OCEAN TWILIGHT ZONE

WOODS HOLE OCEANOGRAPHIC INSTITUTION

# Value Beyond View

## ILLUMINATING THE HUMAN BENEFITS OF THE OCEAN TWILIGHT ZONE

# Executive SUMMARY

The twilight zone is a fundamental part of the ocean ecosystem, playing an important role in **carbon sequestration** and **marine food webs** and supporting the natural function of many planetary processes. Ecosystem services provided by the twilight zone are highly beneficial to humans, but they occur largely out of sight and they are **undervalued by society** as a result. To better evaluate the benefits that the twilight zone provides, an ecosystem service framework provides a way to organize our thinking about them and even to quantify their economic value. With this information at hand, leaders and policymakers can think more carefully about what we stand to gain or lose from actions that affect the twilight zone and the broader ocean environment to which it is tightly linked, particularly as we strive for the **sustainable use of marine resources**.

**KEY TAKEAWAYS**

- Biological processes in the twilight zone are responsible for sequestering **2 to 6 billion metric tons of carbon** annually—at least double and perhaps as much as six times the amount of carbon emitted by all automobiles worldwide—which has an estimated value of **$300 to $900 billion** annually.
- Without this service, atmospheric carbon dioxide levels could be as much as **200 ppm higher** than they are today.
- The value of such a loss in sequestration service could amount to between **$170 billion and $3 trillion** in mitigation costs and **$23 to $401 billion** in adaptation costs by the end of the century.
- Reducing uncertainty in estimates of the amount of carbon sequestered in the ocean could have an economic value on the order of **hundreds of billions of dollars**, leading to improved decision-making and policy formation.
- Twilight zone organisms support economically important fisheries worldwide and are increasingly seen as a source of protein to supply aquaculture operations, which are expected to grow by **37 percent** from 2016 to 2030.
- Greater understanding of the twilight zone provides nonmaterial benefits to society in the form of **research activity, knowledge creation, and aesthetic value** that should not be overlooked.

# Introduction

In 2005, an international effort of natural scientists and policy experts constituting the Millennium Ecosystem Assessment (MA) introduced the ecosystem services approach to categorizing the wide array of goods and services derived from direct and indirect human uses of and other "nonmarket" benefits arising from the environment. This effort was motivated by the realization that, without a comprehensive accounting for the value of natural resources, decisions about most human activities inevitably tilt toward the degradation or loss of many of these environmental amenities.

In the last 15 years, significant gains have been made in characterizing the stocks of the Earth's natural resources, known as its natural capital, and the flows of benefits from those stocks, which include ecosystem services and capital gains. Today, decision-makers and the public can begin to weigh the benefits generated by the environment against the impact of intrusive human activities that could harm or even do away with them. In principle, trade-offs—which are at the heart of environmental policy—can now be assessed more explicitly.

If marine environments are degraded as a result of human activities, then our capacity to derive value from these environments in the future diminishes, to the detriment of future generations. Understanding the ecosystem services provided by the twilight zone is an important step in accounting for progress toward the sustainable development of this extraordinary and important ecosystem, as well as the ocean as a whole. More scientific knowledge of the twilight zone is needed to refine understanding of its ecosystem services, but we are able to draw some early qualitative conclusions.

This report represents a first attempt to identify and characterize the ecosystem services of the ocean's mesopelagic, or ocean twilight zone. Because this region is remote, difficult, and costly to access, and, by its very name, cloaked in darkness, it is not well understood. As it becomes increasingly possible to peer into the twilight zone, we can begin to piece together its hidden benefits and also to discern emerging threats to the vital services it provides society and the planet.

**ECOSYSTEM SERVICES** are the many direct and indirect contributions that nature makes to human well-being, survival, and quality of life. These are broken down into four main categories:

**Regulating services**: those that help govern natural ecosystem and planetary processes

**Cultural services**: non-material benefits people obtain from natural ecosystem functions

**Supporting services**: environmental functions that underpin other ecosystem services

**Provisioning services**: economically valuable products obtained from ecosystems

**Strawberry squid**, *Histioteuthis reversa*. Photo by Paul Caiger, Woods Hole Oceanographic Institution

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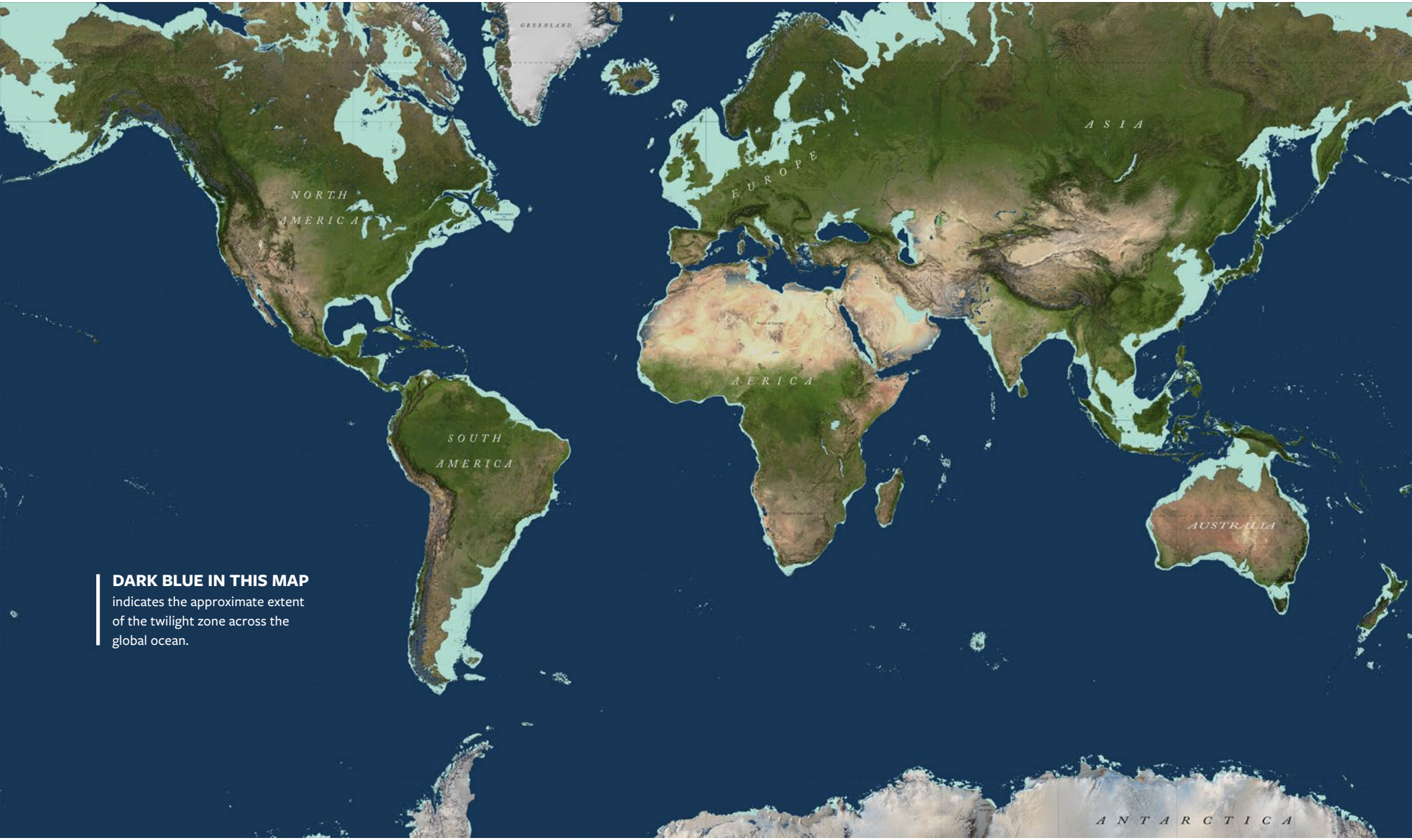
**On the cover,** squid, *Stigmatoteuthis arcturi*. Photo by Paul Caiger, Woods Hole Oceanogrphic Institution




**DARK BLUE IN THIS MAP**
indicates the approximate extent of the twilight zone across the global ocean.

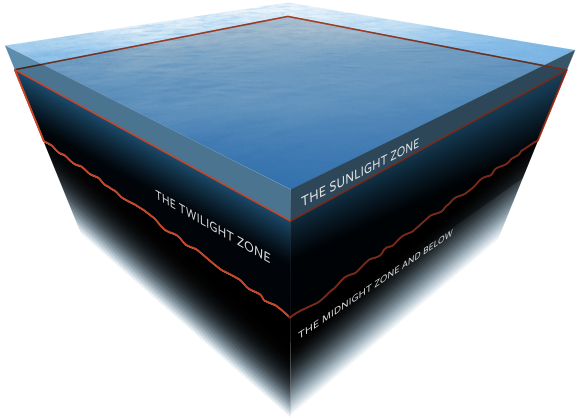
# WHAT IS THE OCEAN Twilight Zone?

The ocean's mesopelagic region, or twilight zone, lies at a depth between approximately 200 and 1,000 meters—a range that varies across the ocean but begins at a point where sunlight can no longer support photosynthesis.

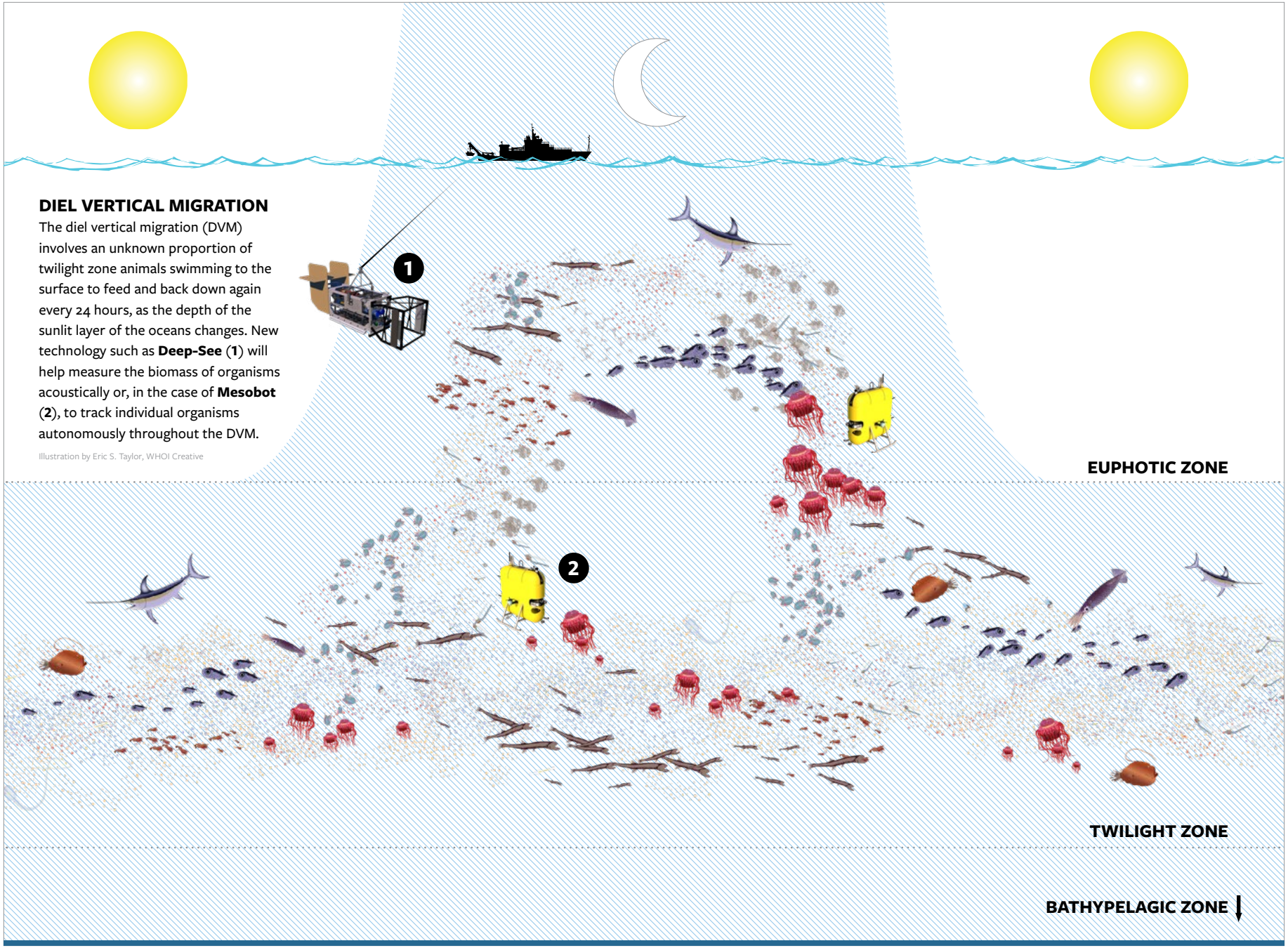
The twilight zone extends across the deep ocean beyond shallow continental shelves and is located mainly on the high seas, but it also extends into the 200-nautical-mile exclusive economic zones (EEZs) of many nations, including those of Small Island Developing States (SIDS).

The twilight zone is known for the unusual life forms it harbors, including 31 species of bristlemouths, which are thought to be the most numerous vertebrates on Earth. In fact, there may be as many as 130,000 of these fish for every human on Earth. The twilight zone also contains many other fish and invertebrates, and **recent estimates put the biomass of midwater fish on the order of 10 billion metric tons** (Irigoien et al., 2014)—at least 10 times previous estimates, 10 times the amount of fish in the sunlit surface waters, and 100 times annual removals through wild harvests.

As a result, some have begun to suggest that the region constitutes a vast reservoir of protein that could "feed the world," but direct consumption of twilight zone fish is unlikely. Instead, they will likely be used to produce fish meal and fish oil for aquaculture and livestock feed or nutraceuticals and cosmetics.




**The traditional division of the layers of the ocean agreed upon by marine scientists** defines the upper boundary of the mesopelagic (the ocean's twilight zone) as the depth at which the penetration of sunlight is insufficient for marine algae to carry out photosynthesis. On average, this boundary occurs at 200 meters, but its position can vary depending on the productivity of the surface waters (i.e., it is deeper in unproductive waters with fewer microalgae). The lower boundary of the twilight zone is located, on average, at 1,000 meters, below which the density of deep-ocean animals decreases significantly. Illustration by Mark Holmes, WHOI Creative




## DIEL VERTICAL MIGRATION

The diel vertical migration (DVM) involves an unknown proportion of twilight zone animals swimming to the surface to feed and back down again every 24 hours, as the depth of the sunlit layer of the oceans changes. New technology such as **Deep-See** (**1**) will help measure the biomass of organisms acoustically or, in the case of **Mesobot** (**2**), to track individual organisms autonomously throughout the DVM.

Illustration by Eric S. Taylor, WHOI Creative

# WHAT IS THE Ecological Importance OF THE TWILIGHT ZONE?

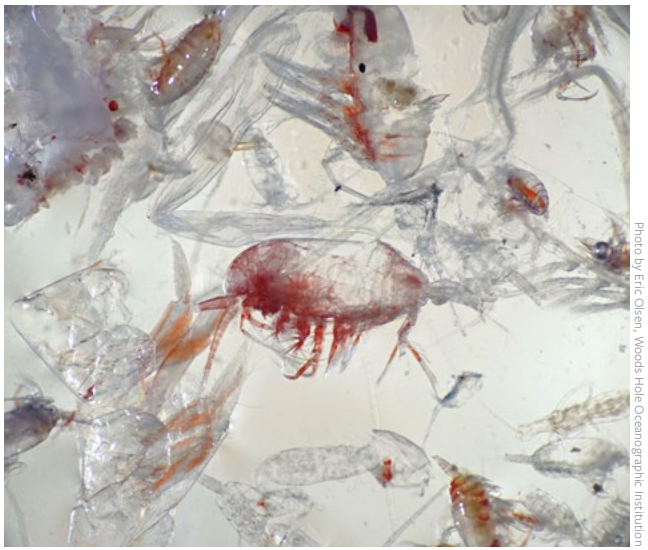


Photo by Eric Olsen, Woods Hole Oceanographic Institution

**IT IS A CRUCIAL PART OF EARTH'S CLIMATE SYSTEM**

Plankton near the surface use sunlight and carbon dioxide to produce energy and grow. As organisms eat phytoplankton, and are consumed in turn, they produce organic carbon particles that descend into the deep ocean, thereby sequestering a significant fraction of carbon emissions each year.

**IT PROVIDES CRITICAL LINKS TO SURFACE SPECIES AND ECOSYSTEMS**

Many apex predators, including commercially important finfish, such as swordfish; protected mammals, such as northern elephant seals; and seabirds, such as king penguins, rely on twilight zone organisms for food.

**IT IS HOME TO THE LARGEST ANIMAL MIGRATION ON EARTH**

The diel vertical migration of zooplankton and other organisms that occurs every day around the world leads to the consumption of phytoplankton in surface waters, a vital step in the marine food web and a critical part of carbon sequestration in the ocean.

**A swordfish** (*Xiphias gladius*) swims near the ocean's surface with a newly applied satellite tag (visible halfway down its back). Technology such as this will help scientists better understand how these apex predators use the twilight zone to feed in order to better manage economically important fisheries and other marine resources. Photo by Steve Dougherty Photography

# Why Should We Care
## ABOUT THE TWILIGHT ZONE?

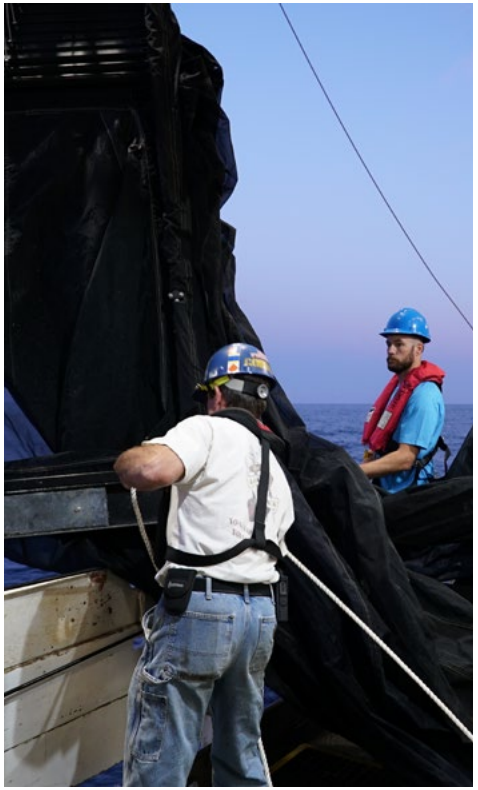


Photo by Eric Olsen, Woods Hole Oceanographic Institution

**IT IS A NATURAL CAPITAL ASSET**

The twilight zone can be seen as a stock of differentiated natural capital that is subject to capital gains or losses and that yields flows of benefits (dividends) known as "ecosystem services."

**THE VALUE OF NATURAL CAPITAL DEPENDS UPON ECOSYSTEM SERVICES**

In any future period, the asset value of the twilight zone's natural capital is the sum of the discounted value of service flows and any capital gains. To express this value in today's monetary units, the discount factor should be adjusted up or down by investments into or drawdowns from the system (cf., Fenichel et al., 2018).

**WE SHOULD MAKE DECISIONS BASED ON ASSESSED TRADE-OFFS**

Understanding and quantifying the benefits associated with twilight zone ecosystem services is critical to characterizing the effects of any activities, such as commercial fishery harvests or greenhouse gas emissions, that might affect those benefits.

**SUSTAINABLE DEVELOPMENT OF THE TWILIGHT ZONE IS A POLICY GOAL**

Along with manufactured, human, and other natural capital, changes in the value of the natural capital of the twilight zone can help map the world's progress toward sustainable development.

**THE TWILIGHT ZONE WILL PLAY A ROLE IN MEETING SDGs**

The twilight zone will play a role in meeting the UN's sustainable development goals (SDGs): In addition to assessing possible trade-offs, the valuation of ecosystem services from the twilight zone should guide our understanding of whether we can safely use marine resources to **help end world hunger (SDG 2)**, whether the ocean will continue to help **mitigate the effects of greenhouse gas emissions (SDG 13)**, and whether **human activities that affect ocean life are ultimately sustainable (SDG 14)**.

# Ecosystem Services

Ecosystem services are the many direct and indirect contributions that nature makes to human well-being, survival, and quality of life. They provide a way to quantify the value of ecosystem components, helping to define what we mean by "sustainable use."

Pteropods, *Diacria dispinosa*. Photo by Paul Caiger, Woods Hole Oceanographic Institution

# Why Think ABOUT ECOSYSTEM SERVICES?


Photo by Jayne Doucette, Woods Hole Oceanographic Institution

Human activities such as overfishing, greenhouse gas emissions, pollution, and submarine noise can adversely affect the natural functioning of marine ecosystems. These effects can be seen as "opportunity costs"—the forfeiting of potential gains when one course of action is chosen over others.

Ecosystem services provide a way to assess these costs in physical or economic terms. From this, we can begin to determine whether the ocean is being used in a way that permits current and future generations to benefit from its continued use.

# How Do ECOSYSTEM SERVICES Interact?

Twilight zone fish, mollusks, crustaceans, and other animals reside in the mesopelagic during the day. This aggregation of marine life can be sensed using acoustic signals, which provide a general picture of a deep scattering layer of organisms. As the sun sets, and darkness descends on the ocean, the upper boundary of the twilight zone ascends, followed by many of the mesopelagic zooplankton and fish.

**REGULATING SERVICE**

Zooplankton feed on phytoplankton, and twilight zone fish feed on zooplankton. Migrating twilight zone fish help move carbon down to the deep ocean, **where it can be sequestered for long periods of time**.

**CULTURAL SERVICES**

Scientific study, education, and art all contribute to the development and expansion of demand for the twilight zone as an **ecological system worthy of appreciation in its own right**, providing a flow of passive nonmarket benefits. Scientific study, in particular, helps define the spatial and temporal scales of the other services, and it is implemented through remote sensing by autonomous vehicles, probes, and towed instrument packages.

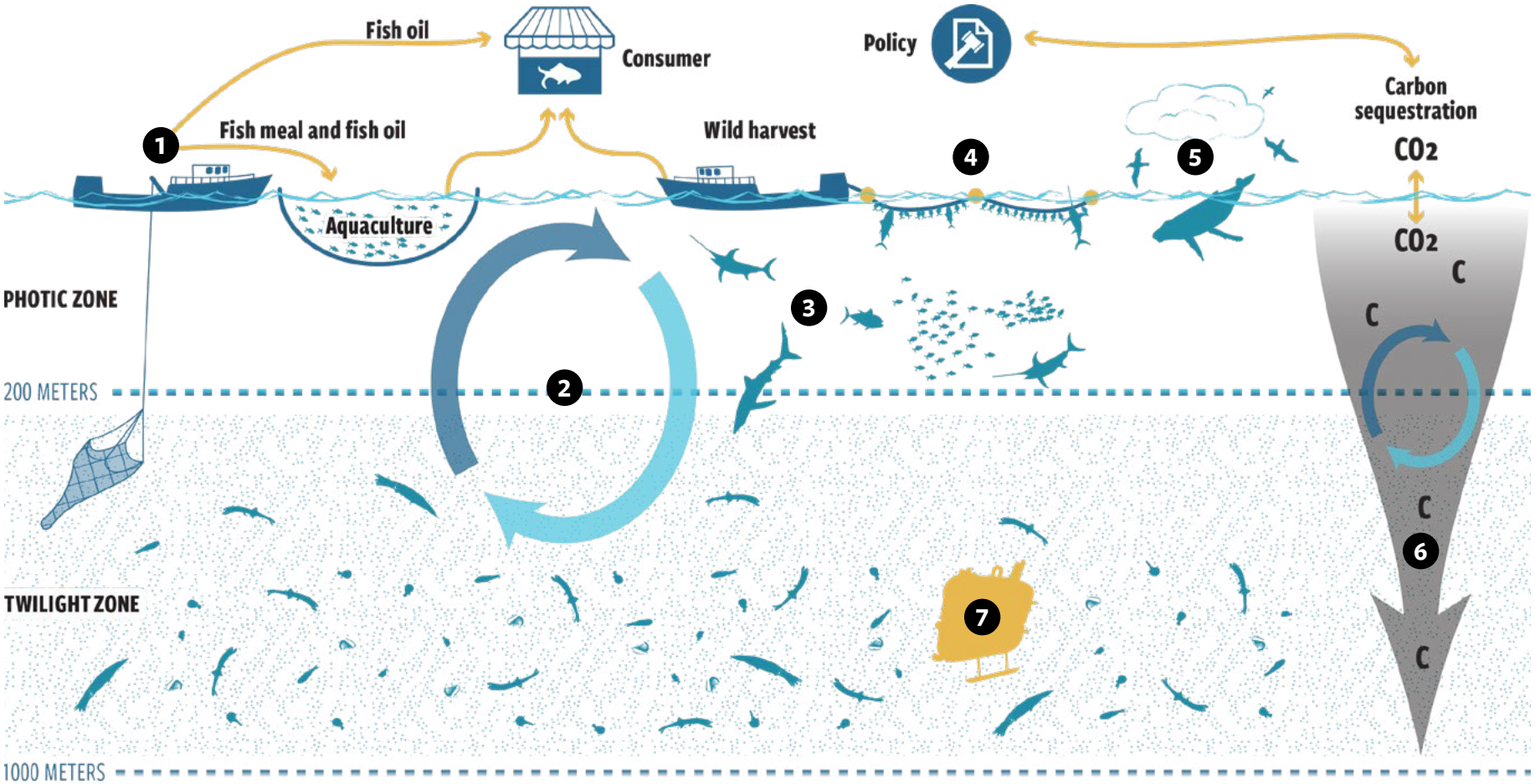
**SUPPORTING SERVICES**

Apex predators feed on twilight zone animals, and the predators are **harvested in capture fisheries and supplied to processors or to consumers directly**. Other apex predators include protected species of marine mammals, and seabirds, healthy populations of which are valued purely for their existence.

**PROVISIONING SERVICES**

Some twilight zone fish might be harvested, "reduced" (pressed for oil, then dried and ground into a flour), and sold into markets for **fish meal, fish oil, nutraceuticals, or cosmetics**. The bulk of fish meal and fish oil would be supplied to aquaculture or livestock producers. Some fish oil may be converted into liquids or capsules containing omega-3 fatty acids or added into processed foods for human consumption. Some DNA sequences collected from twilight zone animals or free-floating genetic materials may also result in new medicines or industrial products.

# Ecosystem Service Interactions




(1) **Provisioning Service:** Fish harvested from the mesopelagic or that rely on mesopelagic organisms are processed into fish meal for aquaculture operations or are turned into fish oil "nutraceuticals."

(2) **Supporting Service:** As mesopelagic animals migrate daily from the midwater to the surface to consume zooplankton, they form ecological linkages between distinct depth regimes in the ocean and help govern carbon sequestration in the ocean (6).

(3) **Supporting Service:** Many species feed on migrating mesopelagic animals, and some ecologically or economically important species, such as swordfish and sharks, make deep foraging dives.

(4) **Provisioning Service:** Wild harvest of apex predators and finfish, many of which rely on mesopelagic species for prey, accounts for nearly 80 percent of global fish capture.

(5) **Cultural Service:** Human appreciation of species such as marine mammals and seabirds or of a healthy marine ecosystem creates passive, nonmarket value made possible by the mesopelagic.

(6) **Regulating Service:** Migrating twilight zone fish help move carbon from the surface into the deep ocean, where it can be sequestered for long periods of time.

(7) **Cultural Service:** Scientific observation and experimentation, data collection, species and ecosystem modeling, and technology development driven by mesopelagic research create knowledge-based value.

Illustration by Natalie Renier, WHOI Creative

# Human Benefits

Twilight zone animals and ecosystem processes have direct and indirect impacts on humans and other planetary systems. An ecosystem services framework provides a way to classify and quantify these benefits to aid decision-making.

Lantern fish, *Lampadena luminosa*. Photo by Paul Caiger, Woods Hole Oceanographic Institution

# HOW DOES THE TWILIGHT ZONE Benefit Humans?

### REGULATING SERVICES

The ocean's biological carbon pump leads eventually to the **long-term sequestration of carbon in deep waters or on the seafloor**. While the net amount of carbon sequestered in this way is highly uncertain, estimates range between 2 and 6 billion metric tons from the twilight zone annually—with the lower estimate equivalent to twice the amount of carbon dioxide emitted by automobiles worldwide.

### CULTURAL SERVICES

Oceanographic research on the twilight zone advances human understanding of the ocean, especially in the face of climate change, which can lead to **improved decision-making and policy formation**. Education about the ocean also helps raise ocean literacy among the general public, leading to a **stronger conservation ethic and sense of environmental stewardship**.

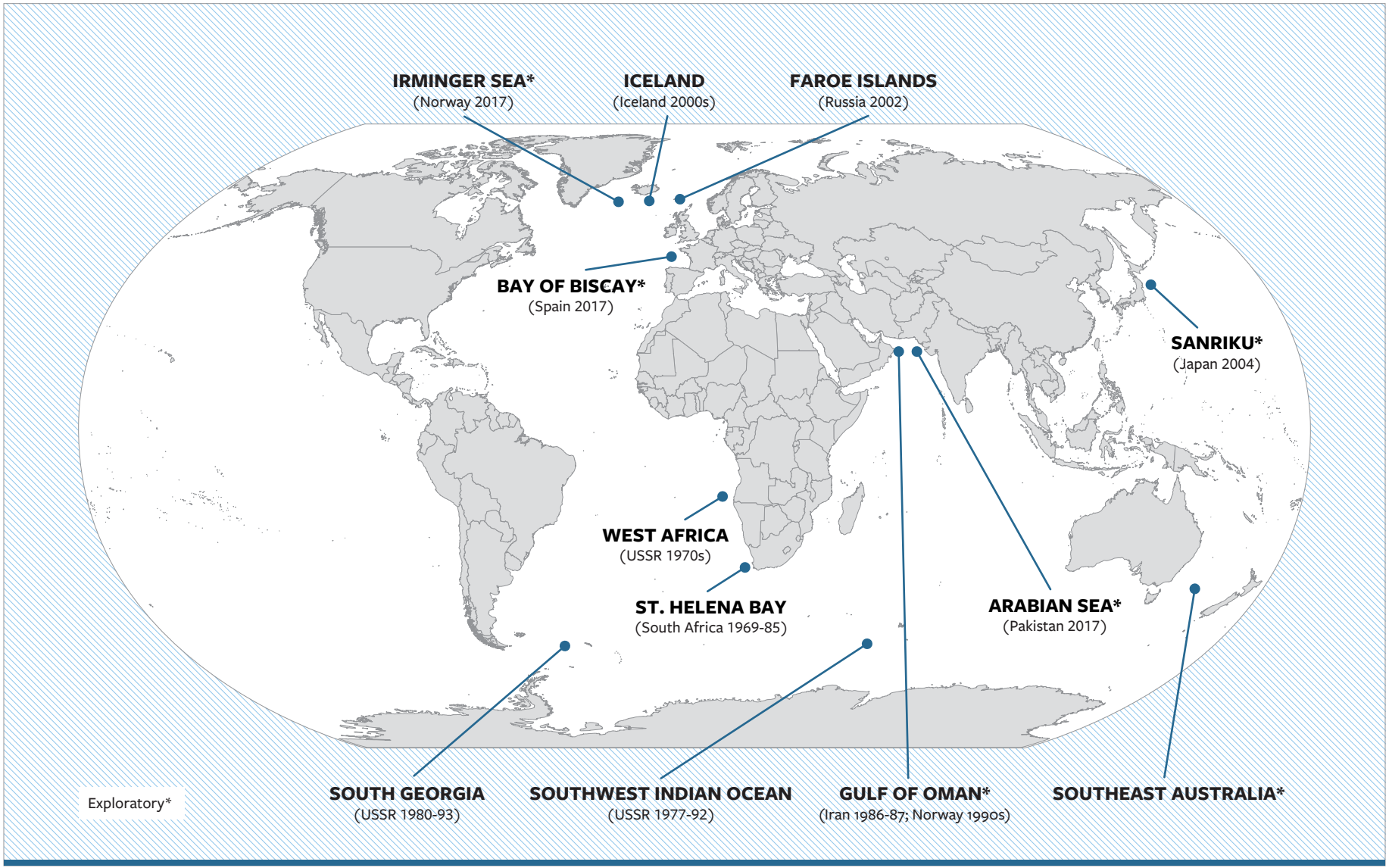
### SUPPORTING SERVICES

Fish and other fauna in the twilight zone are food for many surface fish that are harvested commercially. They are also food for whales, seals, penguins, and seabirds, which are **valued intrinsically**, as well as for their roles as **important components of marine ecosystems**.

### PROVISIONING SERVICES

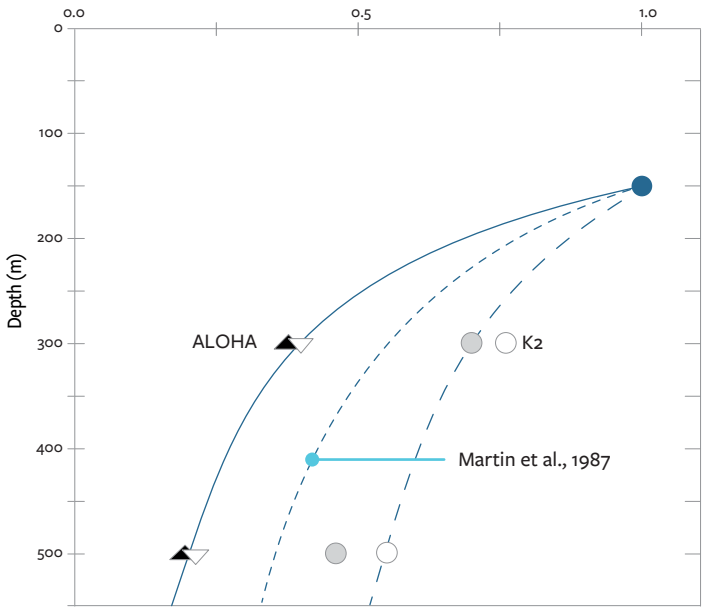
Twilight zone fish have been harvested sporadically in the past, primarily to meet demands for fish meal and fish oil to feed livestock and farmed fish, but currently there is little commercial value to the harvesting of twilight zone fish because of the low value in those end uses relative to the high costs of fishing. This could change as aquaculture continues to grow as a means to **provide food security for large numbers of people worldwide** and technical innovations reduce the costs of twilight zone fish harvests.

# Location of Commercial and Exploratory Mesopelagic Fish Harvests



# Regulating Services

**NORMALIZED PARTICULATE ORGANIC CARBON FLUX**




**A version of the "Martin curve,"** named after John Martin, a marine scientist who headed the Moss Marine Laboratory in California, models the decay in the concentration of particulate organic carbon (POC) with depth in the ocean. It can be used to help understand the extent to which carbon may be sequestered in the deep ocean (below 200 meters in depth, including the twilight zone) and seabed (Buesseler et al., 2007).

> Regulating ecosystem services are "benefits obtained from the regulation of ecosystem processes, including, for example, the regulation of climate, water, and some human diseases" (MA, 2005).

## CLIMATE SYSTEM BEYOND VIEW

The ocean regulates the climate by absorbing about one-quarter of global carbon emissions each year. Approximately 1 percent of the total particulate organic carbon produced by phytoplankton at the surface sinks to the ocean floor where it is considered to be sequestered permanently.

Estimates of the amount of carbon sequestered through the twilight zone range from **2 to 6 billion metric tons per year**. At a conservative carbon price of $35 to $45 per ton of carbon dioxide, this regulating service can be valued at **$300 to $900 billion each year**. A social rate of time preference—a measure of society's willingness to postpone private consumption now in order to consume later—of 3 percent would place the asset value of this service at **$10 to $30 trillion**.

Commercial harvests of twilight zone fish might inhibit the functions of this biological carbon pump in some locations and during some seasons, but not enough is known about the carbon pump globally or regionally to make this determination. In addition, increased greenhouse gas emissions could lead to thermal stratification and declining pH (acidification) that might limit the transport of carbon from the atmosphere to long-term sequestration.

# Cultural Services

Fangtooth, *Anoplogaster cornuta*. Photo by Eric Olsen, Woods Hole Oceanographic Institution

Cultural ecosystem services are "non-material benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experience, including, e.g., knowledge systems, social relations, and aesthetic values" (MA, 2005).

## A CULTURE OF DISCOVERY AND KNOWLEDGE

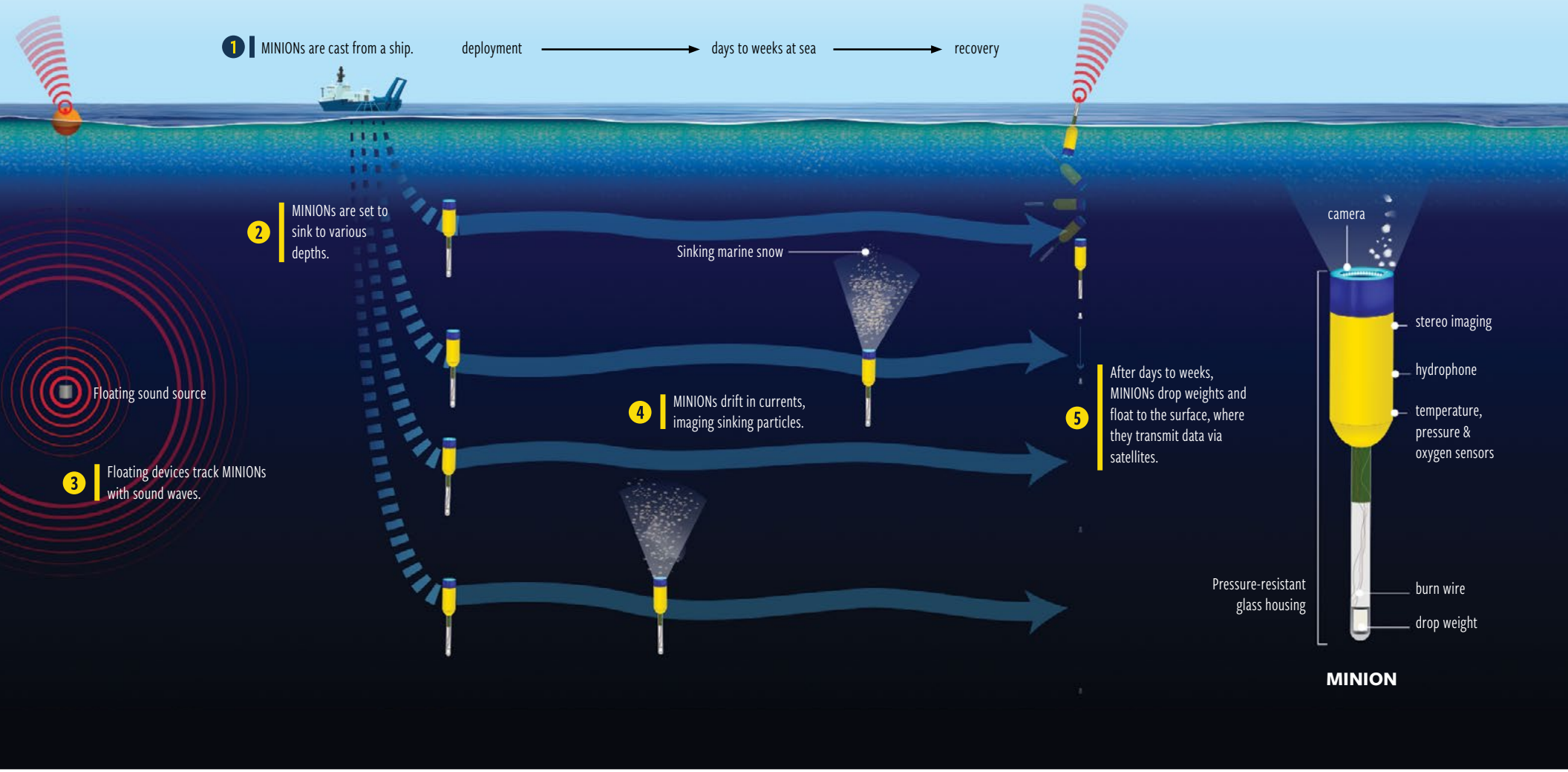
Without the biological carbon pump, atmospheric carbon dioxide levels could be as much as **200 ppm higher than today**. In addition, depending on the emission scenario used, rate of sequestration in the North Atlantic could drop by between 27 and 43 percent by the end of the century, (Barange et al., 2017). The value of this loss could amount to between **$170 billion and $3 trillion in mitigation costs and $23 to $401 billion in adaptation costs by the end of the century**.

Because estimates for the amount of carbon sequestered in the ocean vary widely, the economic value of oceanographic research undertaken to reduce this range could be on the order of **hundreds of billions of dollars** (Jin et al., 2019). With a more accurate estimate of ocean carbon sequestration, society could make better-informed decisions regarding the mitigation of carbon dioxide and other greenhouse gas emissions.

# Casting MINIONs upon the Waters

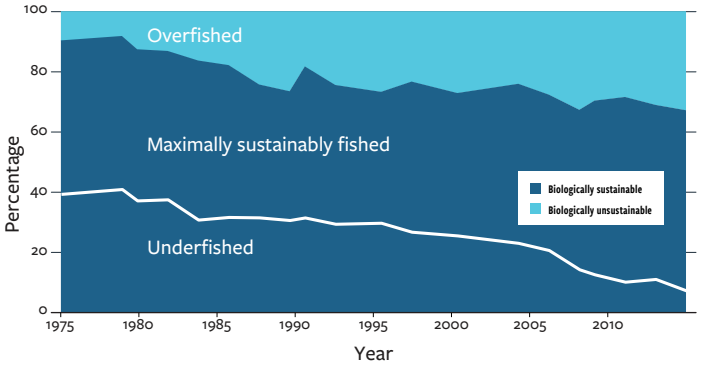
Scientists hope to release a fleet of these relatively inexpensive instruments in the ocean to reveal sinking marine particles that help regulate Earth's climate.

Illustration by Natalie Renier, WHOI Creative



# Supporting Services

**PROPORTION OF FISH STOCKS WITHIN BIOLOGICALLY SUSTAINABLE LEVELS**




**The proportion of the world's capture-fish stocks within biologically sustainable levels has been declining since the 1970s**. This measure is one of the key indicators of the UN's Sustainable Development Goals. Its decline implies that the world's capture fisheries are increasingly overfished, and new economic value has been dissipated on the order of tens of billions of dollars a year (FAO, 2018).

> Supporting services are "those environmental features and ecological elements that contribute to (or support) provisioning, regulating, and cultural ecosystem services" (MA, 2005).

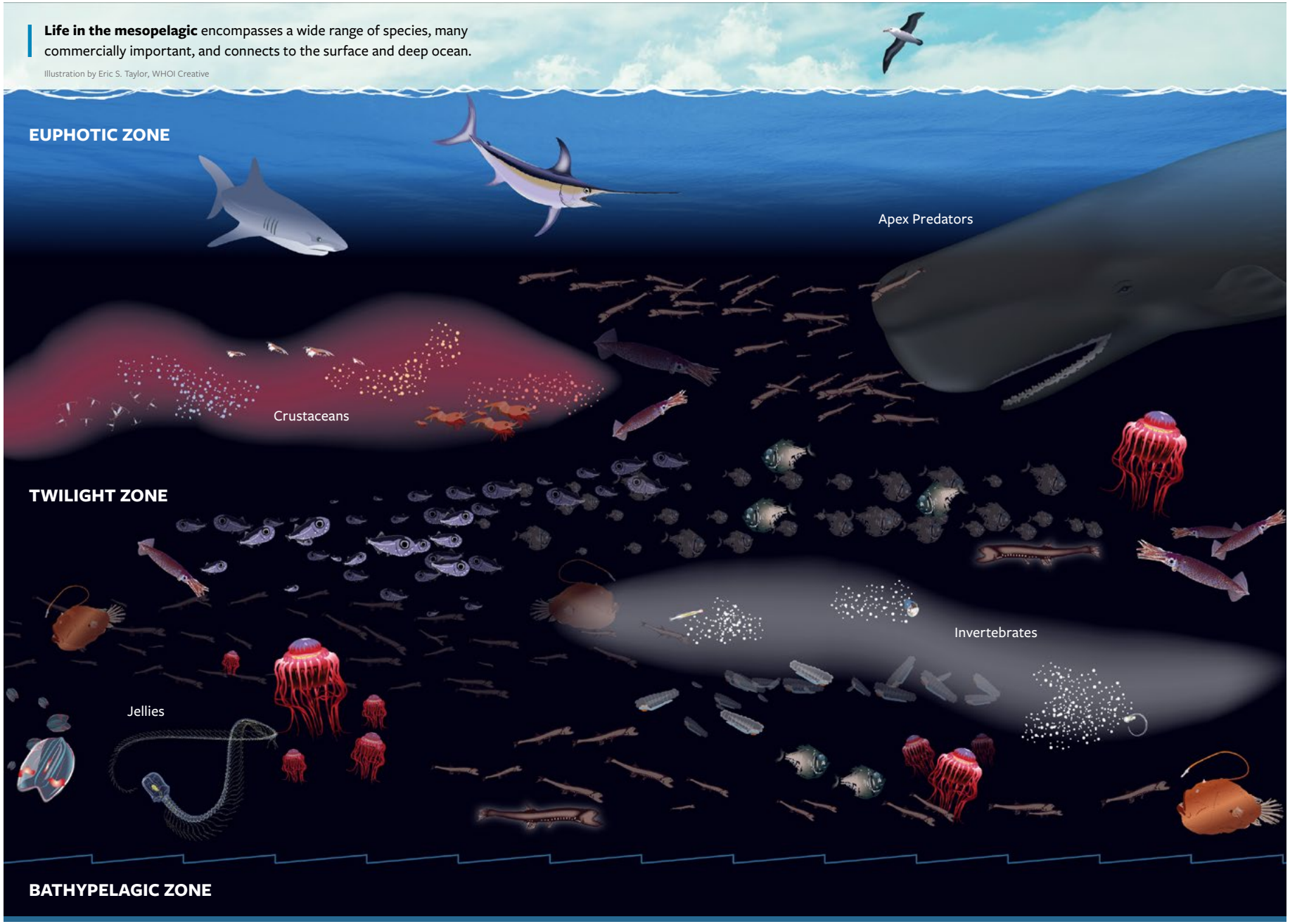
### AN OPEN QUESTION

By definition, supporting services are not used directly by humans, so assigning economic values to these services can be problematic. In the case of twilight zone organisms, these services must be imputed from net values, if they are realized, arising from the commercial harvest of surface water predators, or else from the passive (nonuse) values arising from their importance to a healthy ecosystem.

But most people don't know that these organisms or the environmental conditions that support them exist, so the latter are likely to be very small. In addition, the dissipation of net values due to the overfishing of surface predators prevents an adequate assessment of the value of the supporting role of twilight zone organisms.

**Life in the mesopelagic** encompasses a wide range of species, many commercially important, and connects to the surface and deep ocean.

Illustration by Eric S. Taylor, WHOI Creative



# Provisioning Services

## PROTEIN SOURCES

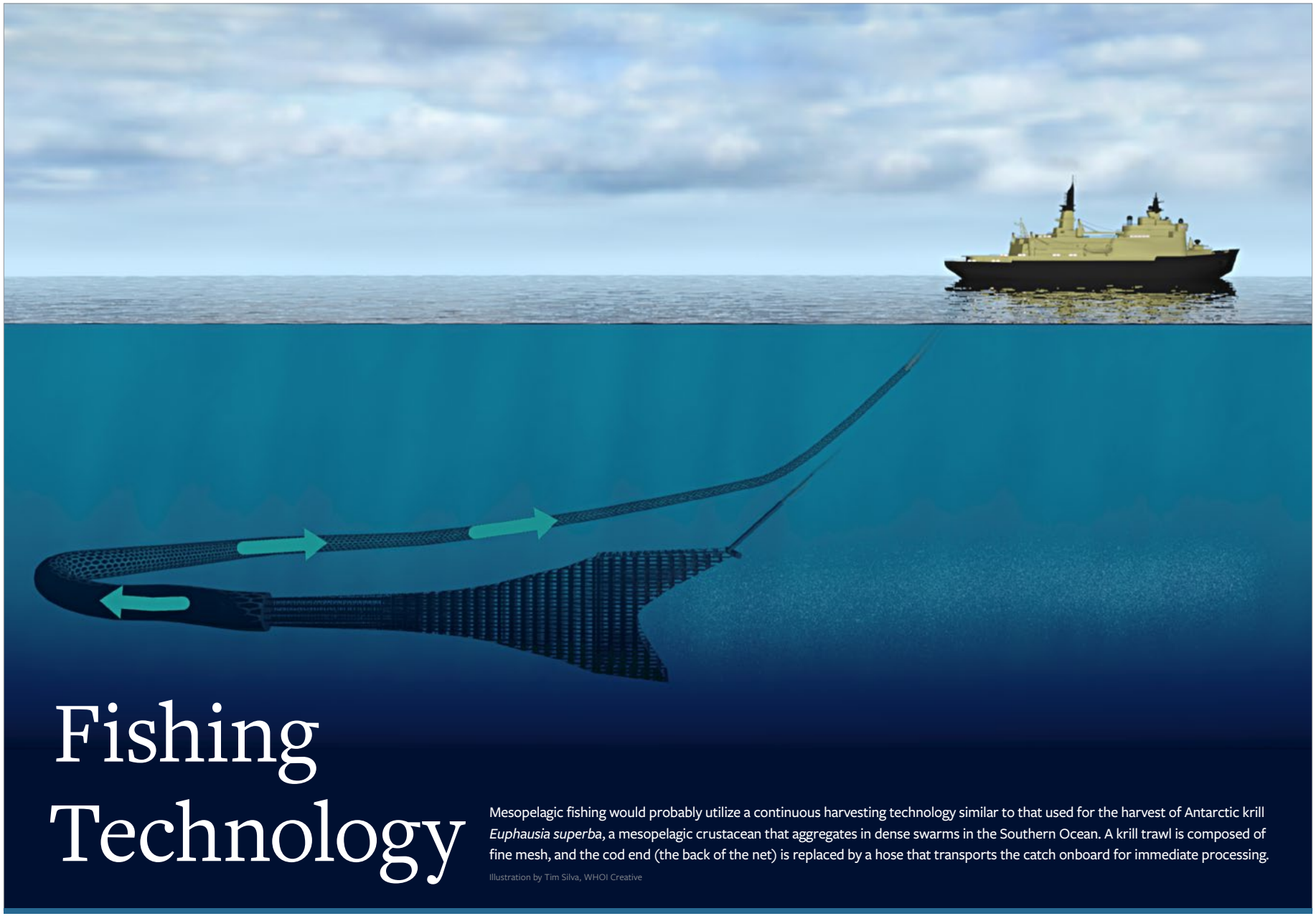
Photo courtesy of NOAA

> Provisioning ecosystem services are "products obtained from ecosystems, including: food, genetic resources, biochemicals, natural medicines, pharmaceuticals, or biological materials that serve as sources of energy" (MA, 2005).

### SIGHTS ARE SET ON THE TWILIGHT ZONE

Early efforts to exploit the twilight zone focused on fishing for lanternfish (myctophids), but most of these were abandoned due to their high cost and relatively low return. More recent efforts, active and planned, focus on **converting protein from the twilight zone into feed for farmed fish and livestock or extracting oils for nutraceuticals and waxes for cosmetics**.

The impacts of these extractive activities, particularly overexploitation of the twilight zone, are not well understood and are expected to grow as technological change inevitably leads to cost reductions in fishing. In addition, **aquaculture production is expected to increase by 37 percent from 2016 to 2030** (FAO, 2018), potentially expanding demand for fish meal. From 2010 to 2030, prices for fish meal are expected to rise by 90 percent and fish oil by 70 percent in real terms (World Bank, 2013).



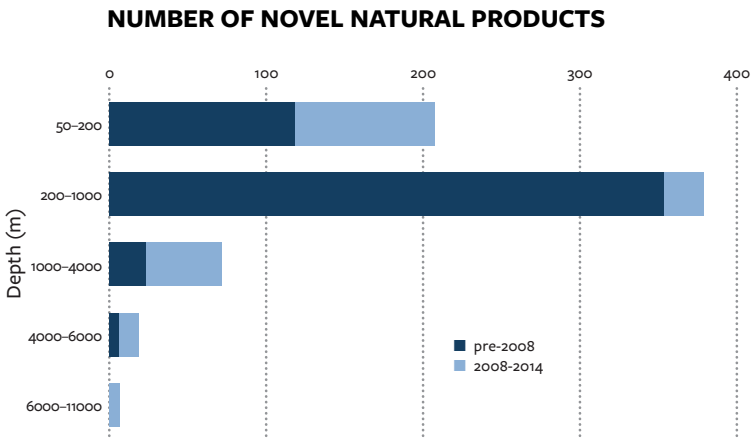
# Fishing Technology

Mesopelagic fishing would probably utilize a continuous harvesting technology similar to that used for the harvest of Antarctic krill *Euphausia superba*, a mesopelagic crustacean that aggregates in dense swarms in the Southern Ocean. A krill trawl is composed of fine mesh, and the cod end (the back of the net) is replaced by a hose that transports the catch onboard for immediate processing.

Illustration by Tim Silva, WHOI Creative

# Provisioning Services

## GENETIC RESOURCES




**Scientific research on marine genetic resources** (MGRs)—one type of provisioning service—is nascent but growing and is a major motivation for ongoing BBNJ deliberations at the UN. This graph depicts the density of novel natural products by depth, showing the relative importance of MGRs from the twilight zone (Harden-Davies, 2017).

The twilight zone contains an unknown diversity of genetic resources that are only beginning to be described but that are receiving increasing interest from commercial entities. Because much of the twilight zone exists beyond the jurisdiction of any nation, use and ownership of these resources are almost entirely unregulated.

### PUTTING THE TWILIGHT ZONE ON THE AGENDA

In September 2018, an intergovernmental conference began work on an international, legally binding instrument under the United Nations Convention on the Law of the Sea on the conservation and sustainable use of the marine biological diversity of areas beyond national jurisdiction—the BBNJ.

A central issue of negotiations concerns the distribution of potential benefits from the discovery and commercialization of marine genetic resources. Scientific research on deep-sea genetic resources is nascent but growing, and initial research findings show that the density of novel natural products is highest between 200 and 1,000 meters—the generally accepted depth range of the twilight zone.

# Challenges & Opportunities

The state of knowledge about the twilight zone remains in flux but is growing, and the combined efforts of researchers worldwide are helping fuel increasing calls for its inclusion in key international agreements aimed at ensuring the long-term sustainable management of its resources.


Photo by Paul Caiger, Woods Hole Oceanographic Institution

# Global Challenges
## AND UNANSWERED QUESTIONS

Photo by Allison Albritton, NOAA

### FOOD SECURITY

World population is expected to grow to 11 billion by 2100, but the continued growth of aquaculture depends on supplies of fish meal and fish oils.

**Could the harvest of twilight zone fish be used to sustainably feed the world by helping supply demand for feedstocks?**

### CLIMATE CHANGE

Worrisome trends already are being seen as a result of continued greenhouse gas emissions, including northward shifts in the distribution of fishery species (Cheung, 2013) and a 30 percent increase in ocean acidity since the beginning of the Industrial Revolution (Walsh et al., 2014).

**How will twilight zone ecosystems and the services they provide respond to such changes?**

### BIODIVERSITY

The conservation and sustainable use of marine biodiversity, which enables ecosystems to withstand environmental changes and human activities such as overfishing and climate change, has now become a part of discussions to extend the UN Convention on the Law of the Sea, but the twilight zone has not been an explicit part of these negotiations.

**Will the twilight zone be recognized as fundamental to the design and implementation of area-based management tools and assessments of environmental impacts?**

### CONSERVATION

Public awareness of the twilight zone is minimal, at best, but it might be leveraged to increase the call for the conservation of mesopelagic resources where warranted, leading to a more sustainable use of ocean resources in general.

**Can public perceptions be raised quickly and effectively in a way that supports policy formation and decision-making?**

# International Institutions

## AND CONNECTIONS

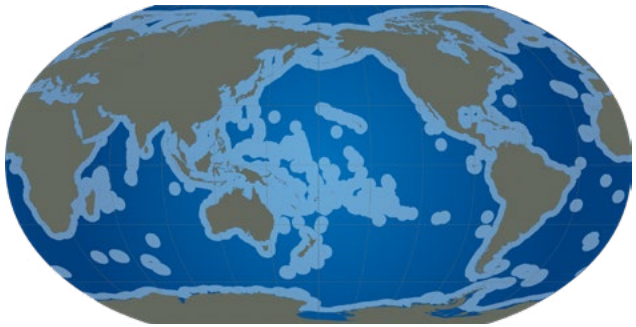
**Planning for the Decade of Ocean Science for Sustainable Development.**
Photo by Joel Llopiz, Woods Hole Oceanographic Institution

Article 192 of the third UN Convention on the Law of the Sea (UNCLOS III) directs signatories to protect and preserve the marine environment. This obligation is coupled with a duty described in Article 117 for states also to conserve the living resources of the high seas.

UNCLOS III was extended by the Straddling Fish Stocks Agreement and, potentially, by negotiations over the conservation and sustainable use of marine biological diversity in areas beyond national jurisdiction (the BBNJ), which would make the convention more consistent with the 1994 Convention on Biological Diversity. Concerns remain, however, that a mesopelagic fishery on the high seas other than the Southern Ocean would be unregulated and unsustainable.

Motivated by the UN Conference on Sustainable Development in Johannesburg in 2002, scientists and practitioners laid out the structure of a system now known as the Millennium Ecosystem Assessment to track the flows of environmental services. This forms the basis for establishing the value of natural capital, including such things as mesopelagic fish stocks and the ocean's biological carbon pump. With these and other tools, international policymakers, national governments, businesses, and civil society will be able to chart progress toward goals laid out in the 2030 Agenda for Sustainable Development.

# FOCUS ON Biodiversity Beyond National Jurisdictions (BBNJ)



**Much of the twilight zone exists outside the exclusive economic zones** (EEZs) of the world's nations, shown in light blue. These regions of the high seas, also known as areas beyond national jurisdiction (ABNJ), are governed by a patchwork of international bodies and treaties that manage primarily surface ocean resources and human activity.

For an international legally binding instrument to lead to sustainable development of the high seas, negotiations must take into account the ocean's vertical dimension, especially the twilight zone, and the ecosystem services it provides on the surface and seafloor.

The implementation of the BBNJ framework, which is being designed to contribute to the conservation of marine biodiversity throughout the ocean, can benefit significantly from scientific research in the twilight zone in many ways.

- The rich diversity of biota in the twilight zone implies that it could be one of the most productive reservoirs of marine genetic resources (MGRs) in the global ocean. A deeper understanding of MGRs is critical for **characterizing the twilight zone's biological diversity and its essential ecological linkages and processes**.
- Known ecological linkages suggest that twilight zone organisms provide key support for apex predators in the surface oceans. Consequently, the design of area-based management tools, including marine protected areas, **must consider the central role of the twilight zone to maximize their effectiveness**.
- The movements of twilight zone organisms make up an important component of the ocean's biological pump, actively affecting the movement of carbon from the atmosphere to surface waters to the ocean floor. This vertical dimension **should be incorporated into environmental impact assessments**.
- State-of-the-art science and engineering will lead to as-yet-unimagined breakthroughs in our understanding of the twilight zone and the services it provides. Research programs are actively seeking opportunities to engage with scientists and students to **build capacity and transfer skills and knowledge worldwide and through generations**.

# Scientific Uncertainties
## AND OCEANOGRAPHIC RESEARCH NEEDS

Photo by Eric Olsen, Woods Hole Oceanographic Institution

Narrowing the uncertainties associated with current understanding of the twilight zone will require fundamental research across a range of questions:

- What is the distribution of twilight zone **biomass and biodiversity**?
- How do **food webs** link within the twilight zone and with other regions of the ocean?
- What are the **life histories and individual behaviors** of twilight zone animals?
- What roles do the twilight zone and its inhabitants play in the **global carbon cycle and in Earth's climate**?

Addressing these questions will require new leaps in technology to explore and map the twilight zone that leverage low-cost, pervasive, and autonomous platforms, such as MINIONs; that take advantage of developments in genetic and genomic analysis, such as environmental DNA; and that find new ways of applying and improving proven techniques, such as acoustic sensing and imaging (WHOI, 2018).

Ensuring that new data and insights reach critical stakeholders is an important link in the chain of knowledge being built about the twilight zone. Scientists, policymakers, the general public, and elected leaders all need to have access to the most up-to-date information about this crucial part of our planetary system.

# Emergent Scientific Efforts

Scientific efforts to study the importance of the twilight zone to ecosystems and planetary processes are growing. These range from understanding the biological significance and connectivity of the region to its role in Earth's climate system. They are also increasing in their collaborative reach to form the foundation of a maturing scientific field of study with the potential to **improve our fundamental understanding of the planet and its ability to sustain human society**. This kind of collective endeavor could serve as a model for international collaboration in marine science, such as that expected to be promoted through the upcoming UN Decade of Ocean Science for Sustainable Development, 2021-2030. These are a few of the many existing and emerging scientific efforts to better understand the twilight zone worldwide.

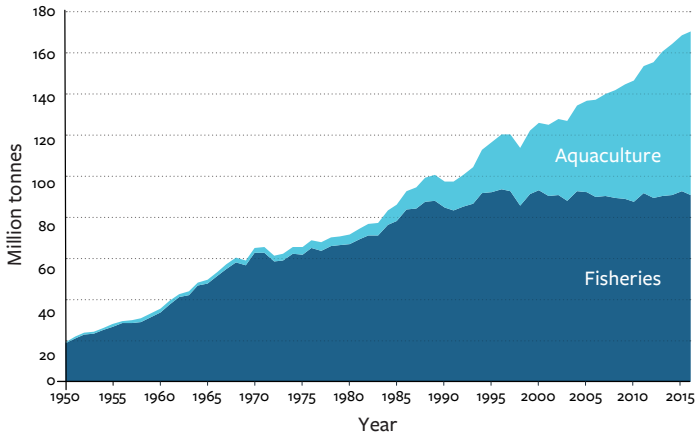
- **Controls over Ocean Mesopelagic Interior Carbon Storage (COMICS)**
  UK, 2017-2021
- **EXport Processes in the Ocean from Remote Sensing (EXPORTS)**
  US, 2017-2021
- **Ocean Carbon and Biogeochemistry (OCB)**
  US, 2006 onward
- **Carbon Uptake and Seasonal Traits in Antarctic Remineralisation Depth (CUSTARD)**
  UK, 2018-2022
- **Gauging ocean Organic Carbon fluxes using Autonomous Robotic Technologies (GOCART)**
  UK, 2017-2022
- **Ecologically and Economically Sustainable Mesopelagic Fisheries (MEESO)**
  EU, 2019-2023
- **Sustainable Management of Mesopelagic Resources (SUMMER)**
  EU, 2019-2023
- **North Atlantic Aerosols and Marine Ecosystem Studies (NAAMES)**
  US, 2015-2020
- **Mesopelagic Southern Ocean Prey and Predators (MESOPP)**
  EU/UK/Australia, 2016-2019
- **Constraining organic carbon fluxes in an Eastern Boundary Upwelling system (FLUXES)**
  Spain, 2016-2018
- **Monterey Bay Aquarium and Research Institute (MBARI)**
  Midwater Ecology Group
  Zooplankton Biodiversity Group
- **Nova Southeastern University, Florida**
  Department of Marine and Environmental Sciences
- **University of Oslo**
  Department of Biosciences

### WHOI'S OCEAN TWILIGHT ZONE PROJECT

Researchers at Woods Hole Oceanographic Institution (WHOI) have embarked on a large-scale, comprehensive exploration designed to transform our understanding of the twilight zone, lay the groundwork for informed decision-making by regulatory organizations responsible for high seas, and capture the public's imagination to enhance ocean stewardship. The project comprises scientific discovery, technological innovation, and enhanced engagement with a wide range of stakeholders that includes scientific collaborators, the general public, and policy-makers worldwide. The team is backed by WHOI's renowned leadership and expertise in ocean exploration and research and has the knowledge, experience, and technical capabilities to confront this enormous global challenge and help conserve a crucial part of the ocean for future generations.

# Future Research Needs
## FOR ECOSYSTEM SERVICES

**GLOBAL PRODUCTION**




**With capture fishery production** (excluding aquatic mammals, crocodiles, alligators and caimans, and seaweeds and other aquatic plants) **relatively static since the late 1980s**, aquaculture has been responsible for the continuing impressive growth in the supply of fish for human consumption (FAO, 2018).

The value of twilight zone ecosystem services depends on the ever-shifting conditions of demand and supply. The demand for service benefits, such as the health benefits associated with fish oils, as well as increasing human populations, economic productivity, and ocean literacy may drive up the value of these services. On the supply side, new discoveries, scientific insights, and technological advances may reduce the costs of accessing and exploiting twilight zone services.

To ensure that twilight zone resources are used sustainably, it is critical that **conservation and management programs are established and updated based on a revised understanding of the characteristics of twilight zone services, changing human preferences and tastes, and technological developments**. Precautionary approaches to the harvesting of twilight zone fish also are called for, as these organisms provide foundational support to marine food webs and play a central role in the sequestration of carbon in the deep ocean.

Today, the most urgent risk to the twilight zone encompasses the potential effects of greenhouse gas emissions on the temperature, circulation, and pH of the ocean. These effects are known to occur, but require further study to understand how they might degrade the twilight zone and its fauna, thereby severely diminishing the economic value of its services.

# Summary


The twilight zone is a **fundamental part of the ocean ecosystem**, playing an important role in carbon sequestration and marine food webs, as well as the natural functions of many processes throughout the ocean.

An ecosystem service framework provides a way to organize our thinking about the twilight zone and to **better understand the benefits it provides**.

Ecosystem services provided by the twilight zone are **highly beneficial to humans**, but they occur largely out of sight.

We need to think carefully about **what we stand to gain or lose from future actions** that could affect twilight zone ecosystem services.

**Greater knowledge is essential** if we are going to move toward the goal of sustainable use of resources in the ocean and twilight zone.


**Silver hatchetfish**, *Sternoptyx diaphana*. Photo by Paul Caiger, Woods Hole Oceanographic Institution

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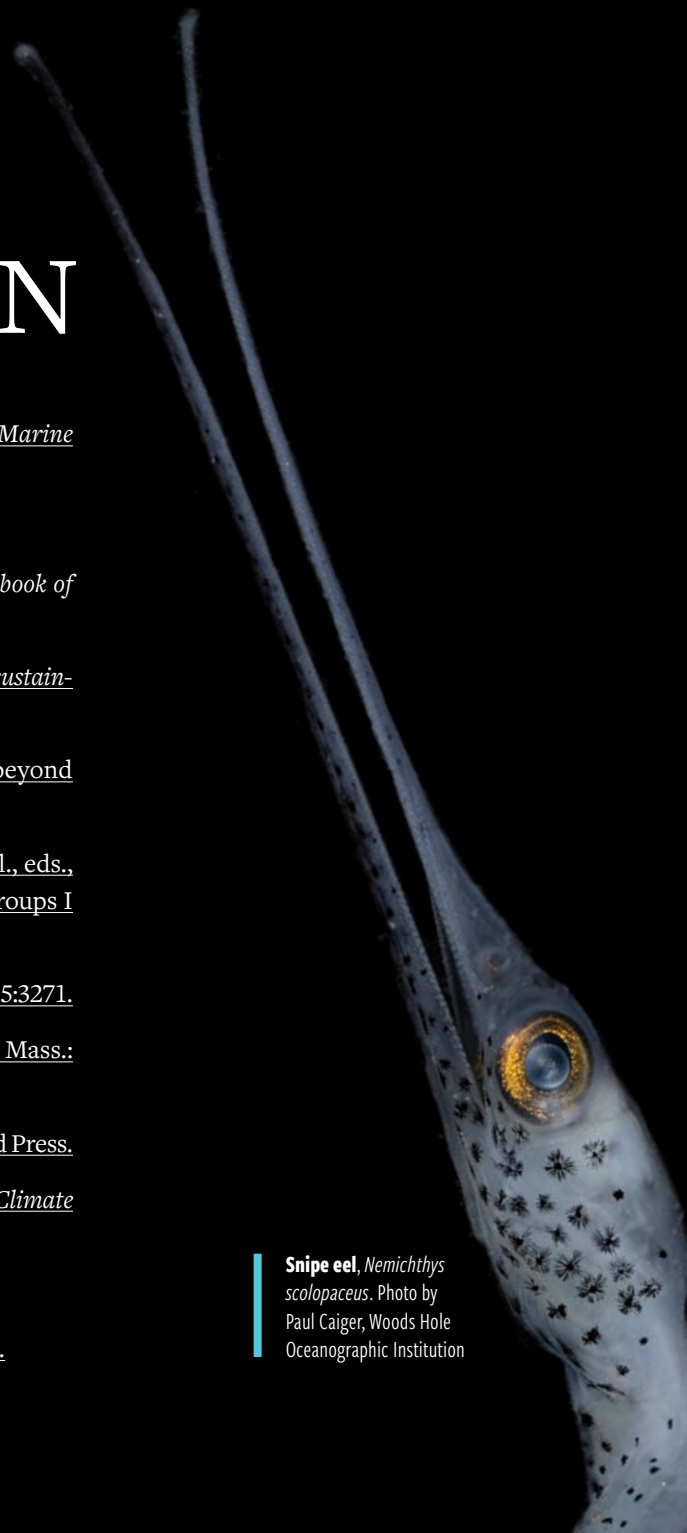
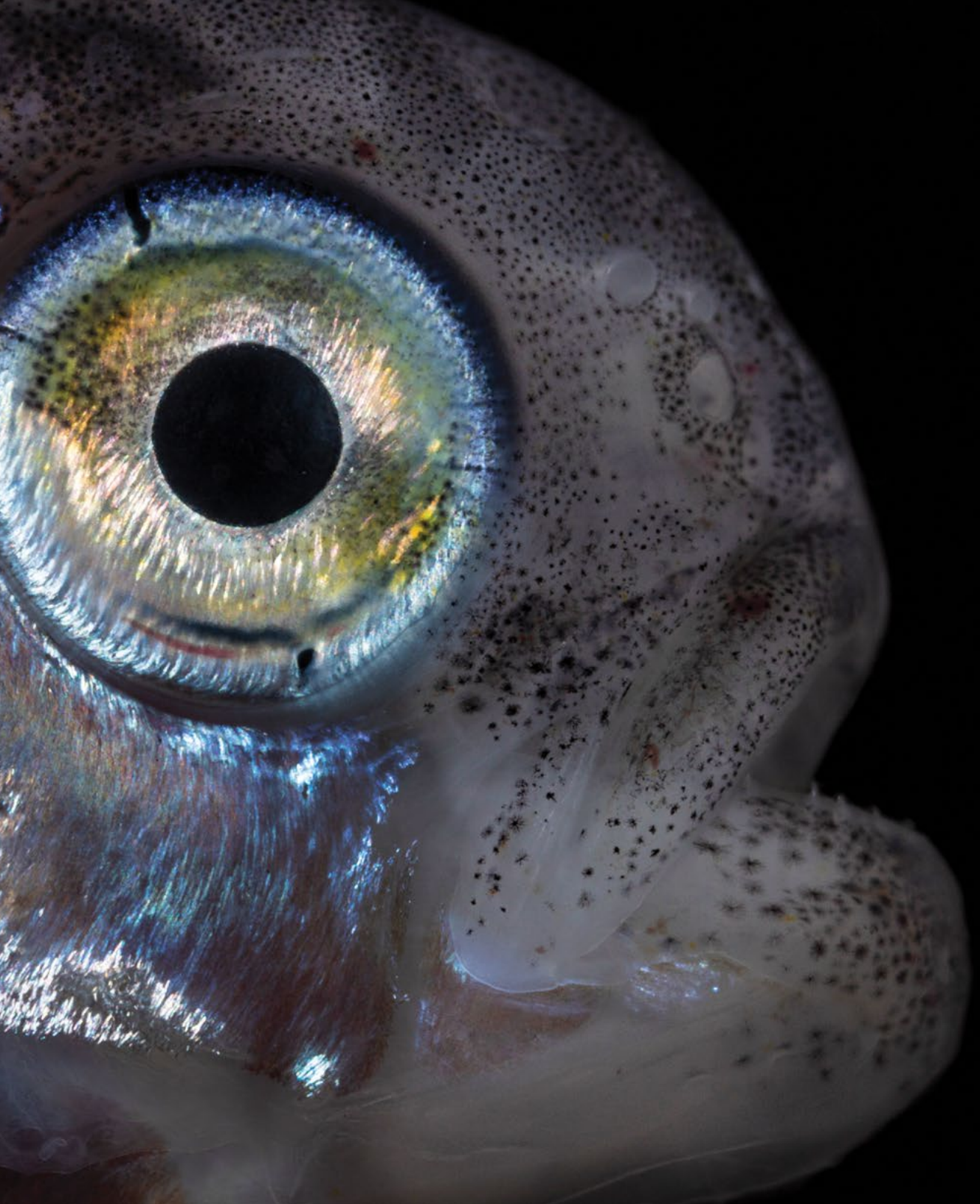


**Snipe eel**, *Nemichthys scolopaceus*. Photo by Paul Caiger, Woods Hole Oceanographic Institution



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**Bluefin driftfish**, *Psenes pellucidus*. Photo by Paul Caiger, Woods Hole Oceanographic Institution