and polar cod stocks in the Arctic vary considerably among years, and the most recent data (Russian-Norwegian Ecosystem Survey and Marine Research Institute of Iceland, unpubl. data 2016) show an increase in polar cod and decline in capelin in the Barents Sea, as well as a decline in Icelandic capelin (Chapter 3.4). Greenland halibut stocks are generally stable or growing and therefore this species still does not yet seem to be adversely affected by climate change.

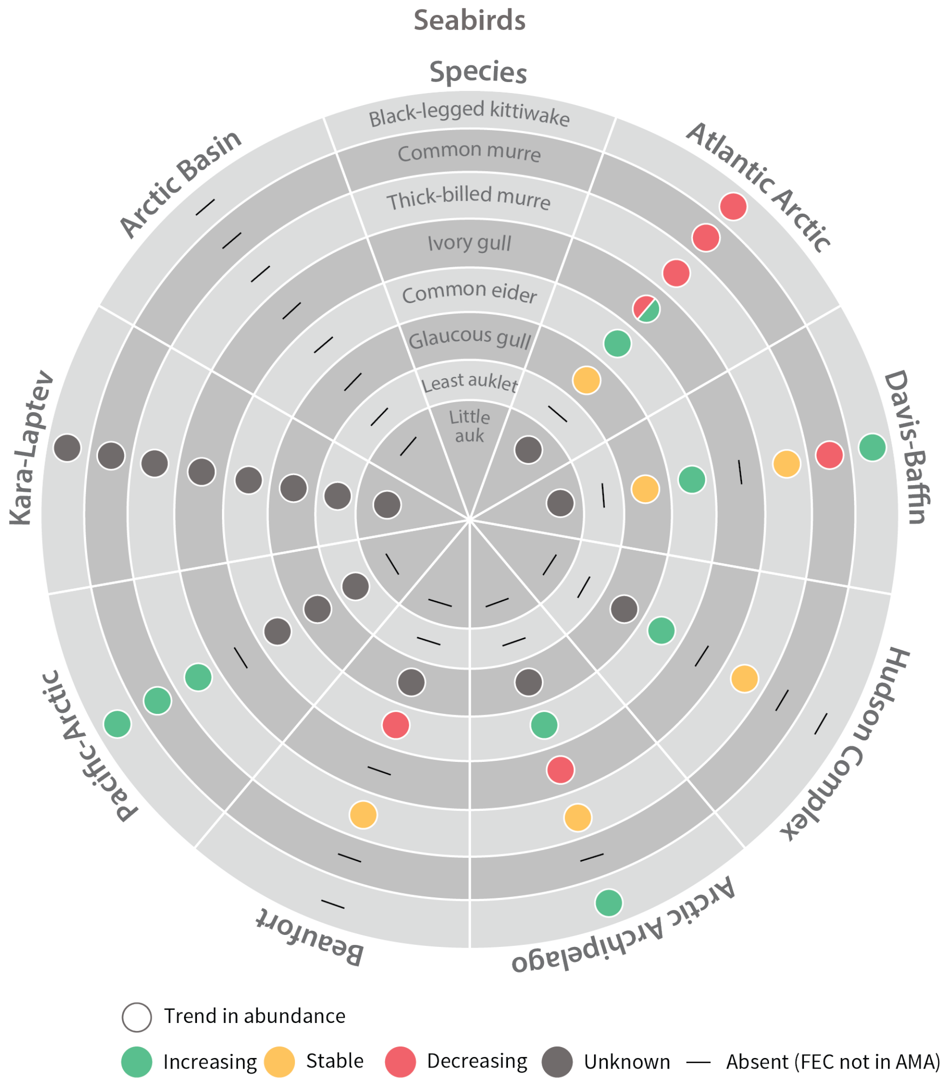

Figure 4.5: Trends in abundance of seabird Focal Ecosystem Components across each Arctic Marine Area.

4.1.5 Seabirds

Around 30 species of seabirds breed in the Arctic as defined here, and most of these are migratory and leave Arctic waters during the winter. The most diverse groups are gulls and auks. Some species are extremely numerous, particularly the little auk which occurs in millions in northern Baffin Bay. Other species are rare and local in occurrence. Seabirds have different ecological roles, and eight species have been selected as priorities for monitoring to reflect this diversity, representing the following five functional groups (see Chapter 3.5): diving piscivores, diving planktivores, surface piscivores, benthic feeders, and omnivores.

Seabird population trends are relatively well known, although not for all species (Table 3.5.2, Fig. 4.5). Several of the monitored species have shown widespread declines in recent years, at least in parts of the Arctic. The piscivorous common murre (*Uria aalge*), thick-billed murre (*Uria lomvia*) and black-legged kittiwake (*Rissa tridactyla*) (Fig. 3.5.3) have declined particularly in the Atlantic Arctic (and to some extent Davis Strait-Baffin Bay), and the two latter species are subjects of detailed investigations. These declines are consistent with wider changes in the pelagic ecosystem in the North Atlantic, affecting seabirds over a wide range (Frederiksen 2010, Frederiksen et al. 2013). A similar geographical pattern is apparent for the omnivorous glaucous gull (*Larus hyperboreus*) and the benthic feeder common eider (*Somateria mollissima*), whereas the ivory gull (*Pagophila eburnea*) has declined throughout its Arctic range. At local levels, some observed changes are counterintuitive. For example, planktivorous seabirds have increased offshore in the Chukchi Sea relative to piscivorous species (Chapter 3.5, Box 1), which is opposite to what is expected in a general warming scenario with less sea ice (cf. Hunt et al. 2002). However, the increase in planktivorous seabirds is consistent with the increase observed for large copepods in the same area, even for the High Arctic *Calanus glacialis* (Fig. 3.2.6). In contrast, most of the seabird species that nest in the Chukchi are piscivorous, thus their response to ecosystem changes might lag behind that of planktivorous post-breeding migrants.

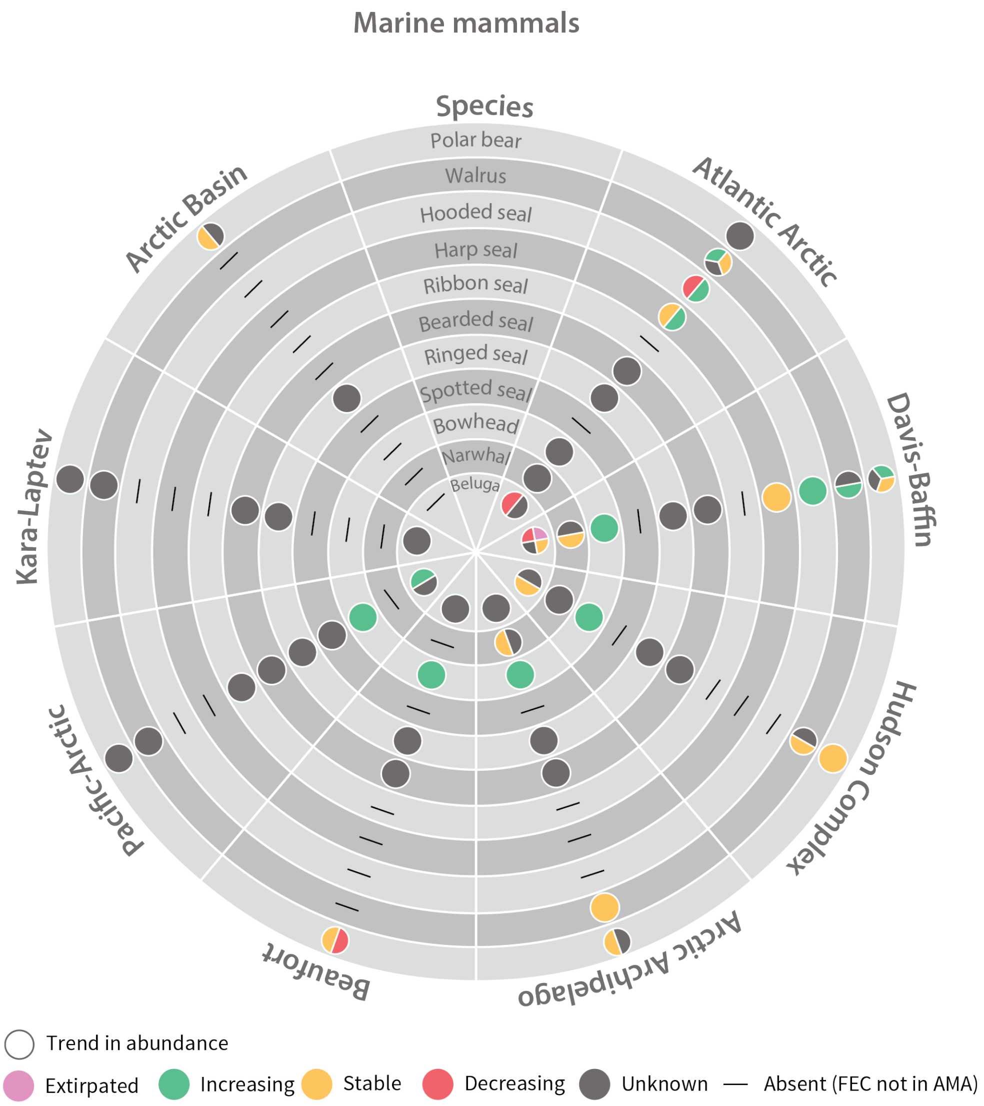

Figure 4.6: Trends in abundance of marine mammal Focal Ecosystem Components across each Arctic Marine Area.

4.1.6 Marine mammals

Eleven species of marine mammals (seals, whales and polar bear (*Ursus maritimus*)) are regarded as Arctic and associate with sea ice for at least part of their life cycle. Four of these are sub-Arctic seals that migrate into the Arctic (two each in the Pacific and Atlantic), while the remaining seven are circumpolar and occur in the Arctic year-round. All species and most populations are, or have been, harvested by humans on a large scale. The current status of some species is still affected by past harvest, for instance hooded seal (*Cystophora cristata*) in the Greenland Sea. Overall, one quarter of all populations (or half of those for which sufficient information exists) are regarded as reduced in size because of unsustainable hunting in the past. In most cases, quotas regulate current harvest, and in many indigenous communities, traditional management practices are still used to govern harvest activities (ICC-Alaska 2015).

Trends are known for approximately half of Arctic marine mammal stocks (Fig. 3.6.2, Table 3.6.1, Fig. 4.6). In general, trends for wide-ranging species (e.g., ringed seal (*Pusa hispida*), bearded seal *Erignathus barbatus*), and ribbon seal (*Phoca fasciata*)) are least understood, while distinct populations or stocks that occur in well-defined geographic areas more often have documented trend information (e.g., narwhal (*Monodon monoceros*) and some polar bear populations). Most populations with known status are increasing or stable, but e.g. those of beluga (*Delphinapterus leucas*) in the White Sea, polar bear in the southern Beaufort Sea, and hooded seal in the Greenland Sea are declining. Because many stocks were reduced by past unsustainable harvest, harvest history has to be included as an important driver of observed trends. Many stocks are still recovering from past harvest (e.g., bowhead whale (*Balaena mysticetus*), walrus (*Odobenus rosmarus*)), while others have not been able to do so, probably due to climate change (e.g., Greenland Sea hooded seal).

For some species, there is considerable regional variation in trends in e.g., body condition. For example, ringed seals experience reduced body condition and reproduction in Hudson Bay and the eastern Beaufort Sea, whereas no decline in body condition has been observed off Alaska (references in Chapter 3.5).

4.2 Evidence for the impacts of drivers on Arctic marine biodiversity

4.2.1 Observed and expected impacts of climate change

Several reviews have assessed the evidence for observed climate-driven changes in Arctic marine biodiversity (e.g., Wassmann et al. 2011, Post et al. 2013). Rather than attempting another review, key contributions from the CBMP Marine Expert Networks are highlighted (referenced to sections of Chapter 3) and placed in a broader ecosystem context. More details about specific cases can be found in Chapter 3. A short description and review of changes and trends in physical drivers and anthropogenic stressors can be found in Chapter 2.

Increasing ocean temperature

Physiological changes among key primary producers may have strong implications for higher trophic levels. In the pelagic realm, increasing temperatures are expected to affect the composition of phytoplankton communities, with flagellates favoured over diatoms (Chapter 3.2). This may have cascading effects on zooplankton communities, where different species and groups are adapted to feed on specific types of algae. In turn, these changes in zooplankton species composition may affect planktivorous fish and seabirds, some of which depend on large, lipid-rich copepod species for growth and successful reproduction (ICES 2016; Chapter 3.5). At the same time, increased primary productivity (due to a longer ice-free season and more wind-driven upwellings) will favour increased zooplankton stocks, but this may be counteracted by increased stratification due to ice melt and limited nutrients, particularly in the Arctic Basin (Chapter 3.2). Regional variation is expected in the relative role of these two processes. If strong algal blooms become increasingly common in Arctic waters, this could have impacts e.g. on seabirds and fish, due to either toxic effects or increased turbidity affecting foraging for visual predators (Chapter 3.5).

Indirectly, increasing temperatures are likely to lead to range shifts in Arctic species, and many such shifts have already been observed. An important example concerns the boreal copepod *Calanus finmarchicus*, which in the Atlantic Arctic is expected to expand northwards at the expense of its larger relatives *C. glacialis* and *C. hyperboreus* (Stempniewicz et al. 2007, Kjellerup et al. 2012). Similarly, capelin is likely to expand northwards into the Arctic at the expanse of polar cod (Chapter 3.4; Hop and Gjøsæter 2013) and indeed this process has already been observed throughout the Arctic (Chapter 3.4). The shift in dominance from polar cod to capelin has led to changes in seabird diet in northern Hudson Bay (Gaston and Elliott 2014) and may also affect the food base for marine mammals, as capelin may be less lipid-rich than polar cod, at least seasonally (Chapter 3.6; Hop and Gjøsæter 2013). While pelagic and deep-water species are able to spread northward into the Arctic Ocean as temperatures increase, this may not be the case for species linked to shelf regions, including benthos, fishes and seabirds (Chapters 3.3, 3.4, 3.5).

At the same time, new species are entering the Arctic from more southern areas as temperatures increase, and this may affect Arctic biodiversity in many different ways. Fish species from warmer waters have been documented in many areas (Chapter 3.4). Pelagic fish predators such as Atlantic mackerel (*Scomber scombrus*) and bluefin tuna (*Thunnus thynnus*) have recently arrived in Arctic waters off Greenland, and mackerel has been observed off Svalbard (MacKenzie et al. 2014, Berge et al. 2015); this may lead to changes in predation pressure on pelagic fishes as well as in human fisheries. 'New' (often migratory) species of cetaceans may act as competitors (e.g., minke whale (*Balaenoptera acutorostrata*) and humpback whale (*Megaptera novaeangliae*)) or predators (killer whale (*Orcinus orca*)) of resident Arctic specialists (Chapter 3.6). In northern parts of the Barents Sea, a pronounced 'borealisation' of demersal communities has been observed, i.e. an increased dominance of boreal species (Chapter 3.3). Atlantic cod has also expanded into the northern Barents Sea and this has led to increased overlap with and predation on polar cod (Chapter 3.4, Box 1). In the Pacific sector, several boreal or temperate seabird species have become increasingly common as non-breeders in the Chukchi Sea (Chapter 3.5).

Higher sea temperatures, combined with reduced sea ice coverage, is also likely to allow movements of organisms (e.g., fish) between the north Atlantic and Pacific Oceans, with unpredictable consequences for resident species and ecosystems (Mecklenburg et al. 2014, Wisz et al. 2015). Likewise, establishment and spread of non-native species may be facilitated.

An increase in contagious diseases affecting seabirds and potentially pinnipeds on their terrestrial breeding grounds may also be linked to increasing temperatures, for example the recent occurrence of avian cholera in the northern Bering Sea and in the Arctic Archipelago (Chapter 3.5, Descamps et al. 2012).

Reduction in sea ice

Species tightly linked to sea ice, often referred to as sympagic biota, are expected to lose habitat and contract their distributional ranges. As an example, polar cod and ice cod (*Arctogadus glacialis*), which are the most widespread and important sympagic fish species, are expected to lose much of their year-round habitat (Chapter 3.4). Because these are ecologically very important, this will affect their predators, which include many species of marine mammals and seabirds (Chapters 3.6 and 3.5). Among sea ice biota more generally, the decline in multi-year ice will affect species composition (Chapter 3.1). This implies that specialist species strictly linked to ice are disfavoured, while more generalist species, able to thrive also in pelagic environments, are expected to increase.

The primary productivity of microalgae may increase with thinning ice (leading to higher light penetration) or stronger upwelling (due to retreating ice), but this may be counteracted by less ice and stronger stratification due to increased freshwater influence, either from melting ice or river runoff (Chapter 3.1 and 3.2). At the same time, increased freshwater influence may favour brackish water (and smaller) species at the expense of marine species (Chapter 3.1

and 3.2). Changes in relative contribution of ice algae and phytoplankton to the primary productivity may potentially lead to reduced benthic-pelagic coupling, which in turn may affect benthos (Chapter 3.3) and lead to reduced food supply for species such as shrimp and walrus (Chapters 3.3 Box 3, 3.6).

For most species of marine mammal, seasonal pack ice is the most important habitat feature. Declines in seasonal ice cover may thus lead to reductions in breeding sites for seals and to a loss of haul-out sites for walrus that may affect their opportunities for foraging during both breeding season and winter (Chapter 3.6). Observed patterns of change can be complex and difficult to interpret, for example harp seals have increased due to recovery from past harvest, but the population increase combined with declining sea ice has at the same time led to density-dependent declines in condition and reproduction (Chapter 3.6, Stenson et al. 2016). As the decline in sea ice cover shows large regional variation, stocks of ice-dependent seals are also likely to show highly different trends, with possible extirpation of some stocks (Chapter 3.6).

A well-known consequence of reductions in sea ice cover is the loss of polar bear habitat (Chapter 3.6). This has been demonstrated to have negative consequences for the bears, because they rely on ice as hunting grounds to access seals, a highly nutritious food source. Observed and expected consequences include reduced body condition, lower survival, and ultimately population declines (Stirling and Derocher 2012). Indirect effects have already been observed, in the form of increased polar bear predation on ground-nesting birds, e.g., common eider (Iverson et al. 2014, Prop et al. 2015). As sea ice cover diminishes, polar bears are forced to spend time on land, which increases interactions with coastal communities (Chapter 3.6).

Some seabirds also rely on access to foraging at or near the ice edge during the summer breeding season. The retraction of the summer sea ice edge has in some cases led to problems for associated seabird populations, notably black guillemots (*Cepphus grylle*) in Alaska (Divoky et al. 2015).

Changes in currents

Global increases in ocean temperature are likely to cause some major currents to strengthen and others to weaken (Chapter 2), which can have implications for biota. As an example, changes in the strength of the Subpolar Gyre south-east of Greenland have been statistically linked to declines in the Spitsbergen thick-billed murre population, although the potential mechanism is unknown (Chapter 3.5, Descamps et al. 2013).

Inuit hold a great amount of knowledge about ocean currents. It is easy to appreciate the extent of knowledge that would be held by a group of people that are culturally and spiritually tied to the ocean and that greatly rely on it for food from time immemorial. Inuit have observed changes in currents over time. Raymond-Yakoubian et al. (2014b) provide a report on use of Bering Strait region ocean currents. Within the report, Indigenous peoples of the Bering Strait region of Alaska share the significance of the ocean and changes that have been observed: "Changing weather and ocean currents have altered the off-shore sea floor, sometimes creating large dips where clams, for instance, become trapped and therefore do not wash ashore in as large numbers as in the past". The change in ocean currents is directly related to change in sea ice and storms. Raymond-Yakoubian et al. (2014a) further report that, "Communities have also reported stronger storms in recent years. These storms move a lot of water (and ice) around, and appear to also be changing the nearshore sea floor. Residents of Wales and Shishmaref report that 'dips' and 'valleys' have developed offshore from their communities. These changes in the sea floor may impact ice formation, where ice piles, and the availability of clams."

4.2.2 Other major anthropogenic stressors

Many of the drivers and threats listed in this section interact with climate change, either because the associated human activities are expected to change in intensity or spatial distribution as the climate warms, or because chemical or biological reactions and pathways are likely to change. Furthermore, the various stressors will interact among themselves in complex ways, and there is therefore a need to address also cumulative impacts across stressors (see Chapter 2.4).

Ocean acidification

Arctic oceans are expected to be particularly vulnerable to the effects of ocean acidification (AMAP 2013). While acidification itself is monitored in some parts of the Arctic (Chierici et al. 2016), there is currently no monitoring of the biological effects and, thus, little specific evidence to inform an assessment of the importance of this driver for biodiversity. Few studies have investigated the potential impact of ocean acidification on Arctic species, especially studies on the entire life cycle and from across the entire Arctic. However, those that exist point to likely ecosystem effects of ocean acidification in the Arctic. For Arctic primary producers, increased pCO_2 may cause an increase in gross primary productivity (though only at low temperatures; Holding et al. 2015), and a shift in community composition with potential to indirectly affect the trophic transfer to grazers (Tarling et al. 2016). Recent studies on the dominant zooplankton taxa in the Arctic, calanoid copepods and pteropods, show mixed effects. Calcifying pteropods appear to be quite sensitive to increased pCO_2, with decreased calcification, increased respiration, increased mortality in juveniles and adults, and decreased recruitment (Browman et al. 2013). On the other hand, many life stages of non-calcifying *Calanus* copepods are tolerant to realistic future pCO_2 levels, including their naupliar development and growth (Bailey et al. 2016) as well as adult respiration and ingestion (Hildebrandt et al. 2014). Arctic benthic calcifiers, including molluscs, echinoderms and crabs, are generally negatively affected by increased pCO_2 (Browman et al. 2013), with the potential to put at risk the many fish species which prey on them at some point in their lives (Mathis et al. 2015). Atlantic cod, which is moving north into the European Arctic, also appears to be affected by increased pCO_2 during its early life phases (Stiasny et al. 2016).

Contaminants

High levels of contaminants have been shown to pose health risks for marine mammals such as polar bears (Sonne 2010) and for the human communities that depend on them (Chapter 3.6, Sonne et al. 2013). At the population level, specific contaminants have been shown to have consequences for predators such as the glaucous gull (Erikstad et al. 2013) and black-legged kittiwake (Goutte et al. 2015). Contaminant burdens can interact with climate change in different ways, either because changes in the physical environment may lead to increased exposure to contaminants, e.g. polar bears affected by reduction in sea ice (Jenssen et al. 2015), or because of climate-related changes in pollutant pathways, e.g. increased biomagnification of pollutants through food webs as sub-Arctic prey species become more common (McKinney et al. 2015).

Industrial developments and activities

Noise is one of the most widespread impacts of industrial activities, including seismic surveys, drilling and shipping. Noise is expected to primarily affect marine mammals, which use sound for underwater communication and foraging (Richardson et al. 1995, Miller et al. 2015). Noise may cause redistribution of marine mammals, particularly whales, thus affecting human communities (Chapter 3.6). If animals are prevented from accessing important foraging areas, there is a potential for population-level impacts.

In addition to noise and the risk of oil spills, increased shipping in the Arctic may also lead to disturbance and habitat loss for seabirds and marine mammals. Direct mortality can occur through vessel strikes of whales (Chapter 3.6) and of seabirds during inclement weather or darkness (Chapter 3.5).

Invasive alien species

The introduction and spread of invasive alien species is regarded as one of the most important threats to biodiversity worldwide. Shipping is the main source of introduction of potentially invasive species in marine environments. So far, there are few examples of invasive marine species becoming established in the Arctic. However, in the Barents Sea two large non-native crab species (snow and king crab) have become very numerous and are under suspicion of affecting benthic communities (Chapter 3.3, Oug et al. 2011).

While the king crab was intentionally introduced from the North Pacific in the 1960s by Russian scientists to create a new and valuable fishing resource in the Barents Sea (Orlov and Karpevich, 1965, Orlov and Ivanov, 1978), the snow crab was originally assumed to be introduced to the Barents Sea via ballast water (Kuzmin 2000, Alvsvåg et al. 2008). However, recent analysis of genetic data from circumpolar samples (Bering Sea, Beaufort Sea, Chukchi Sea, east Canada, West Greenland and Barents Sea) indicate that the snow crabs now observed in the Barents Sea derive from a natural invasion, possibly from the east, i.e., Novaya Zemlya/Kara Sea (G. Dahle, pers. comm). The potential effects of the two species on benthic ecosystems and fisheries are disputed, with some researchers arguing caution while others conclude that no major effects are likely (Britayev et al. 2010, Oug et al. 2011, Falk-Petersen et al. 2011, Dvoretsky and Dvoretsky 2015). Invasive terrestrial predators can be a very serious threat to ground-nesting seabirds, but so far few examples are known from the areas covered by this report.

Harvest (direct and indirect effects)

Many species of fish, seabirds and marine mammals have been harvested by both local communities and international fleets for centuries. Some stocks of fishes, large whales and seals were reduced to a small fraction of their original sizes, and their current trajectories are still to some extent related to recovery from past overexploitation (Chapters 3.4, 3.6). This complicates the interpretation of current trends in relation to environmental drivers. Some seabird populations are still affected by harvest in addition to other stressors, but in most cases harvest has declined substantially (Chapter 3.5, Merkel 2010).

The spatial extent of industrial-scale fisheries has until now been limited by the extent of sea ice. As the ice retreats, there is potential for expansion into previously unfished areas. The main species expected to be of interest to fisheries in the Arctic Basin is the Greenland halibut (Chapter 3.4).

Trawl fisheries have profound impacts on benthic habitats, their biodiversity and connections throughout the food web (Chapter 2). In the Barents Sea, declines in benthic biomass have been linked to the intensity of bottom trawling (Chapter 3.3) and this is likely also important in other parts of the Atlantic Arctic. There is a concern about future impacts of trawling in previously unfished areas (Jørgensen et al. 2015), which become available as a consequence of climate change (Chapter 3.3). The benthos composition is being monitored as the ice retreats, and this is unveiling sea pens (Cnidaria, Pennatulacea, *Umbellula encrinus*) and other large-bodied upraised species easily caught and therefore vulnerable to bottom trawling. Along the western shelf of Norway, there is a risk of strong impacts on cold-water corals and sponges (Chapter 3.3), and large aggregations of sponges have been observed on the slope from the western shelf of Norway and northward along western and northern Svalbard and further east toward the Kara Sea.

Bycatch in gill nets may have negative effects on some species of seabirds locally, e.g., in Iceland, Norway and Canada (Chapter 3.5, Fangel et al. 2015, Hedd et al. 2016), but currently seems to be of less concern in other parts of the Arctic (e.g., Merkel 2011), probably due to the spatial distribution of particular fisheries relative to seabird concentrations. Development of nearshore gillnet fisheries in e.g., the Pacific Arctic, could lead to increased bycatch with potentially major impacts on seabird populations.

4.2.3 Links to non-Arctic ecosystems

Many seabirds and marine mammals spend the summer in the Arctic, but leave when seasonal ice cover and darkness set in. They spend the northern winter in areas ranging from the sub-Arctic (e.g., thick-billed murre, Frederiksen et al. 2016) to the Southern Ocean (e.g. Arctic tern (*Sterna paradisaea*), Egevang et al. 2010). Several studies have suggested causal links between conditions in wintering areas and population trends or demography of Arctic-breeding seabirds (Descamps

Table 4.1: Comparison of FECs as defined in the CBMP Marine Plan *and those reported on in the* State of the Arctic Marine Biodiversity Report *(SAMBR)*

FECs as defined in the *CBMP Marine Plan*		**FECs used in SAMBR**	
Marine mammal			
Walrus	*Odobenus rosmarus*	Beluga	*Delphinapterus leucas*
Ringed seal	*Pusa hispid*	Narwhal	*Monodon monoceros*
Beluga	*Delphinapterus leucas*	Bowhead whale	*Balaena mysticetus*
Bowhead whale	*Balaena mysticetus*	Spotted seal	*Phoca largha*
Polar bear	*Ursus maritimus*	Ringed seal	*Pusa hispid*
		Bearded seal	*Erignathus barbatus*
		Ribbon seal	*Phoca fasciata*
		Harp seal	*Phoca groenlandica*
		Hooded seal	*Cystophora cristata*
		Walrus	*Odobenus rosmarus*
		Polar bear	*Ursus maritimus*
Seabirds			
Black-legged kittiwake	*Rissa tridactyla*	Glaucous gull	*Larus hyperboreus*
Common murre	*Uria aalge*	Ivory gull	*Pagophilia eburnea*
Thick-billed murre	*Uria lomvia*	Least auklet	*Aethia pusilla*
Common eider	*Somateria mollissima*	Little auk	*Alle alle*
		Common murre	*Uria aalge*
		Thick-billed murre	*Uria lomvia*
		Black-legged kittiwake	*Rissa tridactyla*
		Common eider	*Somateria mollissima*
Fishes			
Capelin	*Mallotus villosus spp.*	Capelin	*Mallotus villosus spp.*
Polar cod	*Boreogadus saida*	Polar cod	*Boreogadus saida*
Greenland halibut	*Reinhardtius hippoglossoides*	Greenland halibut	*Reinhardtius hippoglossoides*
Pelagic fish			
Salmon			
Arctic char			
Benthic and demersal fish			
Ice cod	*Arctogadus glacialis*		
Atlantic cod	*Gadus morhua*		
Alaska pollock	*Gadus chalcogrammus*		
Bering flounder	*Hippoglossoides robustus*		
Shorthorn sculpin and related sculpin	*Myoxocephalus scorpius*		
Benthos			
Macrofauna and megafauna		Macrobenthos	
Macroalgae		Megabenthos	
Meiofauna and microbes			
Plankton			
Phytoplankton		Phytoplankton and larger protists	
Protists (e.g., microzooplankton)		Microbial eukaryotes	
Microbes (Archaea, Bacteria)		Bacteria and Archaea	
Zooplankton (e.g., meso- and macrozooplankton)		Zooplankton	
Sea ice biota			
Diatoms		Prokaryotic microbes, including Archaea and Bacteria	
Dinoflagellates		Ice algae and other single-celled eukaryotes	
Flagellates		Ice meiofauna	
Interstitial diatoms		Macrofauna: Under-ice amphipods	
Interstitial and under-ice layer invertebrates		*Note: Sea ice associated fish, specifically polar cod and ice cod, are included in the fish chapter. Viruses and fungi were excluded*	

et al. 2013, Reiertsen et al. 2014). In addition, some southern-hemisphere seabird species spend their non-breeding season in the Arctic summer and may comprise half of all seabirds in some regions, e.g. Short-tailed shearwaters (*Ardenna tenuirostris*) in the northern Bering and Chukchi Seas (Chapter 3.5).

Just as conditions in non-Arctic wintering areas may affect populations of Arctic-breeding birds or mammals, numbers wintering in specific areas may change because of changes in population size or migratory behaviour of Arctic animals. There are as of yet no documented cases of major changes in migration behaviour of Arctic-breeding seabirds or marine mammals. However, some species of ducks breeding in the Siberian tundra and wintering at sea have shortened their migration in response to declines in winter ice cover, leading to declines in numbers wintering in former core areas (e.g., Steller's eider (*Polysticta stelleri*), Aarvak et al. 2013). Beluga in Hudson Bay varied the timing of their migration from year to year, apparently in response to variations in temperature (Bailleul et al. 2012).

Phytoplankton originating from the Arctic Ocean may play a role in spring bloom in the North Atlantic (Chapter 3.2). Luddington et al. (2016) found that autumn communities of diatoms in the Canadian Arctic were similar to those in the North Atlantic in the following spring, suggesting large-scale advection of planktonic algae. These links are likely to change in response to further global warming.

4.3 The state of Arctic marine biodiversity monitoring

4.3.1 Adequacy of existing monitoring

The coverage of existing biodiversity monitoring in Arctic marine ecosystems, both in terms of current efforts and available time series, varies considerably among geographical areas and taxonomic groups (Fig. 4.7). This variation reflects that the CBMP *Arctic Marine Biodiversity Monitoring Plan* (Gill et al. 2011, *CBMP Marine Plan*) is an umbrella program based on existing, national and regional monitoring efforts. Other factors affecting coverage and the ability to deliver robust monitoring time series include extremely high natural variability in time and space, particularly for microscopic organisms, as well as changing views on the taxonomical resolution needed for monitoring. For example, although some zooplankton time series extend back to the 1960s, parts of the data are simply recorded as 'zooplankton' or 'copepods' rather than identified to the species level. This inconsistency makes it very difficult to draw firm conclusions about long-term changes in abundance and distribution of specific species.

While some networks are still documenting the existing biodiversity in the marine Arctic, others have good background knowledge of the identity and range of most or all species. However, both trends in abundance (Chapter 4.1) and underlying drivers (Chapter 4.2) are relatively poorly known.

The Traditional Knowledge (TK) of peoples living along and off the Arctic Ocean is an invaluable resource for our understanding of changes in Arctic marine ecosystems. TK holders have a considerable wealth of information that is needed to increase our knowledge of interconnected systems. For example, TK has identified decreasing volumes of benthic prey, particularly clams, and an increasing volume of pelagic fishes, or simply sand, in walrus stomachs (Chapter 3.3). However, monitoring programs often struggle to find a way in which to effectively utilize TK. The *CBMP Marine Plan* worked to address this issue by engaging and including TK within its design, but the lack of funding support and capacity hindered effective incorporation of TK within the *CBMP Marine Plan*.

Overall, the conclusion of all CBMP Marine Expert Networks is that current monitoring is not sufficient to describe status and trends for many of the Focal Ecosystem Components (FECs) defined in the *CBMP Marine Plan* (Fig. 4.7, Chapter 3). For some (seabirds and marine mammals) they were able to refine and expand upon the original list of FECs while for others (fish and benthos) they were unable to source enough data to report on all the FECs (Table 4.1).

For many taxa, regular monitoring is supplemented by research-driven data collection, but although the additional data collected in this way are extremely valuable, they remain an imperfect substitute for a well-designed monitoring program. It is a recurring theme that data collection relies on a combination of traditional methods requiring fieldcraft and taxonomical expertise, and advanced methods requiring substantial laboratory and/or computing resources. The outcomes of this process will be used to evaluate the *CBMP Marine Plan* and determine, after this first SAMBR, what changes and alterations are needed to improve its effectiveness and implementation.

Some functionally important groups (cf. Gill et al. 2011) are not covered by existing monitoring (e.g. benthic meiofauna and microbes), and besides the incomplete view of biodiversity obtained, this has implications for the ability of the *CBMP Marine Plan* to reflect changes in ecosystem structure and function (see also Chapter 4.1.3).

Biodiversity monitoring spans many levels of detail, from presence/absence surveys via quantitative sampling of abundance to detailed studies of survival, reproduction and other vital rates and related parameters. The choice of detail reflects existing knowledge, practical issues, the life histories of target organisms, and other factors. In particular, for long-lived, highly mobile organisms such as seabirds and marine mammals, large-scale changes in abundance are likely to be slow and affected by conditions over large areas, whereas local abundance can change very quickly, particularly outside breeding areas. Thus, neither local nor large-scale abundance tend to show clear relationships with identifiable drivers, except over long time spans. Monitoring of vital rates, diet or body condition is particularly useful for such organisms, as these parameters often show greater variation and can be related to specific environmental drivers (Anker-Nilssen et al. 2015, Irons et al. 2015). This is particularly the case for species where abundance is very difficult to estimate, e.g., cavity-nesting seabirds and many marine mammals. Monitoring of these additional parameters is improving for several species, but further efforts are needed to assess the status of many populations (Chapters 3.5, 3.6). Further consideration should be given to how TK could contribute to our knowledge on these issues.

For economically important organisms such as commercial crab, shrimp and fish stocks, and marine mammals, harvest data have been collected for long periods, often spanning several decades and, in some cases, centuries. More recently, harvest data have also been collected for other hunted seabirds. Such data contain information on abundance of the target organism, but they are also affected by variation in harvest effort, legislation, technology as well as reporting intensity, thus complicating their interpretation (Moshøj 2014). Harvest data can therefore form a supplement to biodiversity monitoring, but are rarely in themselves sufficient to allow confident assessment of status, trends and drivers.

One option for supplementing official monitoring programs is an increased involvement of and collaboration with local residents. In many cases, indigenous and non-indigenous communities may work collaboratively with scientists to collect scientific measurements and this approach is already used to monitor the condition of marine mammals (Chapter 3.6). This approach is often referred to as "citizen science". Innovative use of recent technology can encourage more efficient monitoring linkages between local residents and scientists. As an example, the wide availability of mobile phones allows the development of apps that can harness the device's GPS capacity to collect accurate spatial information on wildlife encounters (Flora et al. 2016). Local residents are often the first to detect new species in specific areas, e.g. non-native species. Furthermore, residents in remote communities serve as 'first responders' to unusual mortality events, and can assist in efforts to document the extent of these events, such as occurred during a seabird mortality event near St. Lawrence Island, northern Bering Sea, in 2013 (Chapter 3.5).

It is important to note that there are monitoring methodologies within TK. Many communities, such as those on St. Lawrence Island, have monitored their environment from time immemorial. Collaboration between scientists and TK holders through a participatory approach will greatly aid in bringing forward information needed and enhance monitoring programs.

4.3.2 Standardisation and harmonization of national monitoring schemes

The *CBMP Marine Plan* recommends that participating monitoring institutions develop common, standardized protocols for Arctic marine monitoring as well as for appropriate storage and archiving of biological data collections, with permanent museum repositories holding geo-referenced samples, for analysis and reporting (Gill et al. 2011, Barry et al. 2013). The goal is to maximize the use of available data, both existing and future, while allowing flexibility to meet local and international monitoring needs.

Based on this approach, the CBMP Marine Expert Networks are striving to coordinate and standardize sampling methods across institutions and countries as well as to harmonize existing data. Harmonization in this context means combining data collected with different methods, either through direct integration, combining derivative products, or through modelling.

Much work remains before the data collected under national schemes can be compared directly. Many of the CBMP Marine Expert Networks provide constructive suggestions for how to combine existing monitoring elements into a coherent program (Chapter 3), and several initiatives are already under way. For instance, pan-Arctic field guides are being developed for both benthic fauna and fish, and a database of historical population estimates of marine mammals has been compiled.

Internationally coordinated monitoring plans have been developed for some species and groups, but implementation lags behind. Examples include species-specific plans for ringed seal (Kovacs 2014), polar bear and beluga (Chapter 3.6), as well as the *Circumpolar Seabird Monitoring Plan* (Irons et al. 2015).

For some groups, standardization of gear as well as taxonomy is a prerequisite for obtaining comparable data, and this often represents a challenge due to different national or regional traditions. An important step forward is the common standardised approach that has been in use for megabenthos in the Barents Sea since 2005 and is being implemented in the wider Northeast Atlantic (pilot projects in Iceland and Greenland from 2015, the Faroe Islands likely from 2019), concurrent with groundfish surveys (Chapter 3.3), and followed by species identification workshops with development of identification literature and continuously updated photo guides. Attempts to build international collection of benthic species should be initiated. However, it is striking that information on non-commercial fish species collected during the same surveys is not used for biodiversity monitoring, at least not at the pan-Arctic level (Chapter 3.4). A similar approach exists in the Bering Sea, which could profitably be coordinated as far as possible with the Atlantic scheme.

For sea ice biota and plankton, a more synthetic sampling approach is recommended (Chapters 3.1 and 3.2), as current sampling often is fragmented by e.g., taxon, method or sub-habitat. In general, concurrent sampling of relevant physical parameters is also encouraged by the CBMP Marine Expert Networks. Many of these data, however, are costly and/or logistically difficult to collect; for example, the presence of sea ice limits the coverage of remote sensing programs for monitoring sea surface temperature and biological productivity.

A number of actions which would contribute towards standardization of methods include:

- Standardization of methodology for grab and trawl surveys of respectively macro- and megabenthos including development of standardised taxonomic identification across regions and species voucher collections;
- A formalized monitoring plan can build on existing national, annual groundfish-shellfish trawl surveys, such as implemented successfully in the Atlantic Arctic regions;
- Consistent methodology is required for monitoring of sea ice biota. Protocols need to be more

standardized for monitoring. These need to include all aspect from gear, collections, timing, sample preservation and processing, storage, and data management. Researchers in different projects should use a standardized sampling protocol to obtain samples, but a central receiving place as well as long-term funding for monitoring should be considered.
- Targeted surveys and individual tracking studies would improve our understanding of seabird interactions at sea, where seabirds spend most of their time.

CAFF, through its Arctic Biodiversity Data Service (ABDS), is working to facilitate application of common standards and processes to how Arctic biodiversity monitoring data are archived, structured and accessed.

Thus, progress on standardization of methods has been made, recommendations for improvements have been identified, and collating and processing of data has started. This constitutes a platform for continued improvement of the harmonization, integration and analysis of the data collected through the *CBMP Marine Plan*.

4.3.3 Ecosystem-based monitoring – are we getting there?

Ecosystem-based management (EBM): is defined by the Arctic Council as the comprehensive, integrated management of human activities based on best available scientific and traditional knowledge about the ecosystem and its dynamics, in order to identify and take action on influences that are critical to the health of ecosystems, thereby achieving sustainable use of ecosystem goods and services and maintenance of ecosystem integrity (Arctic Council 2013).

The Arctic Council is continuing to advance implementation of the Ecosystem Approach (EA) and to consider scientific and technical aspects related to the implementation of the EA to the management of the Arctic Large Marine Ecosystems. This includes elements of monitoring, integrated ecosystem assessment, and setting ecological objectives as part of the EA (PAME 2011).

The *CBMP Marine Plan* employs an 'integrated ecosystem-based approach to monitoring' (Gill 2011: 14). Although this concept is not defined explicitly in the *CBMP Marine Plan*, it implies a holistic framework where prioritized elements (i.e., FECs) of marine ecosystems are monitored, and where information is integrated and contributes to decision-making (see also Chapter 1). As this report represents the first opportunity to assess the progress made under the *CBMP Marine Plan*, it is highly relevant to consider whether current monitoring can be considered 'ecosystem-based', and to what extent progress is being made in that direction. The term 'ecosystem-based monitoring' is used in different ways in the literature:

- The monitoring needed to support and implement ecosystem-based management (Box 4.1) of (often marine) living resources. A well-known example is the European Union's Marine Strategy Framework Directive, which includes a large monitoring program aimed at assessing whether established goals of the directive are being met. Ideally, this monitoring program is coordinated across all sectors of anthropogenic impacts and scientific fields, including the physical environment and all levels of the ecosystem, so as to achieve an optimal description of ecosystem state and the pressures acting on it (Berg et al. 2015). However, the actual monitoring generally builds on already existing efforts and data series, and coordination and coverage are therefore rarely optimal.
- A site-based monitoring program that aims to collect data on all aspects of the local ecosystem(s), often including both abiotic and biotic aspects. Such monitoring programs are generally highly coordinated using a top-down planning approach. Well-known examples in the Arctic include Zackenberg Basic in north-east Greenland as part of the Greenland Ecosystem Monitoring (GEM) program and the Arctic Long Term Ecological Research at Toolik Lake in Alaska.

The main way in which the *CBMP Marine Plan* can be considered ecosystem-based is that the process of developing the program was based explicitly on a conceptual food web model as well as a detailed scoping process, where the CBMP Marine Expert Networks listed the FECs they considered most important to monitor and how this should be done. The selection of FECs has, in addition, been affected by data availability.

Progress towards ecosystem-based monitoring in the *CBMP Marine Plan* can be evaluated using two criteria: improved coverage (spatial, seasonal, taxonomic, and functional) through coordination among CBMP Marine Expert Networks, and integration of results across the ecosystem levels in line with the defined food web model. Chapters 4.1 and 4.2 represent the first attempt at an integration of the results from the six Expert Networks. An important function of improved coverage is to support upscaling efforts. Methods to detect changes at scales from local to landscape are essential for understanding some of the overall changes relevant for Arctic biodiversity. In this first report, relatively little can be concluded on the circumpolar scale, but the data generated by the Expert Networks and the monitoring efforts started through the *CBMP Marine Plan* have the potential to increase the focus on modelling and upscaling.

A synthetic view of the coverage of the monitoring reported by the CBMP Marine Expert Networks reveals some clear gaps, where missing functional groups representing important trophic links, or more generally ecosystem functions, are covered poorly or not at all. These gaps are primarily due to logistical challenges or lack of expertise in specific fields. Examples include:

1. Larger pelagic crustaceans and other invertebrates. These organisms (e.g. hyperiid amphipods such as *Themisto* spp. and squid such as *Gonatus*

fabricii) are known to be important prey for many vertebrate predators, including fishes, mammals and birds (Chapters 3.4, 3.5 and 3.6). However, they are too mobile to be sampled quantitatively by plankton surveys (Chapter 3.2), and little information exists on their distribution, abundance and trends in the Arctic.

2. Benthic micro- and meiofauna are not covered by current monitoring efforts (Chapter 3.3). These groups are mainly responsible for remineralisation of nutrients in sediments and, thus, perform an extremely important ecosystem function. Their biodiversity is poorly known, and changes in species composition that may affect ecosystem processes may go unnoticed.
3. In the pelagic realm, there is currently no monitoring for Bacteria and Archaea (Chapter 3.2). Molecular monitoring of these taxa would be possible, but is not implemented. They are very important for ecosystem function, particularly with regard to remineralisation of nutrients.

Another issue is that the various taxonomic and functional groups in most cases are sampled independently, at different locations and times. Overarching questions, such as 'who eats who', are not always considered, and therefore limited coordination occurs among various taxonomic and functional groups. This obviously complicates the integration of results. The challenge can be addressed through coordinated, location-based long-term surveys such as the Greenland Ecosystem Monitoring (GEM) program in Greenland or the Distributed Biological Observatory in the Pacific Arctic, but in the context of an Arctic-wide program such as the *CBMP Marine Plan*, it is difficult and expensive to achieve sufficient spatial coverage in this way. Steps forward in the direction of more synoptic sampling include benthic fishes and megabenthos now being sampled simultaneously during bottom trawl surveys in several countries (Chapters 3.3 and 3.4), and that in the Barents Sea observations on algae, zooplankton, mammals, birds, marine litter and the water environment are being done alongside both pelagic and bottom trawling (BarentsPortal 2016).

Overall, there is a tendency that the six CBMP Marine Expert Networks have focused on collecting and compiling pan-Arctic data within each expert network. Following the completion of the *SAMBR*, the Expert Networks should continue their work on data collation and harmonization, with added emphasis on increasing coordination and cooperation between the networks and inclusion of TK holders in order for the *CBMP Marine Plan* to fulfil its intention of being an ecosystem-based monitoring program.


CBMP Marine, Greenland, 2014. Photo: CAFF


CBMP Marine, Iceland, 2015. Photo: CAFF


CBMP Marine, Norway, 2015. Photo: CAFF


CBMP Marine, Iceland, 2016. Photo: CAFF

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Annex 4.1: List of common and scientific species names

Common name used in this report	Alternative common name	Scientific name
Alaska pollock	Walleye pollock	*Gadus chalcogrammus*
Albatross		*Phoebastria spp.*
Ancient murrelet		*Synthliboramphus antiquus*
Arctic char	Arctic charr	*Salvelinus alpinus*
Arctic tern		*Sterna paradisaea*
Atlantic cod		*Gadus morhua*
Atlantic mackerel		*Scomber scombrus*
Atlantic puffin		*Fratercula arctica*
Auk		Member of the family *Alcidae*
Bearded seal		*Erignathus barbatus*
Beluga	White whale	*Delphinapterus leucas*
Bering flounder		*Hippoglossoides robustus*
Black guillemot		*Cepphus grylle*
Black-legged kittiwake		*Rissa tridactyla*
Bluefin tuna		*Thunnus thynnus*
Bowhead whale		*Balaena mysticetus*
Capelin		*Mallotus villosus* (more recently split into several species)
Common eider		*Somateria mollissima*
Common gull		*Larus canus*
Common murre	Common guillemot	*Uria aalge*
Cormorant		Member of the family *Phalacrocoracidae*
Crested auklet		*Aethia cristatella*
Dolly Varden		*Salvelinus m. malma*
Eelpout		Member of the family *Zoarcidae*
European shag	Common shag	*Phalacrocorax aristotelis*
Fork-tailed storm petrel		*Oceanodroma furcata*
Glaucous gull		*Larus hyperboreus*
Glaucous-winged gull		*Larus glaucescens*
Great black-backed gull		*Larus marinus*
Great cormorant		*Phalacrocorax carbo*
Great skua		*Stercorarius skua*
Greenland halibut		*Reinhardtius hippoglossoides*
Grey seal		*Halichoerus grypus*
Gray whale	Grey whale	*Eschrichtius robustus*
Gull		Member of the family *Laridae*
Harbour porpoise	Harbor porpoise	*Phocoena phocoena*
Harbour seal	Common seal, harbor seal	*Phoca vitulina*
Harp seal		*Phoca groenlandica*
Herring gull		*Larus argentatus*
Hooded seal		*Cystophora cristata*
Humpback whale		*Megaptera novaeangliae*
Ice cod	Arctic cod, polar cod	*Arctogadus glacialis*
Iceland scallop		*Chlamys islandica*
Ivory gull		*Pagophila eburnea*
Killer whale	Orca	*Orcinus orca*

Common name used in this report	Alternative common name	Scientific name
King crab		*Paralithodes camtschaticus*
King eider		*Somateria spectabilis*
Krill		*Thysanoessa sp.*
Leach's storm petrel		*Oceanodroma leucorhoa*
Least auklet		*Aethia pusilla*
Lesser black-backed gull		*Larus fuscus*
Little auk	Dovekie	*Alle alle*
Long-tailed duck		*Clangula hyemalis*
Minke whale		*Balaenoptera acutorostrata*
Murre		*Uria spp.*
Narwhal		*Monodon monoceros*
Northern bottlenose whale		*Hyperoodon ampullatus*
Northern fulmar		*Fulmarus glacialis*
Northern gannet		*Morus bassanus*
Northern shrimp		*Pandalus borealis*
Ocean quahog	Icelandic cyprine	*Arctica islandica*
Pacific capelin		*Mallotus catervarius*
Pigeon guillemot		*Cepphus columba*
Pilot whale	Long-finned pilot whale	*Globicephala melas*
Polar bear		*Ursus maritimus*
Polar cod	Arctic cod	*Boreogadus saida*
Razorbill		*Alca torda*
Ribbon seal		*Phoca fasciata*
Ringed seal		*Pusa hispida*
Sandeel	Sand lance	*Ammodytes spp.*
Sea cucumber		Member of the class *Holothuroidea*
Sea star	Starfish	Member of the class *Asteroidea*
Sea urchin		*Strongylocentrotus sp.*
Shorthorn sculpin		*Myoxocephalus scorpius*
Short-tailed albatross		*Phoebastria albatrus*
Short-tailed shearwater		*Ardenna tenuirostris*
Striped shrimp		*Pandalus montagui*
Skua	Jaeger	Member of the family *Stercoraridae*
Snow crab		*Chionoecetes opilio*
Spectacled eider		*Somateria fischeri*
Sperm whale		*Physeter macrocephalus*
Sponge		Member of the phylum *Porifera*
Spotted seal		*Phoca largha*
Steller's eider		*Polysticta stelleri*
Tern		Member of the family *Sternidae*
Thick-billed murre	Brünnich's guillemot	*Uria lomvia*
Tubenose		Member of the order *Procellariiformes*
Tufted puffin		*Fratercula cirrhata*
Walrus		*Odobenus rosmarus*
White-beaked dolphin		*Lagenorhynchus albirostris*

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