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Life Linked to Ice

A guide to sea-ice-associated biodiversity in this time of rapid change

ARCTIC COUNCIL

Figure 1. Map of the Arctic marine environment including features and places referred to in this report
Based on a map designed by Hugo Ahlenius, UNEP/GRID-Arendal

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Front cover photo: Walrus emerging through sea ice, Greenland. Photo: Uri Golman

Back cover photo: Polar bears. Photo: Valerie Ucumari

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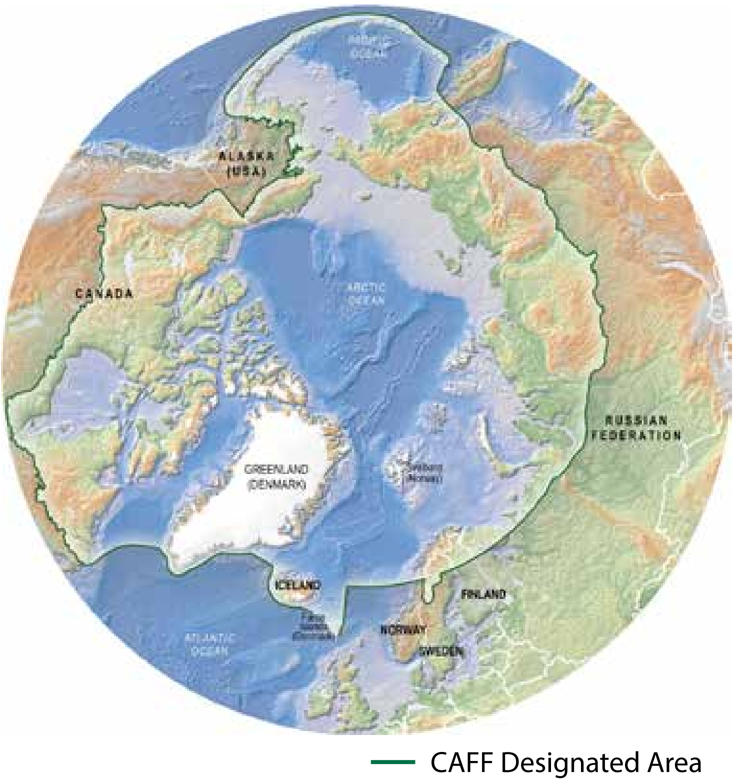

Conservation of Arctic Flora and Fauna

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Abstract

Life Linked to Ice examines the consequences for biodiversity of the dramatic changes occurring to sea ice. It was prepared by the Conservation of Arctic Flora and Fauna working group (CAFF), and both draws from and builds on Arctic Council assessments in order to present an overview of the state of knowledge about sea-ice-associated biodiversity. The report is intended as a briefing and reference document for policy makers.

Recent changes in Arctic sea ice cover, driven by rising air temperatures, have affected the timing of ice break-up in spring and freeze-up in autumn, as well as the extent and type of ice present in different areas at specific dates. Overall, multi-year ice is rapidly being replaced by first-year ice. The extent of ice is shrinking at all seasons, but especially in the summer. The Arctic Ocean is projected to be virtually ice-free in summer within 30 years, with multi-year ice persisting mainly between islands of the Canadian Arctic Archipelago and in the narrow straits between Canada and Greenland.

The most obvious negative impacts of rapid changes in sea ice are on the species that depend on ice as habitat. They include ice algae, ice amphipods, ringed seals and polar bears. The nature of long-term impacts on species that apparently depend partially on ice is less clear. Examples are the polar cod, the dominant fish of the high Arctic, which is strongly associated with ice but also found in open waters, and seabirds that take advantage of high concentrations of food in the productive ice edge zones for egg laying and chick rearing.

Impacts of reduced sea ice on humans are also mixed and uncertain. Declining sea ice threatens some Arctic human societies, notably coastal Indigenous Peoples who depend on ice for harvesting and travel and whose cultures and food security are centered on sea ice and its biodiversity. Reduction of sea ice also brings economic opportunities to people both within and beyond Arctic nations. However, new and expanded activities related to resource extraction, shipping, fisheries, and cruise-ship tourism carry substantive risks and downsides to Arctic marine flora and fauna.

But sea ice's association with Arctic biodiversity goes much further than the direct impacts from its loss. Timing, distribution and characteristics of ice cover define and drive the conditions underlying Arctic marine ecosystems, affecting seasonal cycles of light availability, water temperature, nutrients and the flow of energy among the plant and animal communities within and on the underside of ice, in open water and on the ocean bottom. Ecosystems are intricate relationships among these conditions and among the species themselves—and the extent and direction of change for much of Arctic marine biodiversity remains uncertain.

Primary production, the building block of food webs, increased by 20% from 1998 to 2009, driven by a 45-day increase in the open-ice period and a reduction in summer ice cover of 27%. But this increase in production is not uniform across the Arctic. Production has decreased or remained stable in some areas, likely related to changes in how nutrients are mixed through the water column, and there are recent signs of further decreases in production. The timing of algal blooms is changing, as are the species of algae dominating the blooms. It is not clear how this change in timing and in the base food source will influence production of invertebrates and the fish, birds and mammals that feed on them. Changes are likely to be quite different in the shallow seas than in the deep Arctic basins. The reduction in sea ice needs to be considered in the context of cumulative effects because it is also contributing to or interacting with other stressors, including development impacts, ocean acidification, and accumulation of persistent organic pollutants and mercury in food webs.

Changes in ocean conditions also mean that sub-Arctic species of algae, invertebrates, fish, mammals and birds are expanding northwards into the Arctic, while some Arctic-adapted species are losing habitat along the southern edges of their ranges. Relationships among species are changing, with new predation pressures and shifts in diets recorded for some animals.

To what extent Arctic species will adjust to these changes is uncertain. Changes are too rapid for evolutionary adaptation, so species with inborn capacity to adjust their physiology or behavior will fare better. Species with limited distributions, specialized feeding or breeding requirements, and/or high reliance on sea ice for part of their life cycle are particularly vulnerable.

In light of this rapid change and the uncertainty about cumulative effects on wildlife, informed and flexible approaches are required for Arctic ecosystem conservation and management and to ensure food security for those Arctic residents who harvest from the sea. More reliance will have to be placed on risk assessment and on adaptive, ecosystem-based management. Better monitoring is needed, at the right scale for decision-making, as is greater understanding of the functioning of marine systems. All types of knowledge should be utilized to track and understand change, despite the challenges in working across geographic scales and with science-based and traditional knowledge systems.

Four recommendations to Arctic Council and its participants emerged from this report:

1. Facilitate a move to more flexible, adaptable wildlife and habitat management and marine spatial planning approaches that respond effectively to rapid changes in Arctic biodiversity.
2. Identify measures for detecting early warnings of biodiversity change and triggering conservation actions.
3. Make more effective use of local and traditional knowledge in Arctic Council assessments and, more broadly, in ecological management.
4. Target resource managers when communicating research, monitoring and assessment findings.

Recommendations from recent Arctic Council assessments and expert group reports were reviewed. An annotated synthesis of relevant recommendations is presented, grouped under the following subjects: 1) climate change mitigation; 2) peoples and culture; 3) adaptation and management; 4) protected areas; 5) preventing damage to ecosystems; 6) fisheries in international waters; 7) harvest; 8) communication; and, 9) knowledge. There is a high degree of congruence in themes and content of the recommendations from these diverse reports. Taken as a whole, they provide comprehensive guidance on priorities and actions of particular relevance to conservation and management of sea-ice-associated ecosystems.

Ivory gulls and black-legged kittiwake, Svalbard. Photo: Martha De Jong Lantink

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1. Introduction

This report, prepared by the Conservation of Arctic Flora and Fauna working group (CAFF), is a response to recommendations, made through Arctic Council projects, to focus attention on the consequences for biodiversity of the dramatic changes occurring to sea ice. It is intended as a briefing and reference document for policy makers concerned with adaptive management and setting priorities for research, monitoring, and conservation actions in the context of changing sea ice.

Life Linked to Ice is not in itself an assessment, but draws from and builds on recent and concurrent Arctic Council assessments (see Appendix 1), especially the *Arctic Biodiversity Assessment* and *Snow, Water, Ice and Permafrost in the Arctic* (SWIPA) [1, 2]. The report presents an overview and discussion of the state of knowledge about sea-ice-associated biodiversity and goes more deeply into topics and issues that are of particular relevance to the conservation of Arctic flora and fauna.

Sources for the report also include related initiatives associated with Arctic Council, science agencies, and organizations concerned with Arctic ecosystems, augmented with examples from recent research and expert knowledge from contributors. Authors and contributors include participants at the two CAFF workshops on sea-ice-associated biodiversity held in Vancouver, Canada (2011) and in St. Petersburg, Russia (2012). The Looking ahead section draws on recommendations from these workshops [3], as well as on follow-up discussion with contributors to the report. Many workshop participants and contributors are scientists working through the Circumpolar Biodiversity Monitoring Program (CBMP) and its expert networks to plan and coordinate Arctic marine biodiversity monitoring.

Common species names are used throughout the report. Equivalent scientific names are listed in Appendix 2. Specialized terms are defined in the text and in the glossary in Appendix 3.

The importance of sea ice to Arctic biodiversity

Marine areas seasonally or permanently covered by ice are a very special habitat compared to all other marine regions. Ice provides a substrate on which a diversity of algae and invertebrates make their homes. The ice edges and open-water areas within the ice favor wind-driven mixing of the seawater that enhances local production.

In seasonally ice-covered regions, under-ice production may account for a substantial fraction of total annual carbon fixation [4, 5]. The concentration of food attracts ice-associated fish, birds, marine mammals, and human hunters, all of them interconnected through food webs.

Massive blooms of algae form each spring within the ice, under the ice, and in open water in the wake of the retreating ice edge. This moving feast fuels reproduction of many species, from copepods to seals [6, 7]. Crucially, for people, sea ice forms an excellent travel surface, with dog sleds and, in modern times, snowmobiles making long-distance movement in winter and spring possible, extending the range of hunters and allowing exchanges among communities [8].

Air-breathing vertebrates (birds and mammals) have two strategies to access the biological production in ice-covered water: they must either use holes or cracks in the ice or take advantage of the ice-free period. Although ice may reduce access to these underwater resources, it also provides a platform that is used for resting and reproduction, and one that is inaccessible to many land-based predators. These attributes have led to a variety of unique lifestyles that are not readily transferred to other environments. Consequently, many species adapted to living in or around sea ice are poorly equipped to live anywhere else. For these species, any reduction in the ice-covered areas of the polar seas is equivalent to a loss of habitat and a range reduction, with corresponding consequences for populations and, ultimately, for survival.

Humans, as part of the biodiversity of the Arctic marine environment, are affected by sea ice changes and by impacts of sea ice changes on animals they harvest. Many Arctic indigenous societies are sea-ice-dependent: they evolved around an environment dominated by sea ice and ice continues to be central to cultural and economic activities today.

This report takes a broad approach to sea-ice-associated biodiversity. Flora and fauna that depend on ice for survival are clearly central to the story, as their very existence as species may be at risk. Vulnerable species include the diverse flora and fauna that live in brine channels within the ice pack or graze on the underside of sea ice, as well as polar bears that travel, hunt and make their dens on the ice. Other species are closely adapted to living under ice or at its edge. They may yet survive in an Arctic with reduced ice, although perhaps in fewer numbers and with restricted ranges. The most common Arctic fish, the polar cod, is an example. Although it feeds under the ice and at the ice edge, it is also found in open waters.

But, even beyond the species closely associated with ice, sea ice controls or influences many of the fundamental processes that set environmental conditions and food web connections. Directly or indirectly, the massive changes in sea ice being experienced today are likely to affect all Arctic biota on top of, within and beneath the ice—and also in the open water and on the ocean floor.

The long-term view of sea ice in the Arctic

Sea ice has been present in variable amounts many times over Earth's history. In our current geological Era, the Cenozoic, which started 65 million years ago, northern polar sea ice appeared as early as 47 million years ago. The most recent period of year-round sea ice cover began 13 to 14 million years ago [9]. Since then, ice has been present more or less continuously in at least parts of the Arctic, with intermittent periods that were seasonally ice-free [9]. Species have adapted over this long period to the very particular habitats that sea ice provides (Box 1). About 3.1 million years ago, marine temperatures decreased sharply [10, 11] and extensive permanent sea ice cover in the northern Hemisphere dates from then [9, 12]. Despite major advances and retreats during the ice ages, conditions have probably been adequate to support a diverse ice-associated biota ever since. There is no evidence for large pan-Arctic fluctuations in ice conditions from about 3 million years ago until recently [9]. In the 1970s sea ice extent began to decline sharply, a trend that has accelerated in the past few years. The magnitude and rate of the current decline in ice extent are unprecedented, at least over the past 1,450 years [13] (Figure 3D).

Box 1. The long history of ice-associated marine mammals

Seals and walruses are, for the most part, confined to polar and sub-polar regions [27]. Fossil evidence shows that most of the current ice-associated whales and seals in the Arctic were common throughout the Pleistocene, roughly over the past three million years [28]. The polar bear evolved as a species much more recently [29, 30], as did modern humans [31].

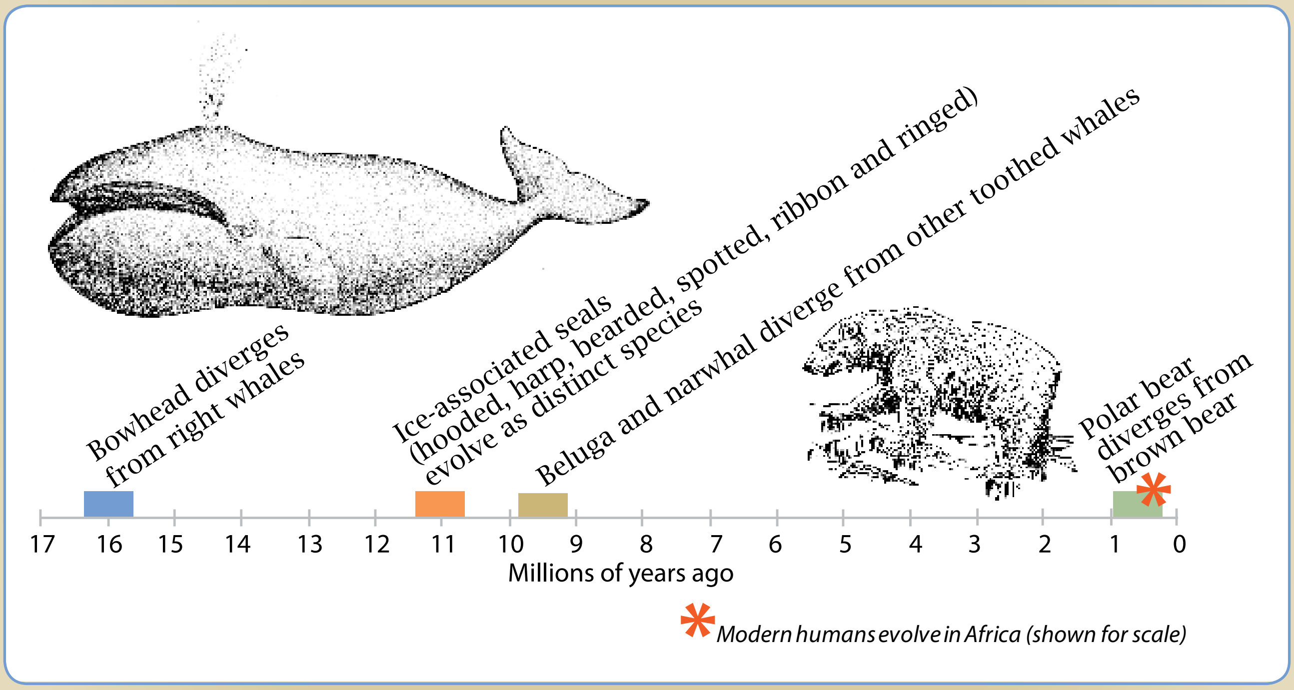


Figure 2. Timeline of evolution of some modern ice-associated marine mammal species
Data from Arnason et al. 2006 [32] (seals); Xiong et al. 2009 [33] (toothed whales: beluga and narwhal); Sasaki et al. 2005 [34] (bowhead whale); Hailer et al. 2012 [30] (polar bear); McEvoy et al. 2011 [31] (humans). Drawings from Wikimedia Commons (bowhead whale: F.W. True, drawn in 1884; polar bear: P.S. Foresman)

Recent and upcoming changes

The recent changes in Arctic sea ice cover, driven by increased air temperatures, have affected the age of the ice, its distribution, the timing of ice break-up in spring and freeze-up in autumn, and the extent and type of ice present in different areas at specific dates [14, 15] (Figure 3). In particular, changes over the past decade have led to a great reduction in the amount of multi-year ice in the Arctic Ocean (Figure 3E) and a corresponding increase in the area of annual ice present in winter [16]. The Arctic Ocean is projected to be virtually ice-free in summer within 30 years with multi-year ice persisting mainly between islands of the Canadian Arctic Archipelago and in the narrow straits between Canada and Greenland [17] (Figure 4).

All of these changes have impacts on Arctic marine ecosystems, affecting the structure of the ice platform, the timing of biological events such as plankton blooms and bird nesting, the amount of primary production [18–20] and the availability of open water at different times of year. Such changes are expected to continue and probably accelerate during the 21st century [21, 22], affecting the functioning of Arctic marine ecosystems. For human settlements adjacent to Arctic seas, negative impacts on health, culture and economies are expected to result from the impairment of harvesting of ice-associated species [23, 24]. On the other hand, increases in marine productivity and range extensions by southern organisms, especially commercial fish species, should present new economic opportunities [25]. However, the way in which change will happen and the speed of these transitions are both uncertain [26].

Children of the ice culture, Chukchi Peninsula, Russian Federation. Photo: A. Borovik

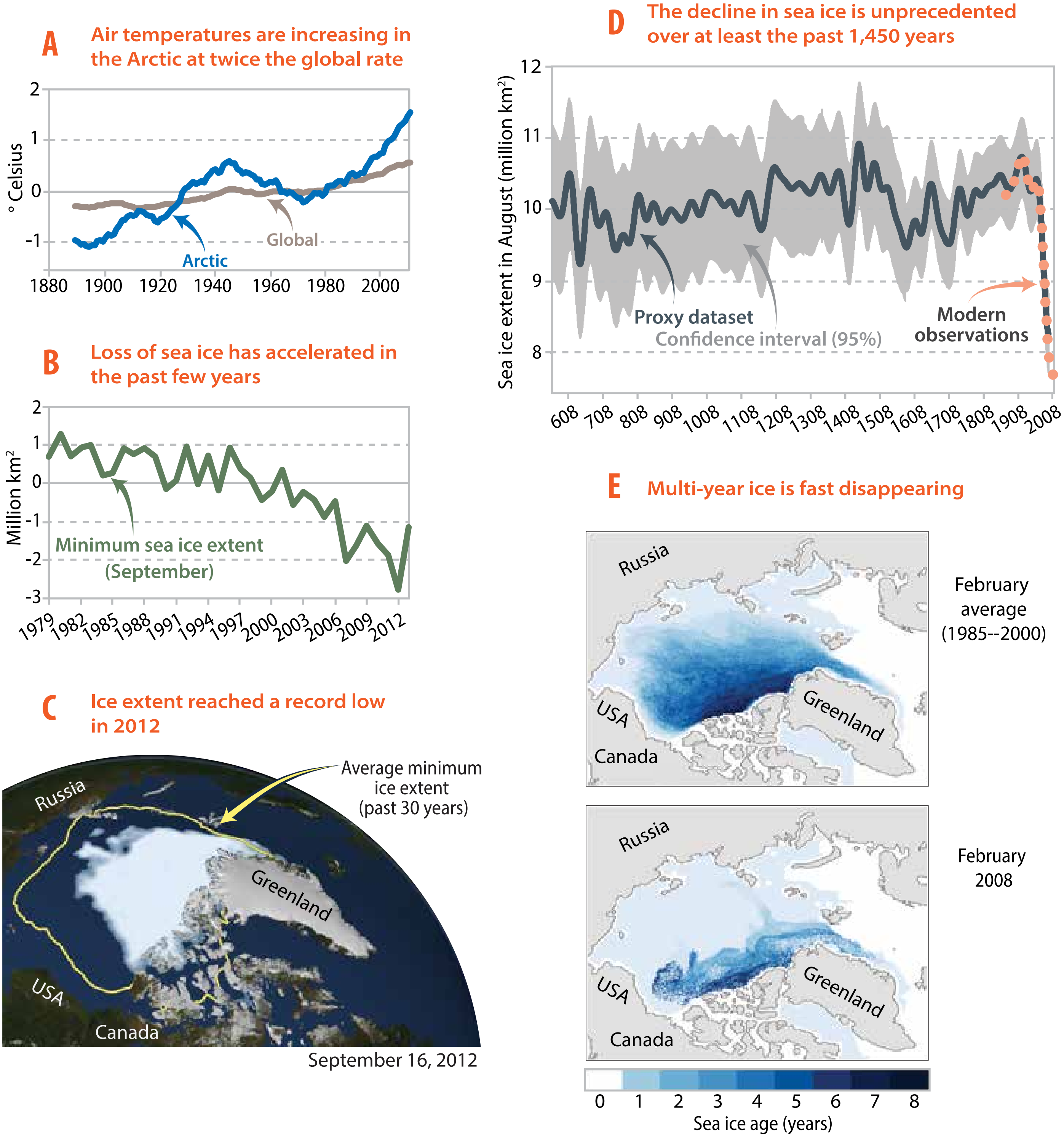


Figure 3. Trends in Arctic temperature and sea ice
A. Land–Ocean Temperature Index annual means, 1880 to 2011. Data (smoothed over ten-year periods) are temperature anomalies compared to the 1951–1980 mean. Data: NASA/GISS
B. Annual minimum ice extent, 1979–2013, based on satellite monitoring. Data are anomalies compared to the 1981–2010 mean. Data: NSIDC; methodology: Fetterer et al. 2002, updated 2009 [35]
C. Satellite image captured at the 2012 minimum of ice extent. Source: NASA/Goddard Scientific Visualization Studio
D. Sea ice cover over the past 1,450 years. The blue line is based on proxy records (mainly ice cores), while the dotted line is based on historical ice records and satellite monitoring. Proxy data were calibrated against modern observations. Data were smoothed statistically over 40-year periods. The record extends to 2008. Source: Kinnard et al. 2011 [13]
E. Distribution of multi-year ice, 2008 compared with 1985–2000 mean. Source: NASA no date [36]

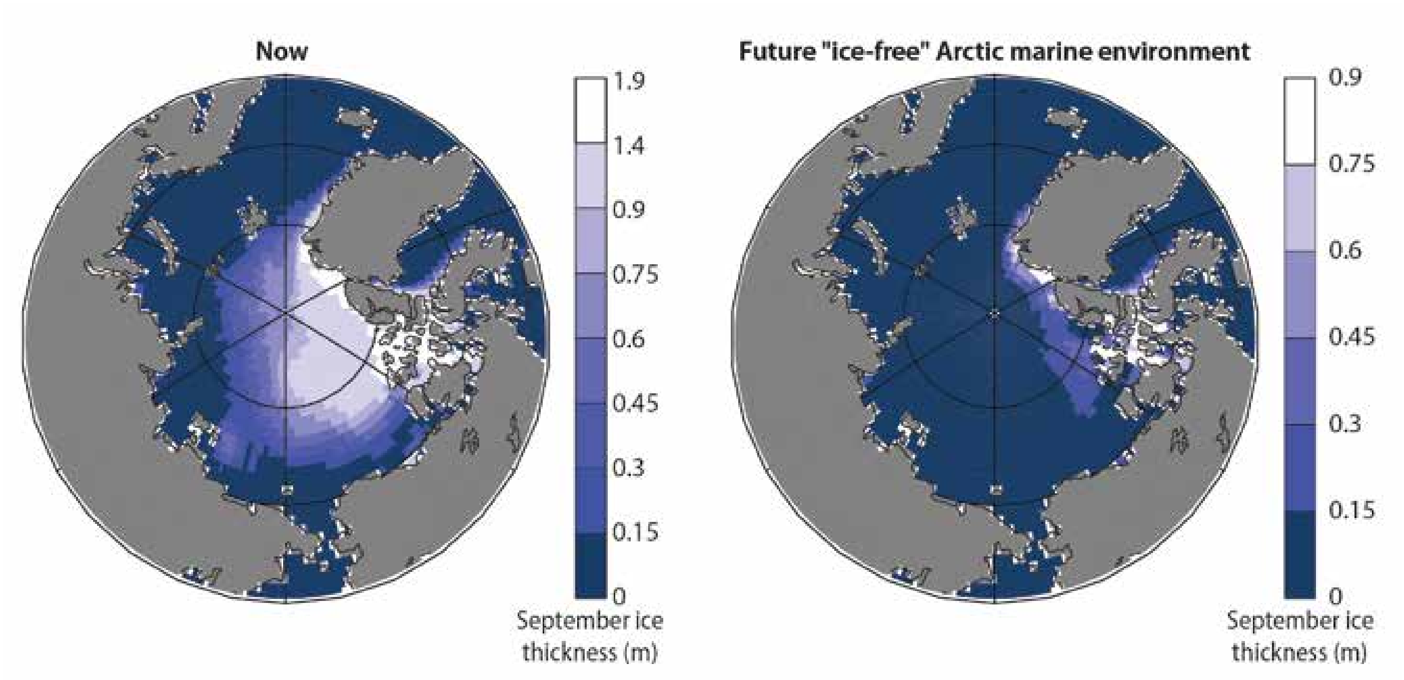


Figure 4. Mean September sea ice thickness averaged over seven selected models at present and by the time the Arctic is nearly sea-ice-free
Note the scale differences between the two panels.
From Wang and Overland 2012 [17]

Scientists watch from the deck of a US Coast Guard ship as it cuts through multiyear sea ice. Photo: NASA/Kathryn Hansen

2. Setting the scene

2a. The Arctic marine environment

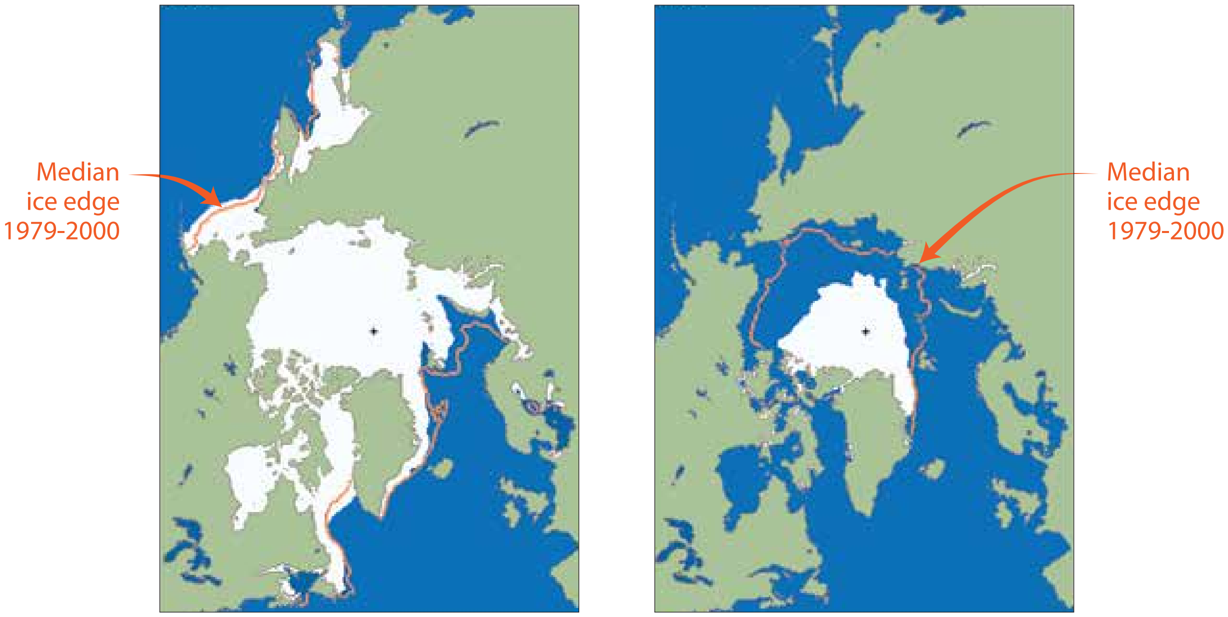
Water mass: a body of ocean water with a common history of formation, giving it distinct physical properties that distinguish it from the waters around it.

The Arctic Ocean is a deep central basin divided by ridges and surrounded by continental shelves (Figure 1). It is the smallest of the world's oceans, but has the highest proportion of shelves, with shelf regions covering about 50% of the Arctic marine area [21]. It is a complex, dynamic environment, with **water masses** changing characteristics, such as salinity and nutrient composition, and shifting position from year to year and on longer time scales.

Relatively warm, salty Atlantic waters enter the Arctic Ocean through Fram Strait. Less salty, and therefore less dense, Pacific waters enter the Arctic Ocean through Bering Strait, forming a layer on top of the Atlantic water mass. Fresh water from sea ice melt and river discharges spreads out over the surface of the ocean, adding to this stratification.

Both Atlantic and Pacific water masses circulate, but at different depths and in different patterns, mixing in some areas and distributing nutrients, organic matter, plankton, and larvae of fish and larger invertebrates. Arctic marine biodiversity is linked to this dynamic pattern of ocean conditions. For example, 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 [21]. This relation of species to water mass also applies to the water column. The vertical distribution of types of zooplankton in deep ocean basins, for example, is associated with layers of Pacific and Atlantic water masses [37].

There is, as one would expect in such a harsh climate, a strong seasonal nature to physical conditions and to ecosystems. The annual pattern of sea ice formation and melting controls much of the seasonal cycle for Arctic marine biota. The 2012 winter and summer ice distributions, along with average ice edge positions, are shown in Figure 5.



Winter sea ice distribution (March 2012) Summer sea ice distribution (Sept. 2012)

Figure 5. Northern Hemisphere sea ice distribution, March and September, 2012
Source: National Snow and Ice Data Center

Timing of ice formation and ice melt, as well as ice thickness and distribution, are ecologically important. Timing affects large-scale processes such as primary production. Changes in timing also have direct impacts on some species, affecting, for example, their access to food at critical periods of the year. Throughout the Arctic, the timing of the spring melt has shifted earlier in the season and, in some areas, the ice is also forming later in the autumn [14].

Features of particular ecological significance, including **polynyas**, **leads**, and the **marginal ice zone**, are defined by sea ice (Figure 6). These areas, where ice meets water and **upwelling** brings nutrients to the surface, are highly productive.

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

Leads: stretches of open water in sea ice, often transient. Flaw leads are situated between land-fast ice (also called fast ice) and pack ice and occur annually.

Marginal ice zone: the transition area from pack ice to open water.

Upwelling: process of deep, often nutrient-rich water rising to the surface due to wind or currents.

Polynyas are of special significance for air-breathing Arctic organisms. They may be created by strong currents, persistent winds, or by upwelling that brings warm water to the surface. Polynyas are a source of abundant food early in the season: they inject a burst of energy into food webs before the surrounding ice has broken up [38, 39].

Some populations of birds and marine mammals depend on polynyas to overwinter in the Arctic [40–42], and these open-water areas also provide important staging habitat for migratory birds moving towards their breeding areas in spring. The locations of large polynyas, with their relatively reliable concentrations of biological activity, have influenced human settlement patterns from the earliest times [43, 44].

Polynyas expand and contract, both from year to year and with longer-term changes in the climate [44]. There are indications of recent changes in some large polynyas. The Wrangel Island polynya in the Chukchi Sea has, on average, doubled in size over the past 30 years [45]. The largest polynya in the world, the North Water polynya between Canada and Greenland, shows signs of breaking down because of changes in ice conditions. Analysis of the annual formation and break-up of this polynya over the period 1968 to 2011 shows a trend to earlier break-up and suggests that a slightly warmer Arctic winter could lead to its disappearance [46, 47].

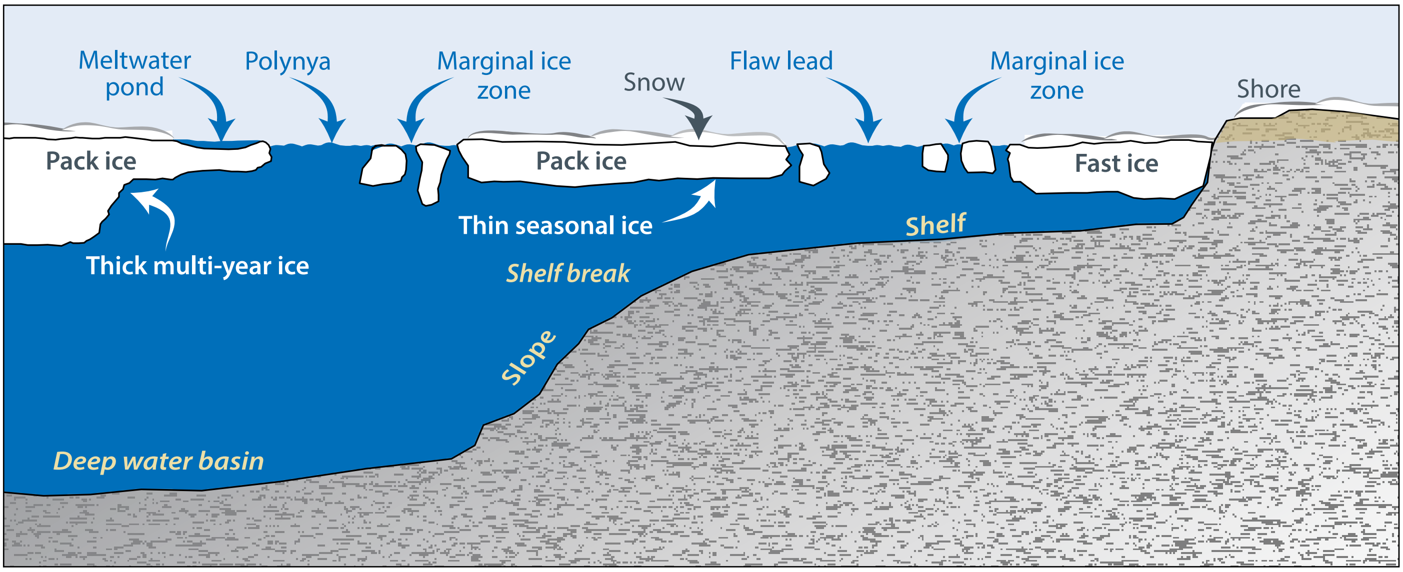


Figure 6. Some features of the sea ice environment

2b. Arctic marine food webs

Food webs trace how plants, animals and microbes are interconnected by different pathways.

Food chains follow a single pathway as animals eat plants and each other.

Trophic levels are the positions on the food chain. Primary producers are the lowest trophic level. In the Arctic, marine mammals and humans are at the top.

Arctic marine plants, animals and microbes are interconnected through a network of relationships that form food webs (Figure 7). At the base of these relationships are the producers, mainly single-celled algae that live within the ice or in the water. These primary producers capture energy from sunlight to support themselves and, subsequently, all other life in the seas. Since sea ice and the snow that covers it reduce the amount of light reaching areas where algae may grow, ice is a major factor controlling the presence and abundance of Arctic species. Nutrients, especially nitrogen, are also important. Knowledge about the circumstances under which primary production is controlled by light or by nutrients is particularly important in predicting how ecosystems will change as ice recedes [19].

A food chain might consist of algae growing on the underside of sea ice, grazed by zooplankton that, in turn, are fed upon by polar cod, which are then eaten by a narwhal [48]. The transfer of energy from primary producers to top predators becomes more complex when more steps are added. For example, many zooplankton are carnivores, feeding on other zooplankton. The earlier view that Arctic food webs involve few species and few pathways arose in part through lack of knowledge. Recent discovery and cataloguing of species at the lower trophic levels and research into food webs reveal that Arctic marine ecosystems are intricate and multifaceted [21]. Although the upper trophic levels are dominated by few species (relative to more temperate ecosystems), the lower levels of the food web are complex, with a high degree of diversity and many interactions among microbes, plankton and other very small life forms.

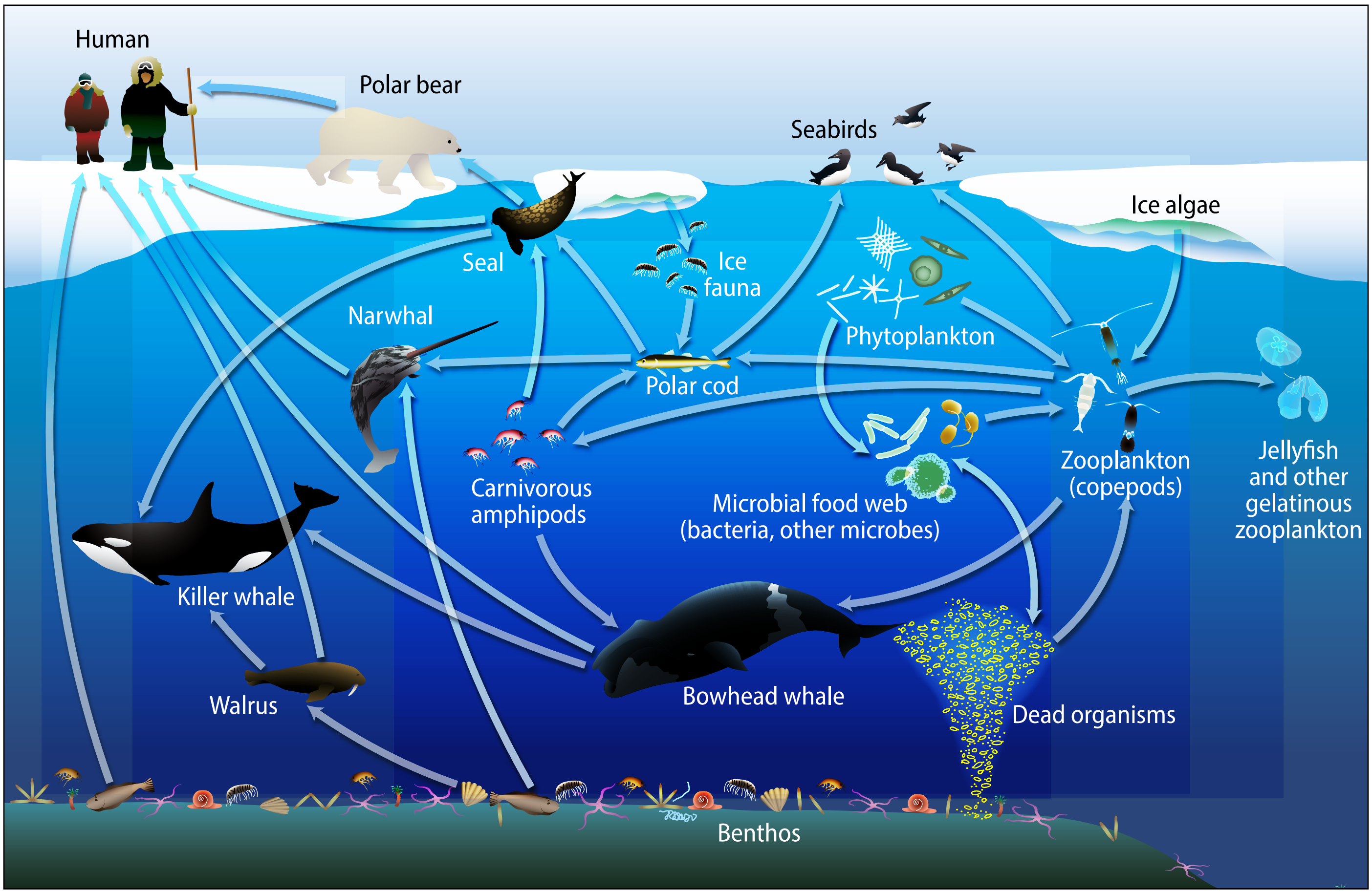


Figure 7. Arctic marine food web. Adapted from Darnis et al. 2012 [57]

Impacts on food webs

As the extent and duration of ice cover decrease, perturbations of existing food webs are expected, including impacts that influence the food web at its base by altering timing or amount of primary production. These are "bottom-up" impacts, because the changes in primary production work their way up the food web, affecting each successive trophic level [49]. Other types of perturbations to food webs start at the upper trophic levels. Reduced ice cover and warmer temperatures, for example, allow new predatory species to move in. The new predators directly affect the existing prey base and indirectly affect other predators through competition. Changes in predators also affect the lower trophic levels because predators alter the abundance and distribution of their prey. These "top-down" impacts work their way down through the trophic levels, eventually affecting the quantity of algae that is left uneaten and sinks to the ocean floor [50].

In past centuries, human interaction with Arctic biota was focused on wildlife-based subsistence activities [51]. The arrival of explorers to the high Arctic and the advent of commercial whaling in the early 19th century altered Arctic marine food webs, for example, by removing a key consumer of low trophic biodiversity: the bowhead whale. Estimated to be currently at 5% of its historical population levels, a more robust population would have competed with seabirds and polar cod, vying for the same prey [52]. While cod and seabirds may have benefited from the removal of bowheads from Arctic seas, reductions in bowhead populations would have also affected the people who hunted the whales for subsistence and also the animals that scavenged their carcasses, such as polar bears and seabirds [53, 54].

At present, human activity is having a far greater effect on Arctic marine species through activities leading to the warming of Earth's climate [2, 55]. Reductions in summer sea ice and the loss of multi-year ice are expected to put even greater stresses on food webs in the future as warming continues. Among the changes expected are the introduction of new species as ranges of more southerly occurring species shift northward, the decline in abundance and reduced reproductive success of existing Arctic-distributed species and associated impacts on species that feed on or are fed by them, and alterations in behavior, such as migratory and reproductive activities, as a result of changes in the timing of ice freeze-up and melt [56].

The following sections describe responses of various components of Arctic marine food webs to recent and predicted changes in occurrence of ice. The sections are structured by the three major realms of the Arctic marine environment: the sea ice realm, the pelagic realm (the water column), and benthic realm (the sea floor). Vertebrates are considered separately, as they move through these realms.

Bowhead whale in Isabella Bay, Baffin Island. Photo: vtluvbug79, Flickr

3. Sea-ice-associated biota

3a. Flora and fauna of the ice realm

When the ice forms in the fall, algae and other tiny plant and animal life forms, as well as organic matter and nutrients, are incorporated into the new layer of sea ice. The flora and fauna within the ice remain dormant or at low levels of activity over winter and grow and reproduce early in spring, fueled by sunlight that penetrates the ice pack (Figure 8) [58, 59]. While still in the ice, they are a food source for crustaceans that graze on the underside of the ice. As the ice melts, many organisms are released into the water column, providing food for zooplankton in the water column [60]. Others remain in multi-year ice throughout the summer.

Microscopic flora and fauna color the bottom of this ice core
Photo: Andrew Juhl

Life within and on the underside of sea ice is vulnerable to changes in ice conditions, as many of these species are closely adapted to feeding, reproducing and overwintering in this habitat. As a high proportion of ice flora and fauna are found only in the Arctic, their loss would be a loss of global biodiversity. Changes in sea ice alter the amount, timing and location of primary production, both within ice and in the water column, with consequent impacts on Arctic marine food webs [22].

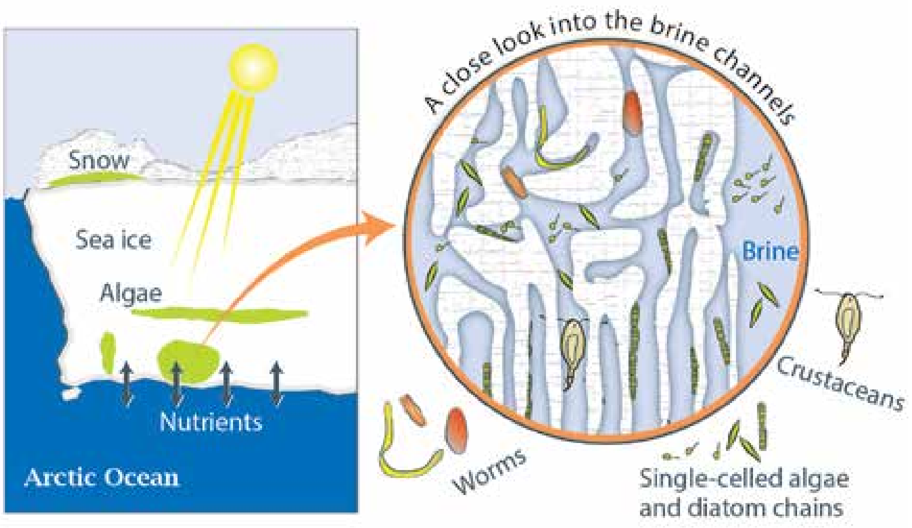
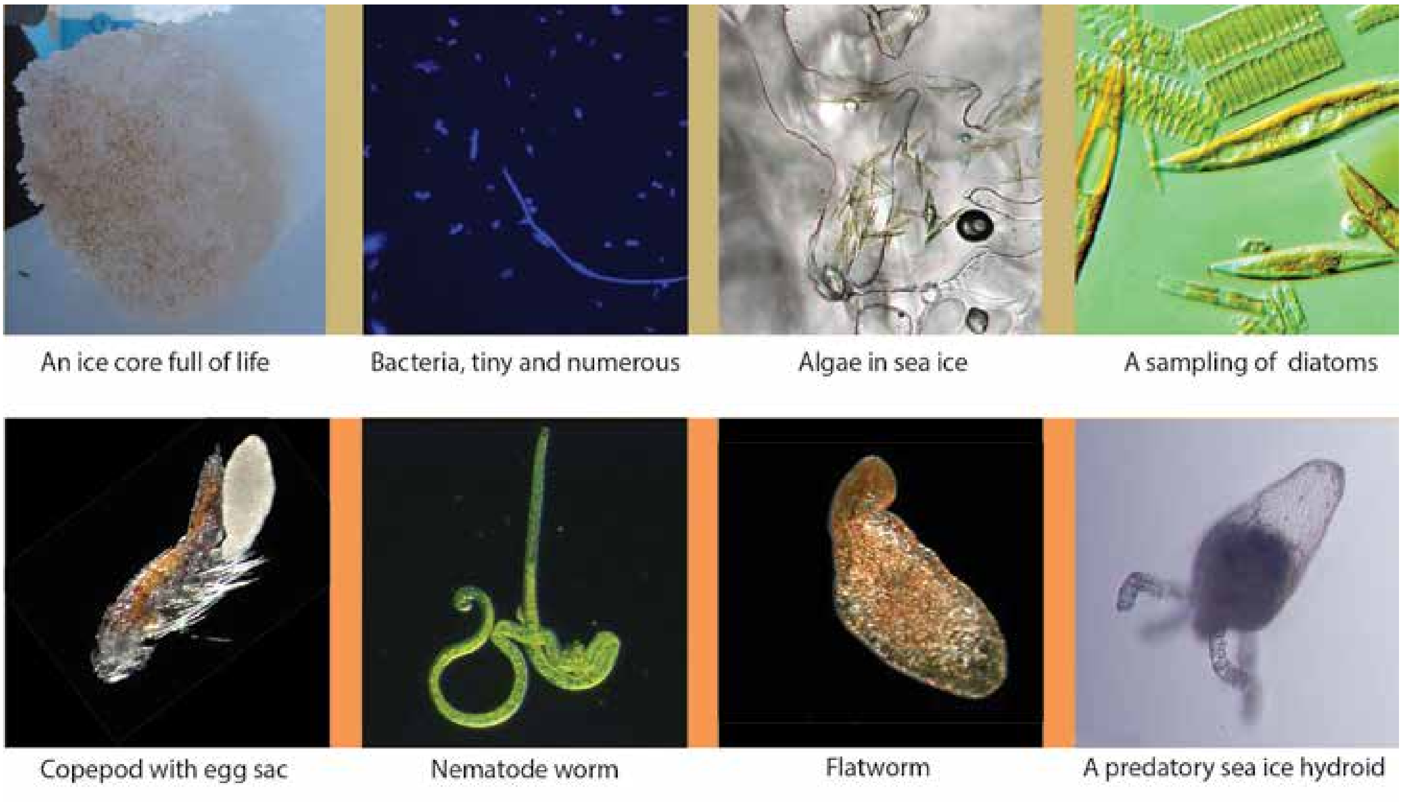


Figure 8. Communities of microscopic algae and other single-celled organisms, as well as the larger ice fauna, dwell in the saltwater-filled pores and channels of sea ice
As sea ice forms, droplets of water with high salt content form and these join into narrow "brine channels" that riddle the ice.
Based on Krembs and Deming 2011 [100]

Ice algae and bacteria

Ice algae, as primary producers, are the foundation of sea ice biological communities. Bacteria are also an important component in the sea ice food web, making up as much as half of the biomass in sea ice in some areas [61–64]. More than a thousand species of algae and similar organisms (those with a cell structure that includes a nucleus) have been reported from Arctic sea ice communities [65]. Some of these do not photosynthesize, subsisting on bacteria and ice algae [66]. Some examples of organisms in ice are shown in Figure 9.



An ice core full of life

Bacteria, tiny and numerous

Algae in sea ice

A sampling of diatoms

Copepod with egg sac

Nematode worm

Flatworm

A predatory sea ice hydroid

Figure 9. A sampling of sea ice life forms
All are less than 20 micrometers in length, too small to be seen with the naked eye. For comparison, a crystal of table salt is about 120 micrometers in diameter.
Photos: top row left to right Marine Productivity Laboratory/Fisheries and Oceans Canada, R. Gradinger/UAF, C. Krembs/UW, R. Gradinger/UAF; bottom row left to right R. Gradinger and B. Bluhm/UAF, B. Bluhm/UAF, R. Gradinger and B. Bluhm/UAF, B. Bluhm/UAF

What we know about these systems is dependent on what we have studied—and, until recently, studies have been biased towards larger organisms that can be identified using a light microscope [65]. Diatoms, the most common type of ice algae, have been the most thoroughly studied of ice algae.

The abundance of ice algae is influenced by variations and gradients in conditions such as light, salinity and nutrients within the ice pack [67]. Because of this variability, it is difficult to estimate ice algal production over any given region [68]. Where estimates have been made, they indicate that ice algae's contribution to the total annual primary production ranges from as little as 1% in some coastal areas to over 50% in the central Arctic Ocean [4, 58, 69, 70].

First-year ice supports a greater abundance of life than does multi-year ice because it has more pores and brine channels for habitat [22]. Sea ice algae flourish particularly at the ice–water interface in the bottom few centimeters of the ice. Algae in this layer can account for up to 95% of the total springtime primary production in first-year ice [22, 71]. Bacteria, however, can be distributed throughout the ice layers [63]. Under some conditions, algae can be abundant in interior ice layers, as demonstrated for first-year ice from the Chukchi Sea [72] (Figure 10).

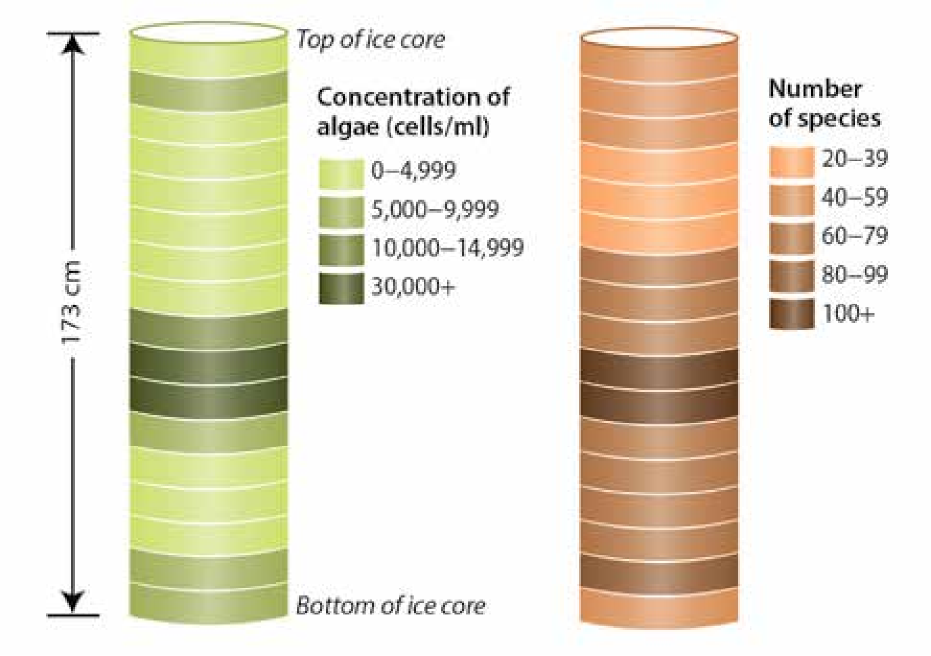


Figure 10. Cell concentration and number of microalgal species throughout a core of first-year ice from the Chukchi Sea, June 1998
The most numerous species identified in the core were ice-associated diatoms, but several different algal classes were represented. Microalgae were distributed throughout the core, but abundance and species composition varied with ice depth. The diversity was among the highest ever recorded in Arctic sea ice: 237 species were identified from the core. Depending on the species, the sizes of microalgae can range from a few micrometers to a few hundreds of micrometers.
Data from von Quillfeldt et al. 2003 [72]

Ice fauna

The fauna of the ice realm consist of tiny multi-celled invertebrates that are small enough to navigate the brine channels (Figure 8 and Figure 9) and larger invertebrates that feed on the underside of the ice [63, 73].

Fauna within the ice include permanent residents: tiny crustaceans and nematode worms, rotifers, and other small, soft-bodied animals. In addition, larvae and juvenile stages of some bottom-dwelling marine worms and snails spend a few weeks or months of their lives within the ice [63]. Many of the invertebrates within the ice feed on ice algae, but they typically consume less than 10% of what is produced in the ice pack [22, 60]. Ice fauna, like algae, are generally concentrated in the lower few centimeters of the ice [74]. They are found in much higher densities in land-fast ice than in pack ice [75].

The main invertebrates feeding on the underside of the ice are amphipods (Figure 11). These relatively large (up to several centimeters long) crustaceans are main prey items for polar cod and some seabirds (see also the Fish section) and play a central role in Arctic marine food webs [48].

Impacts of reduction in sea ice

The degree to which changes have already occurred in ice communities is difficult to evaluate, as there are few studies that quantify trends in abundance and types of species [56]. Analyses of ice cores from drift ice in the central Arctic Ocean indicate a loss of diversity and reduction in abundance in both ice algae and ice fauna since the late 1970s (Box 2). Insights into consequences of the decline in sea ice also come from the growing body of research on ice flora and fauna, especially studies that link specific sea ice conditions with characteristics of ice communities and their relationships with other parts of Arctic marine food webs [76–81].

Many species in ice communities depend on sea ice over all or part of their life cycle. Some algal species may use the sea floor as an alternate habitat, but only where the water is shallow enough for sufficient light for photosynthesis to reach the sea floor [72]. In areas with deep water, these sea ice algal communities will be lost or much reduced as the sea ice continues to decline.

The shift towards less multi-year sea ice is expected to affect species composition. One-year-old sea ice has to be colonized every year while multi-year ice has continuous communities of algae, bacteria, other single-celled organisms, and ice fauna [82, 83]. In addition, some specialized types of algae normally do not occur in younger sea ice [83].

The loss of multi-year ice may lead to major reductions in the larger invertebrates that feed beneath the ice, especially the ecologically important ice amphipods. Although ice amphipods are sometimes found in open water, they are associated with sea ice throughout their multi-year life cycles. Long-lived species like *Gammarus wilkitzkii* (Figure 11) make use of ice year-round and may eventually be reduced to small areas in the Canadian Arctic Archipelago where perennial ice is expected to persist [84]. The extent to which ice amphipods can adapt to ice-free summers remains uncertain [85].

Figure 11. Amphipods attached to ice crystals in Arctic coastal fast ice and two common ice amphipod species
The large *Gammarus* amphipod grows up to about 6 cm in length.
Photos: Shawn Harper/UAF (left photo); B.Bluhm/UAF/CoML (*Apherusa*); Raskoff/MPC (*Gammarus*)

Box 2. Trends in species diversity in sea ice communities

Russian research in the central Arctic Basin provides a long-term record of physical and biological characteristics of the ice pack. The differences in diversity and abundance of sea ice biota between the mid-1970s and the present are remarkable. Researchers catalogued 172 species of sea ice algae over the period 1975 to 1982 [101]. In research expeditions since 1997, they have found only about 30 species and have recorded declines in abundance [79, 102, 103]. Diatoms dominated in both time periods, but less so in the more recent collections, with other types of algae becoming more common [102]. Ice fauna were far less numerous in recent surveys than in those from 1975 to 1982 [102].

The observed changes are considered to be related to the trend towards replacement of multi-year ice with seasonal ice over this time period [102]. However, as seasonal ice has been shown to support a high diversity of algae in other locations [72] (Figure 10), it is unknown how widespread this loss of diversity might be.

Pan-Arctic Ice Camp Expedition, North Pole, 2011. Photos from Igor Melnikov

Ecological context of change: connections with the benthic and pelagic realms

Primary production of sea ice algae plays a crucial role in the life cycle of some zooplankton and benthic animals [22, 86]. When the ice melts and algae are released into the open ocean they become an early-season food source for zooplankton [77]. When the ice algae and organic matter produced by the ice communities drop to the sea floor, they provide food for invertebrates living on the bottom of the sea. Ice algae may be essential for some zooplankton and selected by some benthic species because of the essential fatty acids they contain [81, 87].

Sea ice algae start their growth earlier than phytoplankton, providing a source of food when little or no other food is available [88]. Even in coastal areas where ice algae contribute only a small proportion of the total annual production, they are significant in the early spring (Figure 12). This early-season food source allows some zooplankton species, notably the ecologically important *Calanus* copepods, to extend their growth season [77]. Ice algae provide essential fatty acids at a critical time for copepod reproduction [81].

The current trends of rapid decline in ice thickness [17] and in the depth of Arctic spring snow [89] alter how much light is available for growth of ice algae [90]. Thinner ice and less snow allow more light to penetrate to the bottom layer of the ice. However, the increased light for photosynthesis may be countered by a rapid loss of the productive bottom layer of the ice as it melts faster and the ice algae slough off the ice surface [91, 92]. The intensity of ice algal production is also related to availability of nutrients, which is in turn related to freshwater input and the degree of stratification in the water column. Consequently, it is difficult to generalize about the net effect of changing ice conditions on amount and timing of ice algal production.

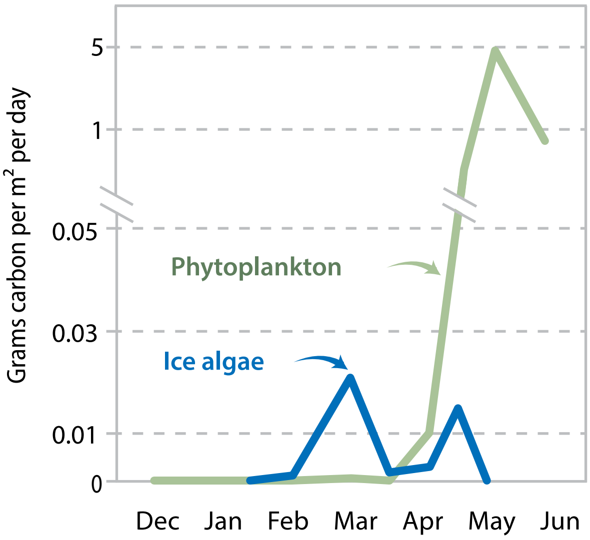


Figure 12. Primary production of ice algae and phytoplankton from December to June, in a fjord near Nuuk, Greenland, 2005/2006
Ice algae accounts for less than 1% of the annual primary production at this coastal location, but the bloom occurs at least a month before any primary production is available from phytoplankton. Farther offshore, ice algae contribute much more to the total annual production: as much as over 50% [4].
Adapted from Mikkelsen et al. 2008 [58]

Stills from a video of the underside of nearshore fast ice in spring, near Barrow, Alaska. Strands of Melosira arctica *are visible in the center and right photos. Photo: Andrew Juhl*

Box 3. Ice algae and deep-sea benthic ecosystems: findings from 2012

In the record low-ice summer of 2012, a scientific expedition to the eastern-central Arctic Ocean basins found widespread deposition of ice algae on the ocean floor at depths of about 4 km [94]. The main species was the diatom *Melosira arctica*, which grows in long filaments anchored to the underside of ice floes (left photo, Figure 13).

The piles of algae strands that settled on the ocean bottom were being eaten by a few larger, mobile invertebrate species, including sea cucumbers (right photo) and sea anemones, but were mainly being broken down by bacteria. The biomass of sea cucumbers was substantially higher in areas with many piles of algae and there were few signs of the small invertebrates such as marine worms that are normally found within the sediment in this type of habitat.

Oxygen penetrated only a few millimeters down into sediments beneath piles of algae, due to the bacterial activity. By contrast, oxygen penetrated over 50 centimeters in surrounding sediments. As sediment cores showed no sign that oxygen penetration was reduced in past years, researchers concluded that the widespread deposit of strands of ice algae in the deep central basins is a rare or new phenomenon. They attributed it to the rapid, early melt of ice causing the algae to fall to the ocean floor. Younger, thinner ice with more melt ponds likely also enhances algal growth as more light penetrates to the bottom of the ice floes. Thick multi-year ice in the study area has been largely lost: first-year ice with an average thickness of less than a meter dominated over 95% of the study area and melt ponds covered on average 30 to 40% of the ice surface.

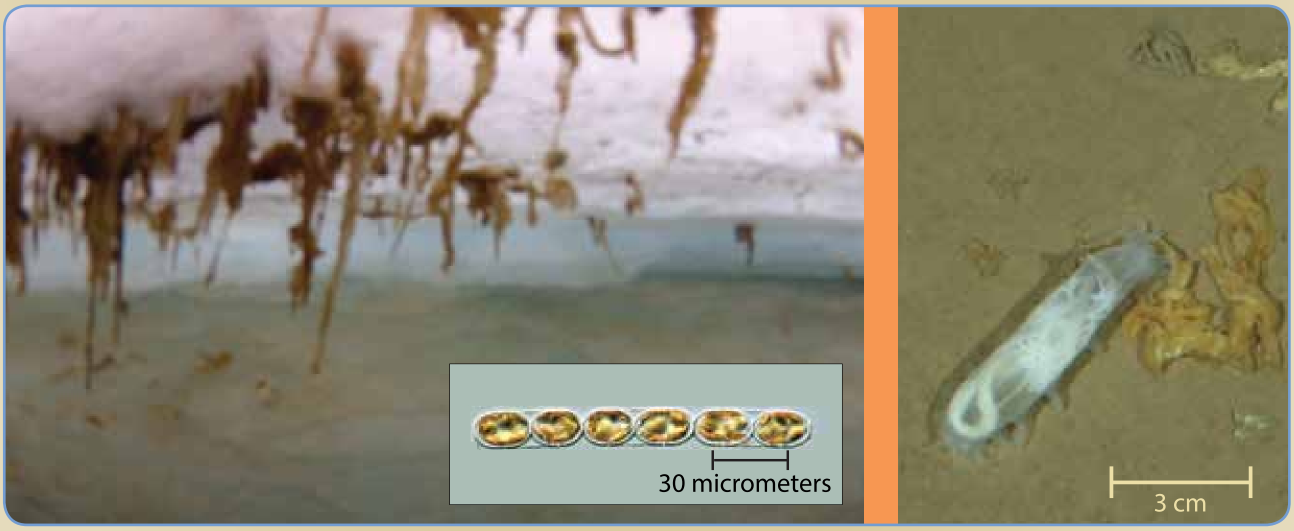


Figure 13. *Melosira arctica* under ice and on the ocean floor
Photos: M. Fernandez-Mendez (left) and A. Boetius/Alfred Wegener Institute (right); Seija Hällfors/ Finnish Environment Institute SYKE (inset microscopic view of the diatom *Melosira arctica*)

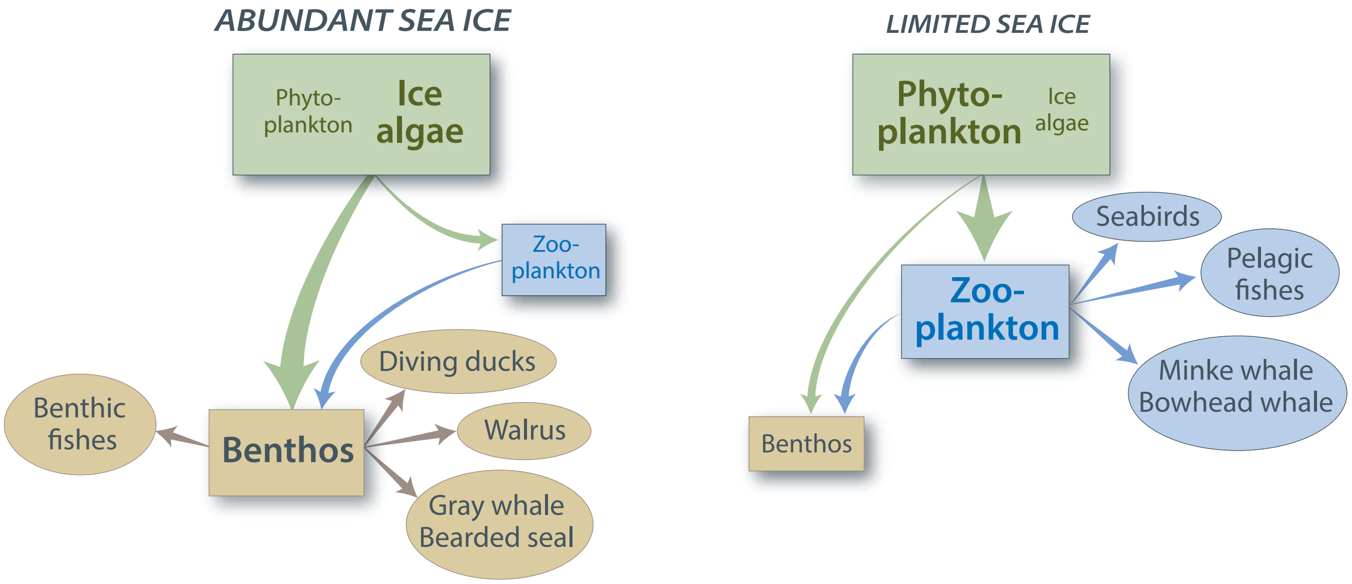
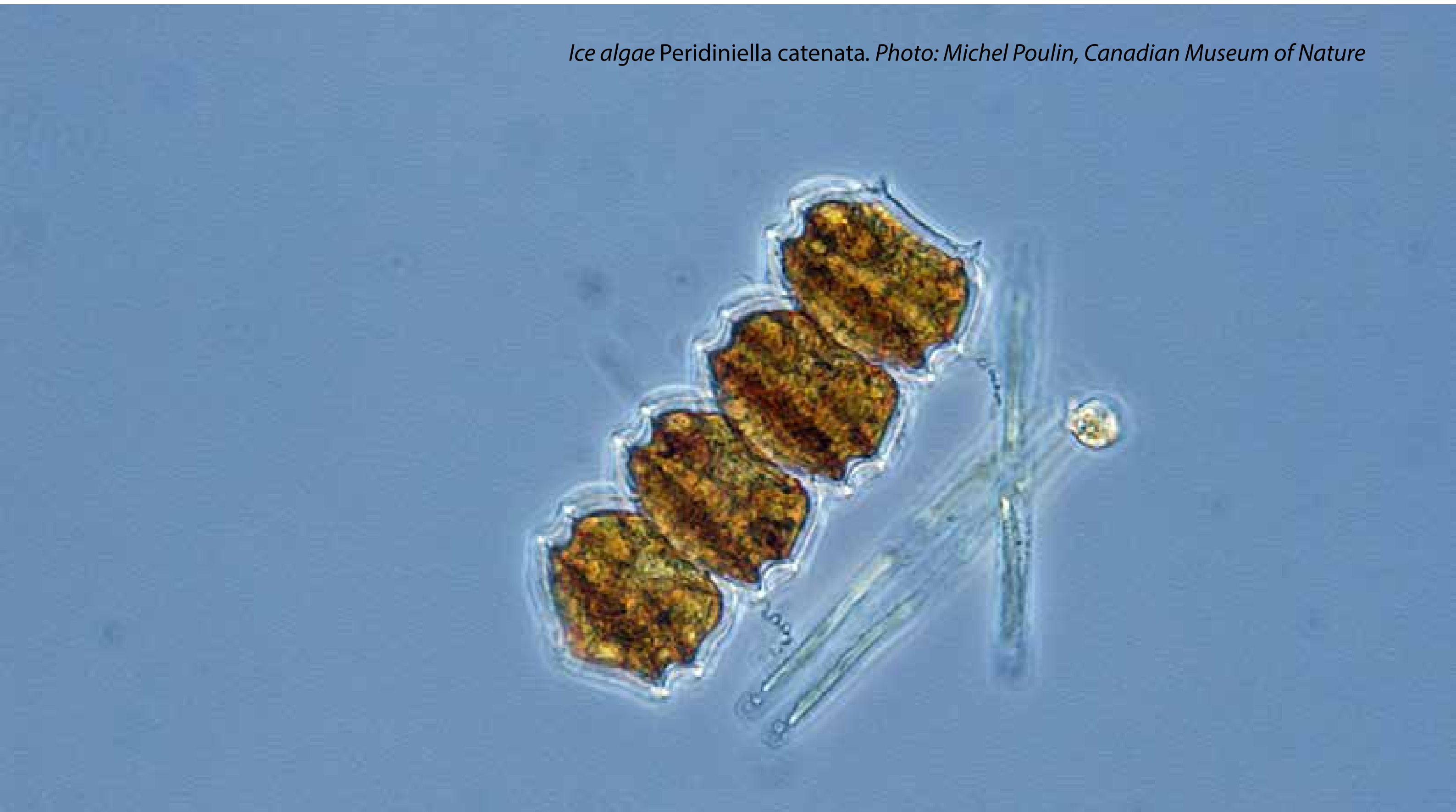


Figure 14. Change in ecosystem structure that may result from reduction of sea ice and related temperature changes: an illustration based on the Chukchi Sea food web
Adapted from Hopcroft et al. 2008 [95], based on Carroll and Carroll 2003 [98]

The relative importance of ice algae for grazing zooplankton and benthic communities depends partly on the rate at which the algae are released from the sea ice. When a pulse of algae is released, the zooplankton are not able to consume it all and the remainder drops to the sea floor, at least in relatively shallow waters [93]. This provides an annual source of energy to the benthic realm, strongly influencing these sea bottom communities. Recent observations indicate that deep-water benthic communities can also be affected (Box 3) [94].

If, as seems likely, the sea ice cover is reduced and seasonal ice disappears early in the season, there will be a shift from a system strongly influenced by ice algal species towards a system more dependent on phytoplankton species [95, 96]. If the zooplankton are able to graze most of what is being produced, less will reach the sea floor [93, 97, 98] (Figure 14). Thus, marine life forms heavily dependent, directly or indirectly, on ice algae will be particularly affected by reduction of sea ice, in contrast to the current situation, where they rarely experience food limitations [99].

Ice algae Peridiniella catenata. *Photo: Michel Poulin, Canadian Museum of Nature*



3b. Plankton and the pelagic realm

Plankton live in the water column and are not directly ice-associated. Sea ice, however, influences their distribution and abundance throughout the Arctic. It structures, in time and space, the light available to phytoplankton in the water column and the supply of nutrients needed for their growth.

A prominent feature of Arctic marine ecology is the phytoplankton bloom at the edge of the ice [6, 104, 105]. Stable water masses are created by the freshwater input from sea ice melt. Improved light conditions and a surface layer rich in nutrients that have accumulated over the winter result in intense production of algae in the waters of this marginal ice zone. The bloom follows the ice edge as it retreats northward over the summer.

The supply of phytoplankton controls the populations of zooplankton, the main phytoplankton consumers. This indirect effect of sea ice on phytoplankton is felt throughout the food web because of the importance of zooplankton as a food source.

Many common phytoplankton and zooplankton species are not Arctic specialists—they also occur in oceans that are never ice-covered [63]. Most will likely persist under the new sea ice regime. The abundance, timing and spatial distribution of types of plankton, however, are likely to be strongly affected by reduction of sea ice.

Pelagic primer

Pelagic organisms live in the water column (the pelagic realm). **Plankton** are organisms that drift with the currents as opposed to other pelagic organisms like squid, fish and whales, that propel themselves.

Phytoplankton are tiny single-celled algae. Most of them **photosynthesize**: using the energy of sunlight, they produce carbohydrates from carbon dioxide and water. **Zooplankton** are the animals of the plankton world: mainly small crustaceans and other invertebrates that feed on phytoplankton or particles of organic matter.

Plankton also include single-celled organisms that do not photosynthesize, such as amoebae, as well as various animal larvae and larger floating animals such as jellyfish.

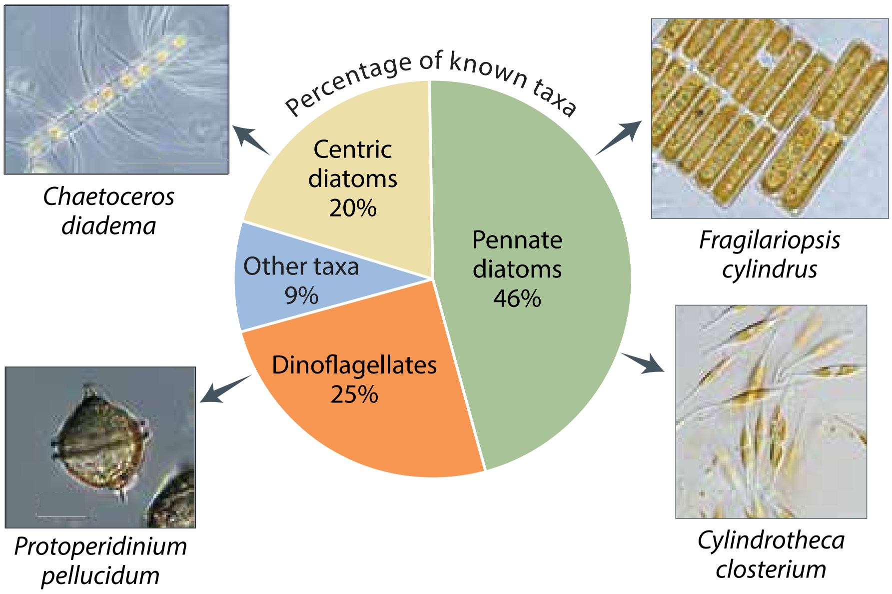


Figure 15. Diversity of Arctic marine phytoplankton: based on surveys in the Russian Arctic
The number of species depends partly on what has been studied. Proportions vary somewhat around the Arctic, but diatoms and dinoflagellates are the most diverse groups everywhere. The greatest sampling effort has been in the Laptev Sea, Hudson Bay, and the Norwegian sector of the Barents Sea. Species shown are among the most commonly recorded.
Data from Poulin et al. 2011 [65]
Photos (taken through light microscopes): clockwise from top right Dr. Gerhard Dieckmann/Alfred Wegener Institute; Gert Hansen/Nordic Microalgae (www.nordicmicroalgae.org); Alexandra/Alfred Wegener Institute; Marine Productivity Laboratory, Fisheries and Oceans Canada

Phytoplankton

Over 1,800 types of single-celled phytoplankton have been reported from the Arctic (Figure 15) [65]. Diatoms are the most abundant and the most diverse.

In general, small-celled phytoplankton species are more widespread and important in cold waters than once believed [106]. As with ice algae, cells not visible through low-powered light microscopes were less studied until recent years. Nonetheless, overall primary production in the Arctic Ocean is dominated more by larger plankton types than in other parts of the global ocean [107] (Figure 16).

Communities of phytoplankton change with the seasons [105, 108–110]. While many species are mainly winter, spring, summer or autumn species, a few are found year-round. Stability of the upper water column, light, nutrients, grazing and sedimentation control the seasonal shifts in the types of phytoplankton present. As many of these environmental factors are strongly influenced by sea ice, loss of summer ice will affect this seasonal pattern.

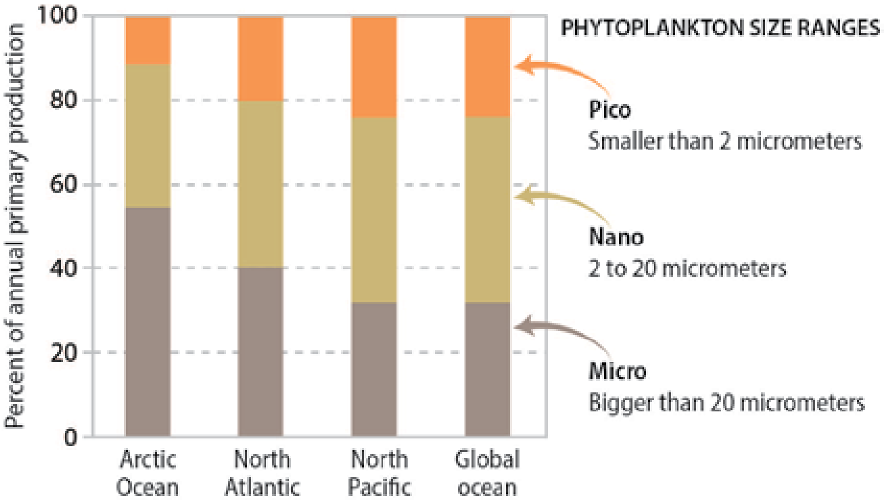


Figure 16. Primary production by phytoplankton size class for the Arctic, North Atlantic, and North Pacific oceans and for the global ocean
Estimates of average annual primary production by size class were based on relationships with pigment types as detected by satellite monitoring, 1998 to 2007. Data from Uitz et al. 2010 [107]

Lead in Milne Fjord, Ellesmere Island. Photo: njwilson23, Flickr

Zooplankton

The tally of multi-celled Arctic zooplankton species is now close to 350 [111]. About half of them are copepods (Figure 17), a group of small crustaceans that are most abundant, most diverse and have the greatest biomass in the majority of samples of Arctic zooplankton [37].

About 175 zooplankton species have been documented in studies throughout the deep basins of the central Arctic Ocean [112]. Records of zooplankton in the Canada Basin date back to studies from the Russian drift stations of the 1950s. Scientific expeditions in each decade since have included zooplankton sampling. Authors of a 2005 study in the basin [37] reviewed past results and concluded that zooplankton communities appear unchanged over the previous 50 years. The 2005 study found greater zooplankton diversity at lower depths than in surface waters, although 50% of the biomass was in the upper 100 meters. Copepods made up 85% of the biomass and arrow worms (Figure 17) made up a further 13%.

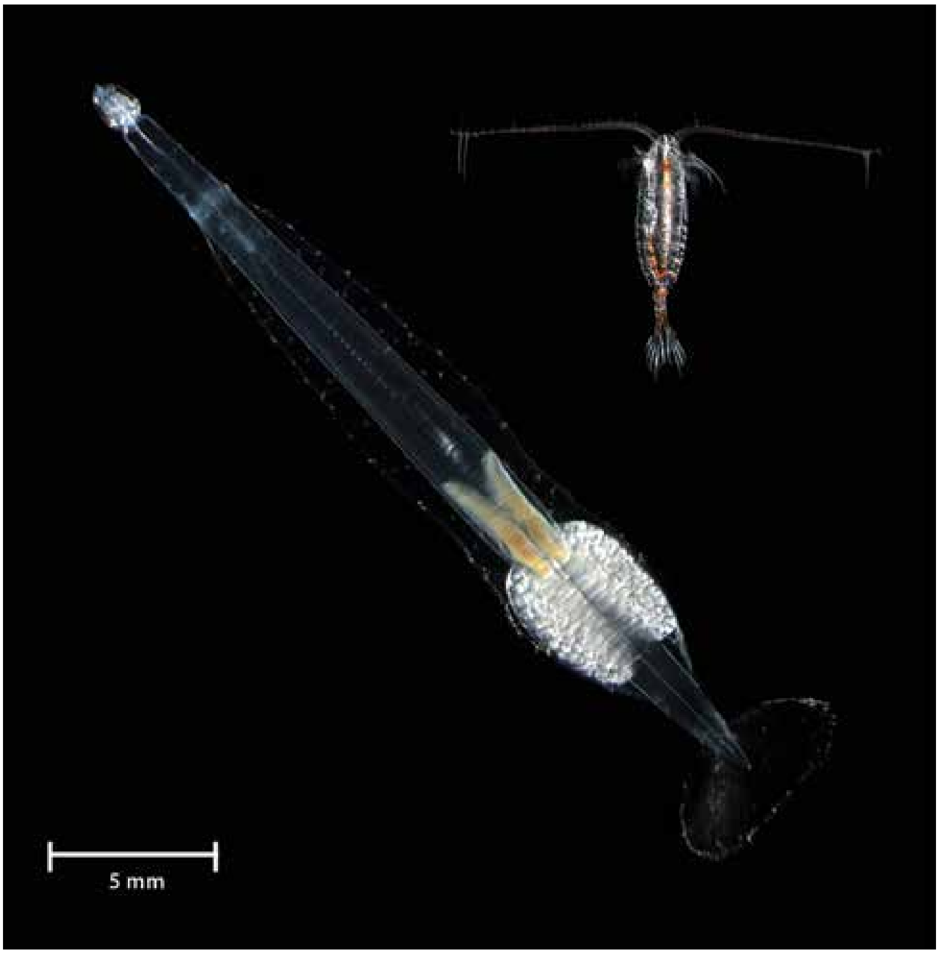


Figure 17. *Calanus* copepods and arrow worms, two common Arctic zooplankton groups
Calanus glacialis (top right) is one of a few common copepods that make up a large proportion of the zooplankton biomass throughout the Arctic. They live two or three years, concentrated in surface waters from spring to fall and overwintering in deeper waters. The large oil sac that is visible within the translucent body stores energy for growth and reproduction and makes these copepods a popular prey item. *Eukrohnia hamata* is the dominant arrow worm (chaetognath) of Arctic basins. Arrow worms are predators on other zooplankton, hooking them with the barbs on their heads and ingesting them whole.
Photos: Hopcroft/UAF/CoML/NOAA

Rising temperatures could result in shifts to sub-Arctic species. The copepod *Calanus glacialis*, for example, is restricted to waters with temperatures below about 6°C [113]. It is generally believed that current Arctic temperatures are too cold for the long-term survival of many sub-Arctic species and that, once transported into the Arctic Ocean, they will be unable to establish viable populations. However, the smaller-bodied sub-Arctic species may remain viable in Arctic waters if temperatures rise (for example, Hopcroft and Kosobokova 2010 [114]). Animals that feed on zooplankton could be affected by a shift to smaller zooplankton types, as most predators select their prey on the basis of size.

Deep central Arctic basins have lower zooplankton biomass than do slope and shelf areas [115]. As low zooplankton productivity in the Arctic basins is mainly due to their low primary production, increases in primary production could be accompanied by increases in zooplankton production and biomass. It is, however, difficult to predict whether the decline of summer ice will lead to decreases or increases of zooplankton biomass, due to uncertainty about future trends in primary production.

Primary production

Primary production in the pelagic realm has increased, but not uniformly. Rising Arctic air temperatures have reduced summer ice extent by 27% and increased the open-ice period by 45 days between 1998 and 2009. Primary production of the Arctic Ocean increased by about 20% over this period, based on estimates from satellite monitoring. Increases were especially large in the Kara Sea and off the coast of Siberia [116]. Other analyses highlight how variable this change is from year to year and from region to region [117, 118]. In the Pacific Arctic, for example, primary production (also estimated from satellite monitoring) showed no clear trend from 2003 to 2008, despite a steep decline in summer ice [119].

The overall increase in production may have been underestimated, as massive algal blooms have recently been observed under sea ice [7]. Under-ice production of algae may have increased in recent years as the ice has thinned and more meltwater pools form on its surface, allowing more light to penetrate to the water below [120]. Little is known about under-ice algal blooms and how they will influence future trends in primary production [7].

The relationship of sea ice to Arctic-wide primary production in the water column was examined by comparing the summer of 2006 with the summer of 2007, which was a year with particularly low ice cover. Thirty percent of the higher primary production in 2007 was accounted for by the greater area of open water for phytoplankton growth and seventy percent was due to the longer growing season afforded by an earlier spring melt [18]. Extending this analysis leads to a projection of as much as a three-fold increase in primary production above 1998–2002 levels in an Arctic devoid of summer ice [18]. The actual change in primary production will also depend, however, on nutrient limitations [19, 118] and will not necessarily translate into increased production of marine animals [21, 22, 121].

Primary production is part of a complex picture involving ocean currents, wind patterns, river flows, water temperatures, when and where the sea ice freezes and melts, and how nitrogen, the nutrient that often limits algal growth, is moved through the ocean waters. All of these are influenced by climate change and all are interlinked. In broad terms, one recent prognosis is that primary production will continue to increase in most shelf regions and increase less, not at all, or even decline, in the deep basins [121].

Sea ice, stratification of the water column, and nutrients

The water column in the central basins of the Arctic Ocean is highly stratified—separated into distinct layers by density, mainly determined by differences in salinity. The fresh water introduced by the large rivers that flow to the Arctic in Russia and North America and, in the Canada Basin, the inflow of Pacific water low in salinity through the Bering Strait are the main determinants of this stratification [122]. Sea ice is also important, as it both inhibits wind mixing and adds fresh water to the surface sea-water layer when it melts. Polynyas, shelf breaks, and other areas with upwelling from currents and from wind, mix the water layers and bring nutrients to the surface [46, 123]. These areas are high in biodiversity [40], fuelled by primary production that is high in comparison with the more stratified water where nutrients become depleted by phytoplankton growth and are not replenished by mixing. Shallow seas and broad shelf areas, like the East Siberian shelf, are less stratified and much more productive than the central basins and the Beaufort Sea [121].

Upwelling through wind mixing is likely to become more common in waters over the shelf and at the shelf break, due to reduction of sea ice cover in combination with a climate-change-related increase in strong winds [124]. Deeper mixing of the upper layer is likely to influence the relative importance of different algal groups and, therefore, the quality of the food available for zooplankton [118].

Wind mixing has less effect farther offshore and may not be enough to overcome the increased stratification that results from greater melting of the ice. Studies in the Canadian Arctic show a strong increase in stratification in offshore waters over the past decade, especially since 2007 [125].

Increased stratification has consequences for primary production that are felt through the food web. Diatoms, which are of high nutritional value to copepods, grow well in conditions of stable water layers with high nutrient availability. After the nutrient levels are reduced, smaller types of phytoplankton that are poorer-quality food for copepods grow better [126, 127]. Trends to smaller types of algae in years with extensive sea ice melt have been documented in the Canada Basin (Box 4) and on the Chukchi shelf [128]. Planktonic bacteria that recycle organic matter and do not photosynthesize may also increase and become a significant part of the biomass [127, 129]. Some bacteria may have an important role in reducing concentrations of critical nutrients [130].

Box 4. Increased stratification in the Canada Basin leading to changes in the food web

Stratification of the water column increased throughout the Canada Basin over a recent five-year period, accompanied by a change in phytoplankton communities [127, 152]. The upper ocean layer showed trends of increased temperature and decreased salinity (Figure 18A), which combine to make this layer progressively less dense. The layer of water below this did not change in density over this period (not shown). The larger size class of phytoplankton (which would include diatoms) decreased in abundance, while the smaller types of plankton increased (Figure 18B). In addition to the trends shown, nutrient content in the upper ocean water layer decreased. Abundance of microbes (bacteria and similar organisms) that subsist on organic matter increased. Total phytoplankton biomass, however, remained unchanged.

If this trend towards smaller species of phytoplankton and microbes is sustained, it may lead to reduced production of zooplankton [5, 148], an impact that would be transmitted through the food web to birds, fish and mammals [21].

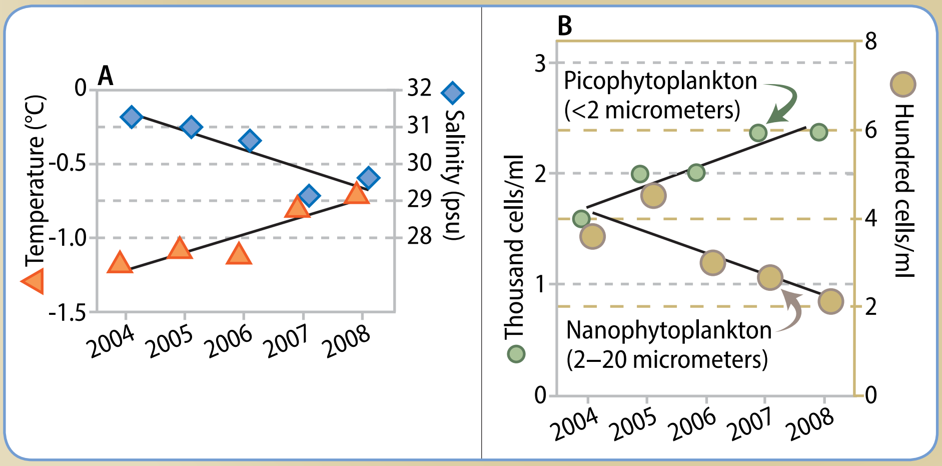


Figure 18. Trends in water temperature and salinity (A) and density of phytoplankton of two size ranges (B), Canada Basin, 2004 to 2008
Samples are from the upper ocean during summer. Points on the graphs are averages of data for 23 stations that were distributed across the Canada Basin.
From Li et al. 2009 [127]

Blooms of coccolithophores, a type of small phytoplankton that is abundant in the oceans south of the Arctic, appear to be expanding northward into Arctic seas, as observed in both the Barents and Bering seas [131–133]. Large blooms of coccolithophores have occurred in the southern Barents Sea since at least the late 1980s, originally just in some years, and more recently, every year. The blooms occur in late summer, when nutrients in the upper water layer have been depleted and the diatom-dominated larger plankton have declined (Figure 19). Coccolithophores are swept along with deep-water currents that move Atlantic water to the edge of the western Eurasian shelf. If ocean conditions are favorable, they may then rise to ice-free surface waters and flourish. Blooms of coccolithophores in the northern Barents Sea were first recorded in 2003 [131].

A massive late-summer bloom of coccolithophores occurred in the southeastern Bering Sea in 1997 and annually thereafter. The blooms have decreased in intensity since 2001. Researchers consider that the main factor in the decrease is the difference in temperatures between the bottom and surface waters and how easily they are mixed by the wind [133]. In years with large coccolithophore blooms, the dominant zooplankton species in the southeastern Bering Sea shifted from crustaceans to jellyfish and other gelatinous plankton [134]. In general, longer ice-free periods extending over greater areas are likely to lead to further northward expansion and more frequent blooms of coccolithophores and other open-water species from the Atlantic and Pacific oceans.

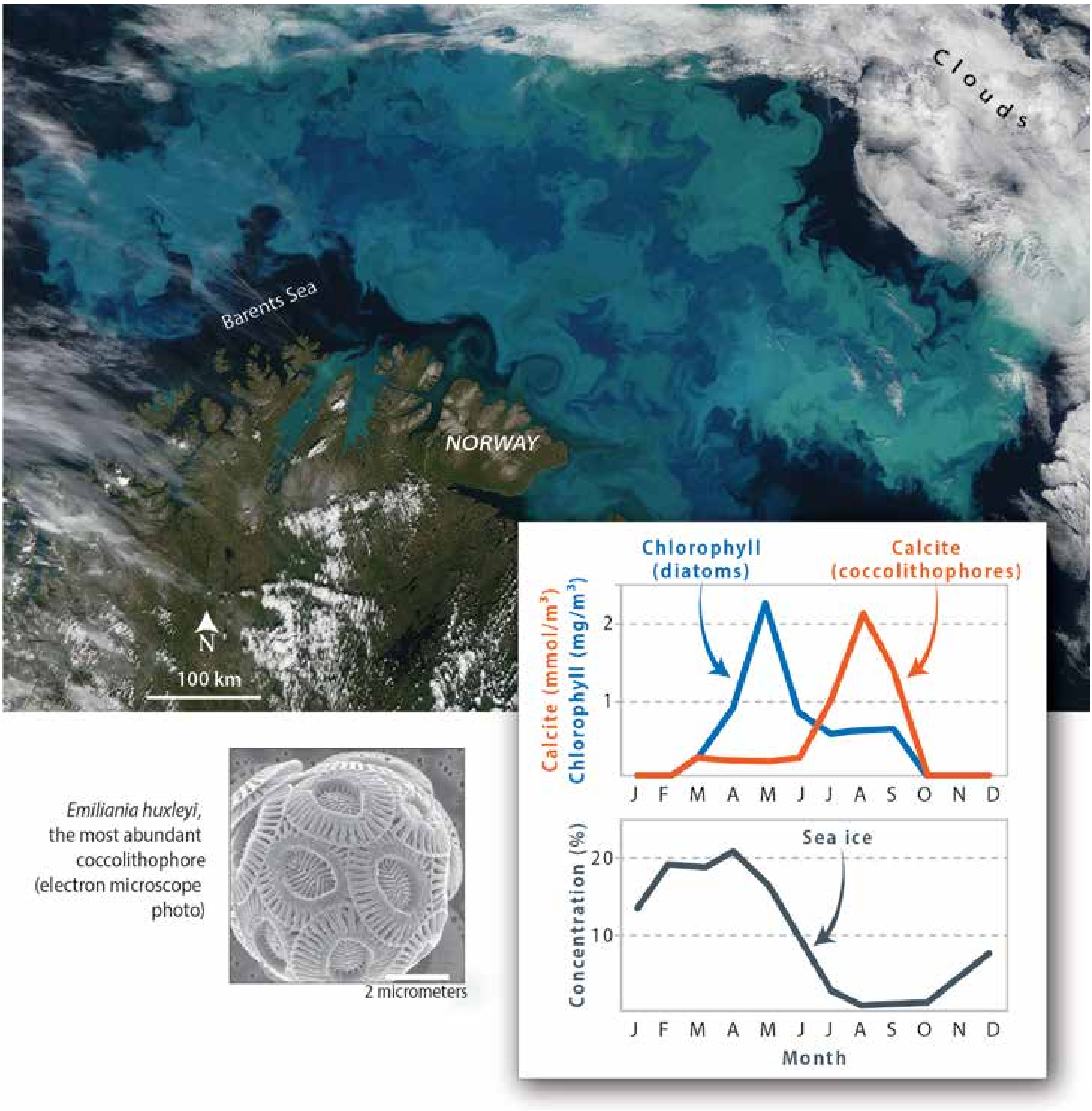


Figure 19. Phytoplankton bloom in the southern Barents Sea, August 14, 2011 and relationship between timing of blooms and sea ice

The color in this satellite image is created by a massive phytoplankton bloom. The milky blue areas indicate a high abundance of coccolithophores, plankton that are plated with white calcium carbonate. Other colors may be from other plankton types and suspended sediment.

The graphs, which are from a study over approximately the same area, show the relationship between the timing of blooms and the timing of sea ice. Diatoms (indicated by chlorophyll concentrations) dominate the earlier bloom that is associated with ice melt. Coccolithophores (indicated by calcite concentrations) dominate late summer bloom. They thrive in stable surface layers of warm, low-salinity, low-nutrient water. Coccolithophore blooms are becoming more frequent in the southern Barents Sea and expanding northward to the high Arctic.

All data shown are based on analysis of satellite imagery. This natural-color image was taken by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on the Aqua satellite.

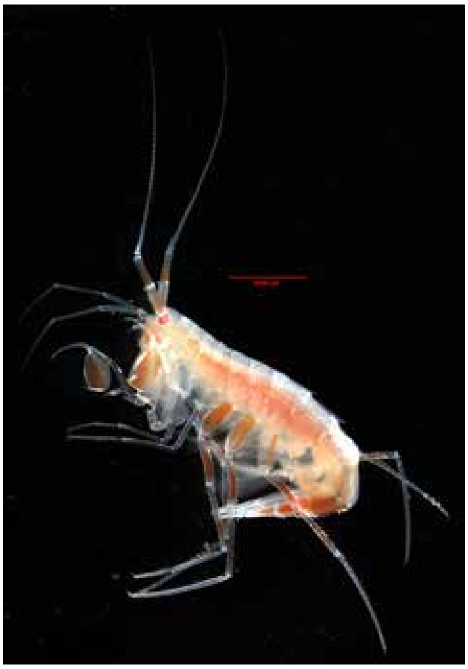
NASA image courtesy Jeff Schmaltz, MODIS Rapid Response Team at NASA GSFC; graph from Signorini and McClain 2009 [153]; caption based on Signorini and McClain 2009 [153], Carlowicz and Riebeek 2012 [154]

Potential mismatch in timing between phytoplankton and zooplankton production

Changes in the extent and timing of the ice cover could have major impacts on zooplankton communities because zooplankton seasonal life cycles are tuned to the annual patterns of ice break-up and phytoplankton blooms [135]. The seasonal success of the zooplankton communities determines what food is available at critical times in the life cycles of larger invertebrates, fish, seabirds and marine mammals [136]. Because of these food-web linkages, major changes in zooplankton abundance at specific times of the year would ultimately affect commercial fishing and subsistence harvesting.

One of the areas of uncertainty that make it hard to predict what earlier and more extensive ice melt will bring is what is happening in the pelagic realm under the sea ice during winter. Most zooplankton sampling has been carried out in summer, with the exception of studies from stations on ice drifting over the deep basins of the central Arctic [137–139] or from land bases on the White and Laptev seas [140, 141]. The prevailing view has been that zooplankton overwinter in dormant states and numbers are much reduced due to lack of food [142, 143]. In spring, the zooplankton become active and need a burst of concentrated food resources for reproduction and growth of juvenile stages.

This annual cycle raises an important question: Are zooplankton able to adjust their life cycles to take advantage of earlier spring blooms or will a mismatch between phytoplankton and zooplankton timing lead to declines in zooplankton?



The amphipod Eusirus holmii*, found both in association with ice and in the open ocean*
Photo: Hidden Ocean 2005 Expedition/ NOAA Office of Ocean Exploration

While low light conditions limit phytoplankton development under thick ice, early algal production occurs in polynyas and will always have started earlier in years when little snow cover allowed more light to penetrate the ice, as observed in the Barents Sea [144]. The large algae-eating copepods like *Calanus glacialis* are known to take advantage of early production where and when it occurs [145–148].

Recent winter studies in ice-covered Eurasian Arctic seas [149, 150] and the Canadian Arctic [57] found that, contrary to the long-established view, zooplankton communities in late winter are not in a “sleeping” state. While many zooplankton were dormant, others were active and reproducing, presumably feeding on particles of organic matter and bacteria in the water column [57]. These research results indicate that zooplankton communities may well have the capacity to adjust to more variable and earlier ice algal and phytoplankton blooms. The degree of adjustment, though, will depend on the species composition and on how well each species can deal with a rapid transition to new conditions [151].

The amounts and timing of plankton production also affect the benthic realm. Algae that are not consumed by zooplankton, as well as organic material from plankton production, sink to the seafloor in areas where the water is relatively shallow. This source of organic matter provides food for the benthic food web. The implications of a changing sea ice regime on this transfer of carbon to the benthic realm are discussed in the next section, Benthos.

3c. Benthos

Benthos, the flora and fauna dwelling on the ocean floor, are not directly ice-associated but are strongly influenced by sea ice distribution and its annual cycle of melting and refreezing. The longer ice-free season and greater extent of ice-free seas are altering benthic ecosystems by changing the environment in which benthic algae and invertebrates live.

Arctic benthos ranges from unicellular life in the spaces among sediment particles to large invertebrates (Figure 20). Much, however, remains unknown about the species composition of Arctic benthos, particularly in deep waters. Several new species have recently been described from a broad range of taxa and regions [63, 155, 156]. After research and review of past records through the Arctic Ocean Diversity project (2004–2011), part of the global Census of Marine Life, researchers estimated that several thousand benthic species are present in the Arctic but are not yet documented. This includes species known from other ocean regions but not yet recorded in the Arctic, as well as species not yet discovered or described [63].

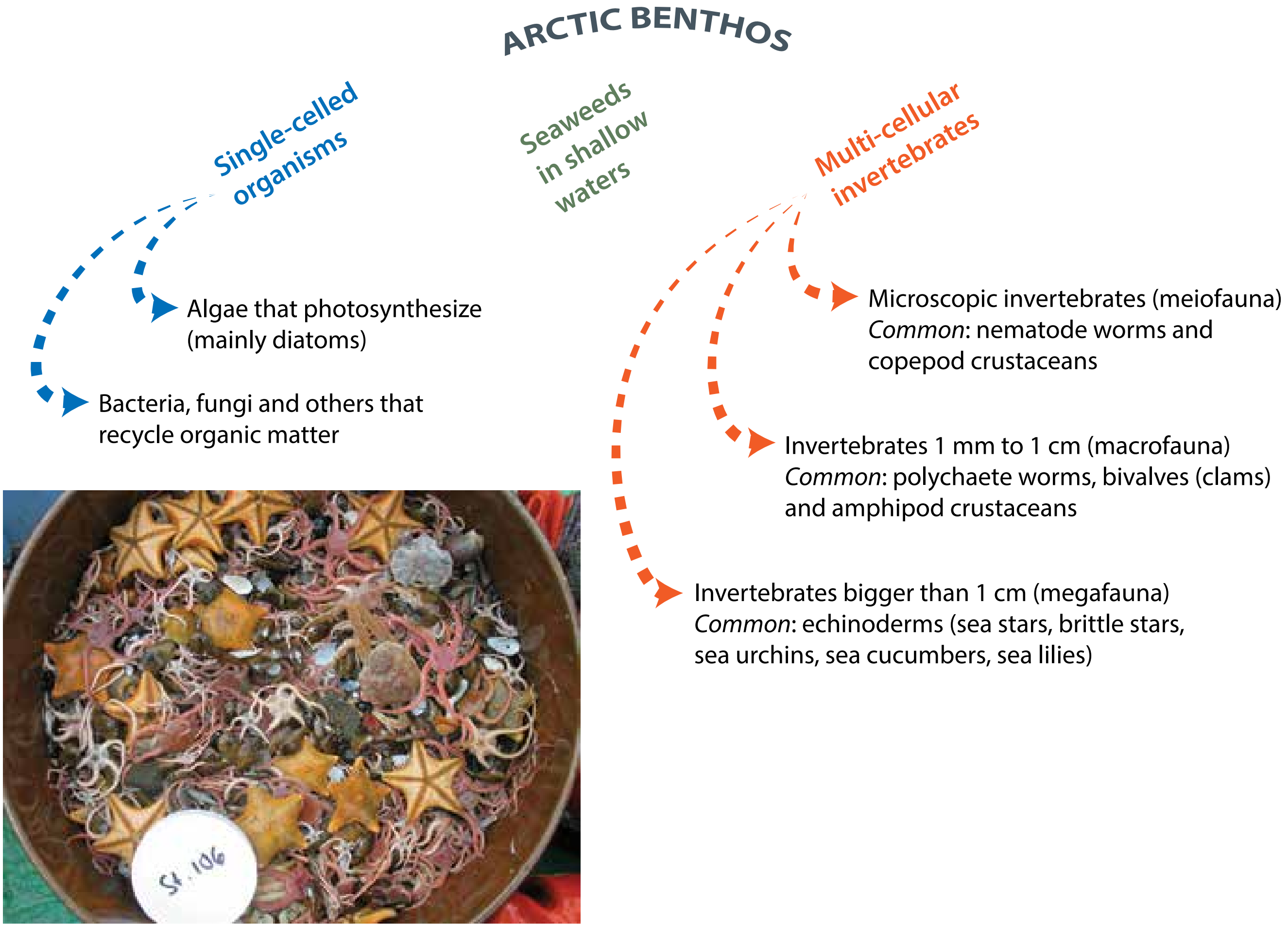


Figure 20. Arctic benthic diversity
There are about 4,500 known species of multi-cellular benthic invertebrates, with highest diversity in the shelf areas, and about 160 to 210 species of seaweeds (macroalgae).
Based on Josefson et al. 2013 [73] and Bluhm et al. 2011 [63]
Photo: Benthic samples from the Chukchi Sea, 2004–2005 Russian-American Long-term Census of the Arctic (photo by B. Bluhm/UAF/RUSALCA 2004)

Connections between the pelagic and benthic realms

With the exception of some coastal waters, the bulk of the primary production that fuels benthic food webs originates in the pelagic realm. Plankton, ice algae, and an assortment of organic matter drift down through the water column. Sea ice affects how much of this potential food ends up being recycled through the pelagic food web versus how much descends to the ocean floor.

Amounts of phytoplankton and zooplankton production and the timing of algal blooms and peak zooplankton production are important factors in determining this "coupling" of the benthic and pelagic realms [157]. If, for example, the earlier ice-algal production and phytoplankton blooms associated with advancing sea ice melt are mismatched in timing to zooplankton peaks, more algae could fall to the ocean floor, enhancing benthic production [118]. On the other hand, longer ice-free seasons and algal production that is either reduced or extended over the summer could lead to a larger proportion of algae being grazed by zooplankton, with less ending up on the ocean bottom [22, 97]. Reductions in the transfer of production to the ocean bottom accompanied by reduced biomass and changed species composition have been observed in the Bering Sea [158] and Fram Strait [159] (see also Figure 14 in the section on Ice flora and fauna). There are many factors that influence this balance, so regional differences will play a role in how changes in sea ice affect the coupling of the benthic and pelagic realms [57].

A recently described new species of sea cucumber, Elpidia belyaevi, *that is now known to be widespread through the central Arctic*
Photo: A. Rogocheva/Shirshov Institute of Oceanology, Moscow

Distribution of benthos and changes in benthic communities

Where, when and over what period plankton, ice algae and organic matter sink to the ocean floor is important in determining the biomass and composition of benthic communities [22, 26, 57]. Ice-edge conditions that promote high plankton production, including in polynyas, also tend to be associated with high benthic production. In the Eurasian shelf seas, analysis of long-term data sets shows that benthic invertebrate biomass is particularly high in areas that experience ice-edge conditions over long periods (Figure 21). Polynyas are especially important as they represent areas of consistently favorable ice-edge conditions, high production and, therefore, reliably high export of food supplies to the benthic realm. (See the Bird section for examples of polynyas' value to mollusk-feeding seabirds.)

Changes in sea ice that affect the location of marginal ice zones, leads and polynyas, alter the distribution of the food supply for benthic invertebrates and, thus, will affect how biomass is distributed [160, 161]. This, in turn, affects the distribution of food supplies for the fish, seabirds and mammals feeding on benthic invertebrates. Benthic communities have experienced changes over the past few decades, especially in the Arctic seas [22, 162]. These changes include shifts in biomass and species, likely due to a range of factors, among which changes in ice and resulting alterations in water temperature and productivity may be important. The commercially fished snow crab has expanded northward in the Bering and Chukchi seas and moved into the Barents Sea [22, 163]. Other species extending their ranges northward include several crab and mollusk species in the Chukchi Sea [162] and the blue mussel in Svalbard [63].

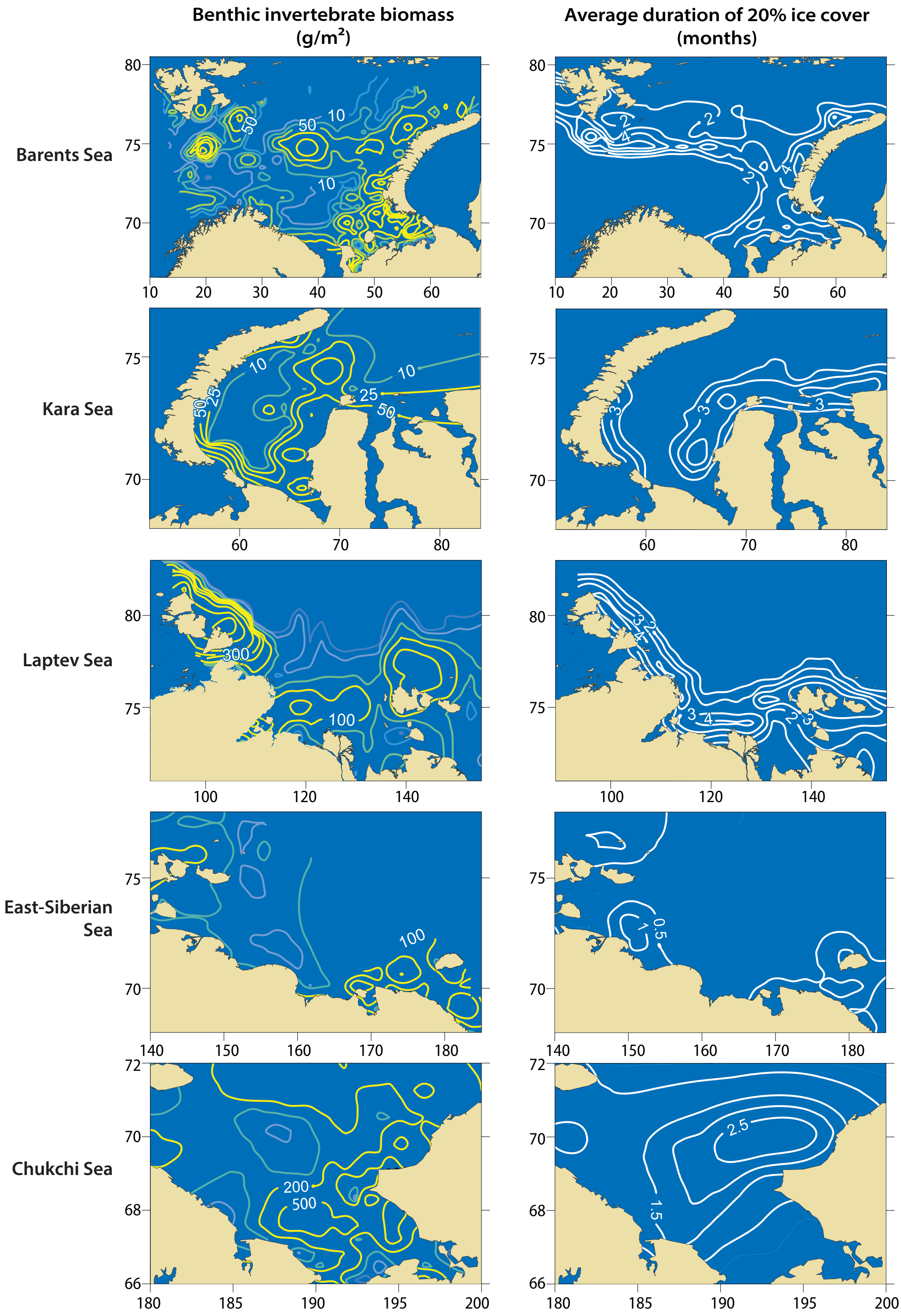


Figure 21. Zones of high benthic biomass correspond with marginal ice zones: Barents, Kara, Laptev, East-Siberian and Chukchi seas, based on long-term Russian datasets

The lines are "isolines", meaning they connect areas with the same value of benthic biomass (left column) or ice concentration (right column). They are displayed the same way a topographic map shows elevation contours. For example, the area enclosed by the isoline labeled 500 in the map in the lower left hand corner has a biomass of 500 g/m^2 or more. The zones with average long durations of 20% ice cover (right column) are polynyas and marginal ice zones associated with land-fast ice. Statistical analysis reveals that the zones of high biomass are significantly associated with the zones of long duration of ice-edge conditions.

Figure prepared for this report by S. Denisenko, Zoological Institute, Russian Academy of Sciences, St. Petersburg, based on archived data from 950 stations from scientific expeditions conducted 1932–1935, 1968–1970, 1975–1986 and 1993–1995. Ice concentration data from Schlitzer 2012 [173], calculated as 1960–1990 averages

Water depth and the type of sea floor (rocky or with soft sediment, for example), as well as water characteristics such as temperature and freshwater content, are important for distribution and productivity of benthos [63, 164]. In coastal areas, expansion of seaweeds can alter benthic communities. There are fewer seaweed species in the Arctic than in other oceans (except in the Antarctic) because of the limitations imposed by factors such as shortage of rocky substrates and ice scouring [165, 166].

In the shallow waters of the shelf regions, physical disruption of habitat by ice scouring is particularly important in determining the distribution of both seaweed and benthic invertebrates. Few species and low biomass are generally found in areas with frequent ice scouring [63, 167], though infrequent ice scouring can also increase benthic diversity by creating a patchwork of communities at different stages of succession [168]. Changes in sea ice will alter the process of ice scouring. In some shelf areas, reduced ice extent and thickness are likely to reduce the frequency and intensity of ice scouring, leading to more diverse and productive benthic communities [63]. On the other hand, delayed freeze-up might move the zone of piled-up, deformed ice that forms seaward of the land-fast ice closer to shore in some areas, increasing ice scouring [169].

In Svalbard fjords, increased water temperatures in the past three decades have had little effect on benthic communities on soft, sediment-rich substrates [170, 171]. Increases in seaweeds on rocky substrates in the same area, however, have led to abrupt shifts in benthic invertebrate communities. These changes are attributed to increased growing periods afforded by the reduction in ice, along with higher water temperatures [172] (Box 5).

Brittle stars. Photo: NOAA Ocean Explorer

Box 5. Abrupt ecosystem shifts in benthic communities

A combination of warmer waters and increased light from longer ice-free seasons led to shifts in benthic ecosystems in two Svalbard fjords. Seawater temperatures and ice cover changed gradually over the study period from 1980 to 2010, but the flora and fauna on the rocky bottoms of both fjords remained stable and then changed abruptly at the end of the 1990s, with sudden increases in growth of filamentous and leaf-like seaweeds. The dominant invertebrate fauna also changed at both locations (Figure 22). This is believed to be a regional trend, as seaweed biomass increased three-fold between 1988 and 2008 in Hornsund, to the south of Svalbard [174]. In West Greenland, kelp beds have become more productive and grow to greater depths, changes that are strongly associated with the increase in the length of the ice-free season [175].

If these increases in seaweed persist and expand around the Arctic, as is projected [175, 176], they will be accompanied by changes in the species composition of invertebrate communities on coastal rocky sea floors. These seaweeds provide more food and living space than the thin layer of rock-encrusting algae they replace, so are capable of supporting a greater biomass and diversity of invertebrates [172]. On the other hand, species typical of communities dominated by rock-encrusting algae may decline in numbers or even disappear.

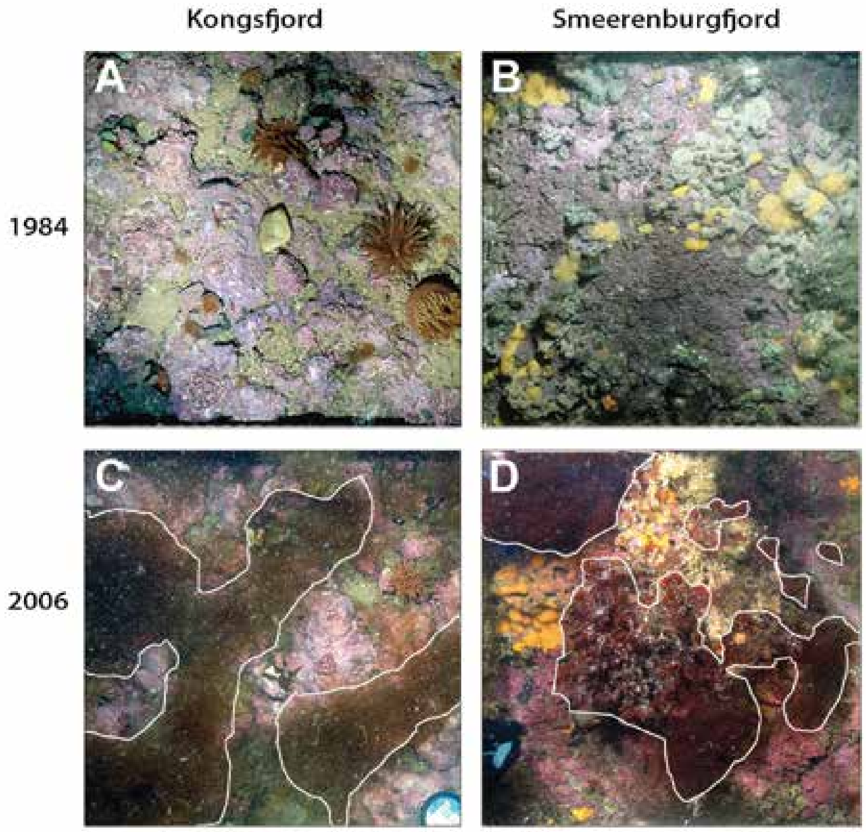


Figure 22. Changes in benthic communities in two Arctic fjords, Svalbard, Norway: photographs from 1984 and 2006
The photographs represent benthic communities in the two fjords before and after abrupt ecosystem changes characterized by a shift from rock-encrusting types of algae to taller filamentous (C) and leaf-like (D) forms of seaweed. Areas within the white lines are covered by these seaweeds. The invertebrate communities changed at the same time. In Kongsfjord, for example, the sea anemones that were common before this regime shift (visible in A) declined rapidly and sea urchins increased. From Kortsch et al. 2012 [172]

3d. Fish

At least 750 fish species frequent Arctic waters, the bulk of them marine (Figure 23). Of these, only two are known to be closely and directly associated with sea ice year-round: polar cod *Boreogadus saida* and ice cod *Arctogadus glacialis* [82].[1] Others, however, are undoubtedly influenced by sea ice presence and dynamics through physical and ecological pathways.

Polar cod is particularly abundant and widespread. It is of great importance in Arctic marine food webs, providing, for example, the bulk of the spring food intake of ringed seals in Svalbard [177], Greenland [178], and northern Baffin Bay [179].

Polar cod and ice cod feed on amphipods and other invertebrates under the ice and in water pockets within the ice [180, 181]. Polar cod also rest in cracks and cavities in the ice, likely as a strategy to avoid predators (Figure 24).

Both species are widespread and found in a range of habitats, including habitats without ice. In Greenland fjords, polar cod are found primarily in the water column, while ice cod are mainly at the bottom of the ocean [182], but this division of habitats does not hold everywhere. Ice cod are known to also feed in the upper part of the water column at offshore locations [183]. This inborn flexibility may mean that the ice-associated cods will be able to adapt to new conditions, at least in some areas.

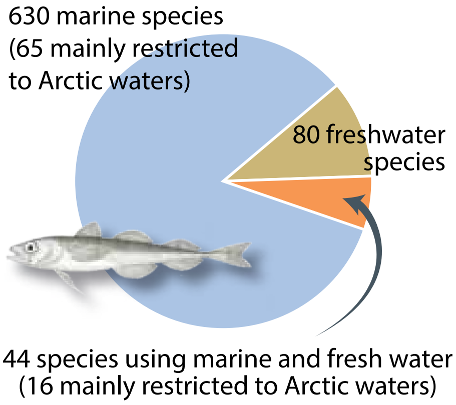
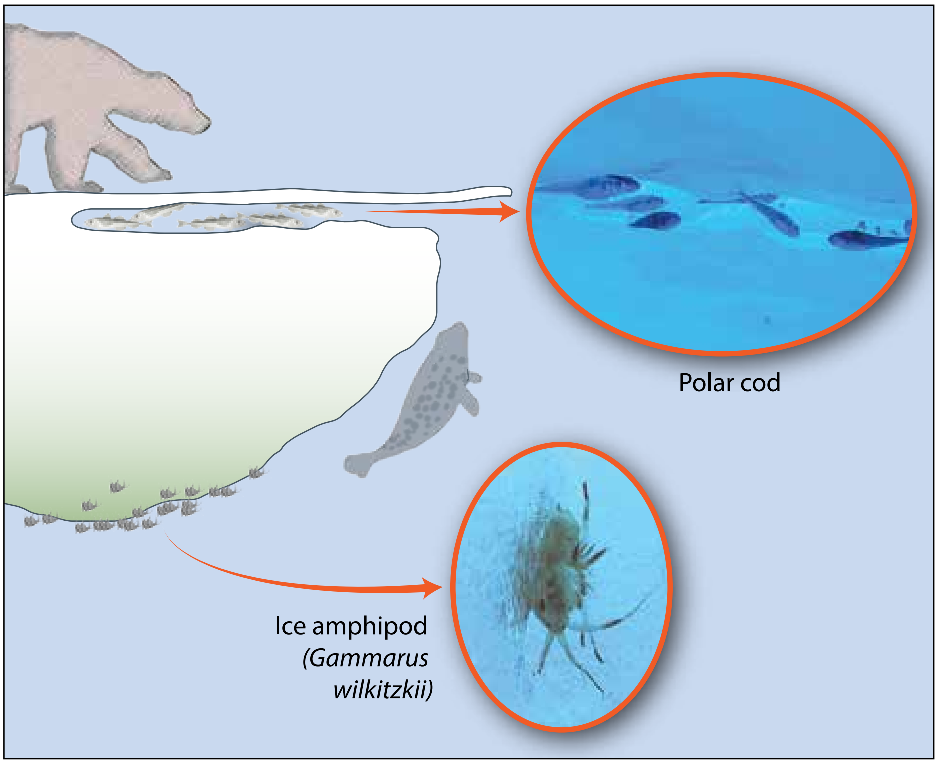


Figure 23. Number of fish species found in Arctic waters.
Species numbers are approximate.
Drawing is of a polar cod.
Data from Christiansen et al. 2013 [207]

Figure 24. A simple sea ice food web with polar cod, amphipods, ringed seal and polar bear
Polar cod feed on amphipods under the ice and rest in sheltered spaces in the ice such as the seawater wedges shown.
Based on Gradinger and Bluhm 2004 [208]; photos: Gradinger and Bluhm / UAF/NOAA/CoML (top), Shawn Harper/ UAF (bottom)



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[1] The common names for these two cod species can lead to confusion, as in North America *Boreogadus saida* is known as Arctic cod and *Arctogadus glacialis* is sometimes called polar cod.

Ice edges, food webs, and shifting distributions

Huge concentrations of polar cod have been reported under the ice in winter [184] and at ice edges as the ice recedes in the spring [6, 48, 185]. Ice edges are active zones of high production and intense activity. Currents and upwellings distribute nutrients and organic matter through the water column, algal blooms form in the meltwater, and invertebrates graze on the algae, providing food for fish, birds, and marine mammals [48, 186].

Sub-Arctic fishes are also associated with these productive ice edges, wherever the water is not too cold for them. Capelin—small forage fish eaten by seabirds, marine mammals, and other fish—follow the southern edge of seasonal ice in the northern Atlantic Ocean and Barents Sea as the ice melts each year, feeding on ice-associated, lipid-rich zooplankton.

Ice is now melting earlier, and more of the southern part of the Arctic Ocean is ice-free in summer. Changes in the diets of seabirds in the Canadian Arctic over a 30-year period provide evidence that capelin are extending their distribution northward and polar cod are retreating from the southern regions of the Arctic in response to these trends in sea ice (Figure 25).

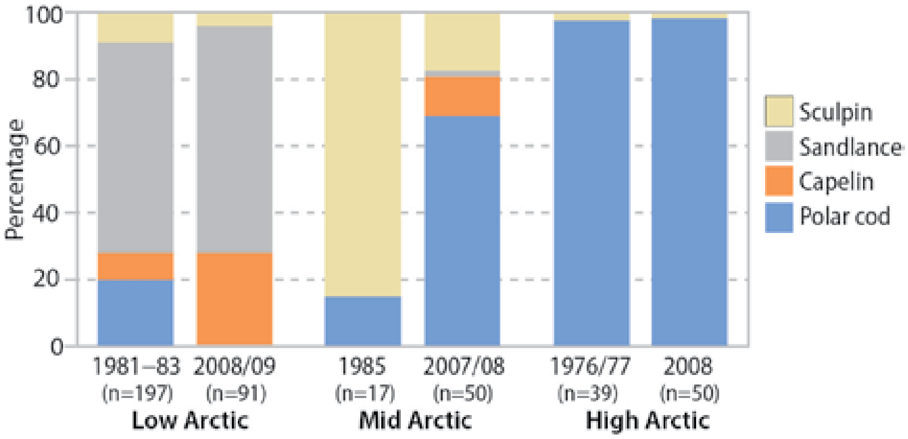


Figure 25. Polar cod and capelin in diets of thick-billed murres, comparing a recent study with 30 years ago: low, mid, and high Arctic locations in eastern Canada

This chart shows the breakdown by species of identified fish in stomach samples of murres. Polar cod continue to dominate the diets of high Arctic murres, but capelin appear to have replaced polar cod in the low Arctic, where ice has retreated to the greatest extent. Capelin have also appeared in the mid Arctic, where the species was absent in 1985 samples but present in a third of the samples from 2007/08.

From Provencher et al. 2012 [209]

Northward shifts in fish distribution have been documented in the Barents and Bering seas [187–189]. These shifts are generally considered to be partially related to changes in zooplankton caused by periods of warmer sea temperatures and accompanying changes in sea ice timing and distribution [190–192].


Murre feeding on capelin. Photo: Kyle Elliot

The sub-Arctic fishes that dominate the deep waters of the central and southern regions of the Bering Sea, including walleye pollock and Pacific cod, are limited in how far north they can expand by the “cold pool” [193]. This deep, cold water forms under the ice every winter in the northern part of the Bering Sea and remains until fall, even in warm years. It acts as a barrier to species that cannot tolerate low temperatures. It is not, however, a barrier to range expansion for more cold-tolerant species and those that live closer to the sea surface, including Pacific salmon [193]. The cold pool is expected to continue to reappear each year as long as winter ice forms in the north Bering Sea.

Box 6. Earlier sea ice melt may lead to a decline in the Bering Sea pollock fishery

The walleye pollock fishery is a commercial fishery in the northwestern Pacific Ocean, with landings of 1.3 million tonnes in 2011 [210] valued at 375 million US dollars. Until recently the prevailing view was that climate warming would lead to greater pollock production, but this has been shown not to be the case [211, 212].

Conditions in the Bering Sea shift between warm and cool phases, driven by the broad-scale climate pattern of the Pacific Decadal Oscillation [213]. In warm years, the sea ice melts early in the year and the sea becomes well mixed by winter storms that are still prevalent. Instead of following the general pattern of earlier melt leading to earlier algal blooms [214], the wind mixing keeps the surface waters from warming up and delays the annual algal bloom. In cold years, ice breaks up later and algal blooms develop quickly in the stable layer of meltwater that forms on the surface of the sea [212].

The net result is that in years with earlier ice melt the delayed algal blooms lead to a reduced crop of the large crustacean zooplankton that are the best food for pollock in their first summer. The young pollock do not build up the energy reserves they need to survive the winter and they are more vulnerable to predation and to cannibalism by larger pollock. The following spring, there are few year-old pollock entering the population [212]. High sea-surface temperatures in late summer also reduce the availability of large crustaceans for the young pollock [211].

Poor survival of first-year fish during the warm years with early sea ice melt from 2002 to 2005 led to a severe decline in Bering Sea pollock. Stocks rebounded in the colder years that followed [193]. A Bering Sea climate regime with more prolonged warm periods, as is projected by climate models, will likely lead to a decline in stocks and a reduced walleye pollock fishery [211].

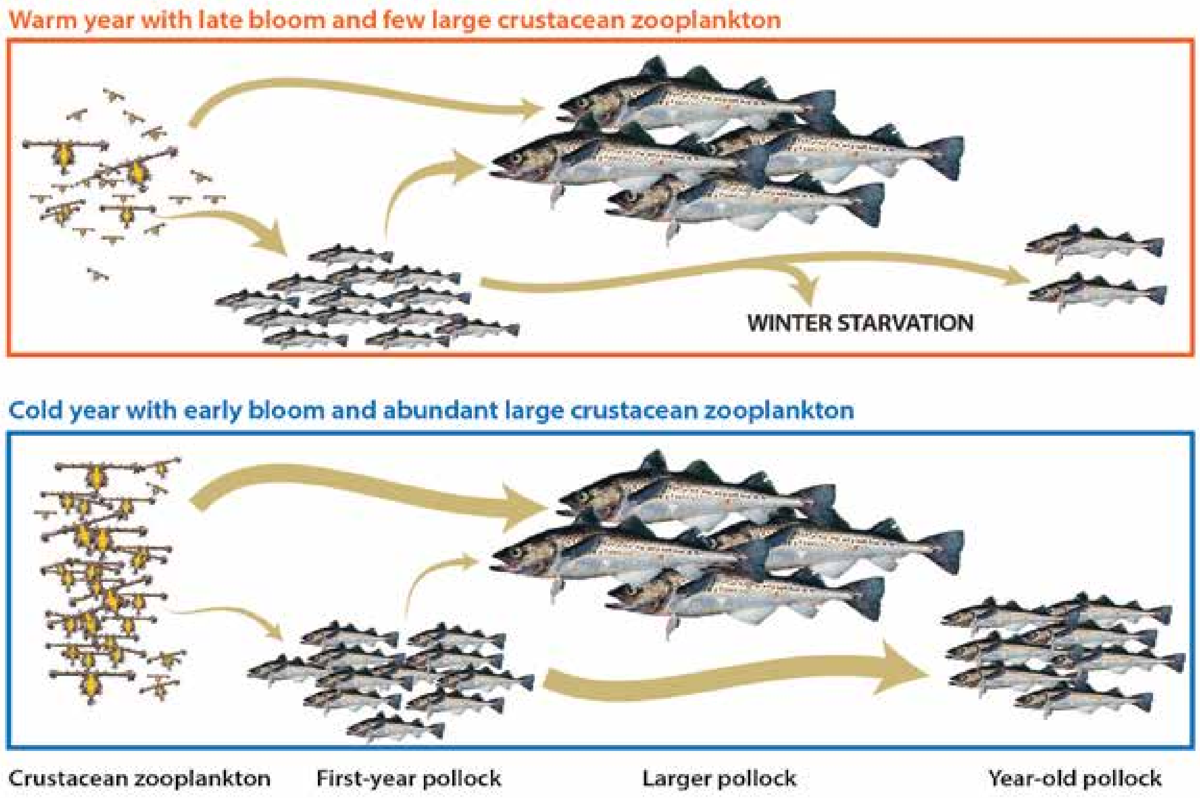


Figure 26. The fate of first-year pollock in fall and winter depends on availability of large crustacean plankton
Predation, cannibalism by larger pollock, and starvation in winter increase for first-year pollock in years with earlier sea ice melt (top diagram).
From Hunt et al. 2011 [212]

Anadromous fishes

Fishes that spend part of their life cycle in marine environments and part in freshwater (anadromous fishes), including Pacific and Atlantic salmons, Arctic char, and whitefish species, are important in northern fisheries [194]. Anadromous fishes are especially important in subsistence fisheries that supply cultural and food services to Arctic Indigenous Peoples [195, 196].

Whitefishes and chars derive most of their energy from feeding in the nearshore and shelf marine environments during the open-water season [197]. Sea ice influences the productivity of these waters and controls when fish can migrate along the coast. Changes in extent and timing of coastal sea ice are likely to lead to earlier and longer access to marine systems for whitefish and char species [198]. If the nearshore feeding grounds remain as productive as they are now, or increase in productivity, the overall abundance, survival, and growth of these fishes may stay the same or even increase.

Fisheries

Effects of changing sea ice on most fish stocks remain uncertain. Many Arctic and sub-Arctic fish species are influenced by ice, especially through its effect on the timing and abundance of their food supplies.

Increases in primary production resulting from warmer water and reduced sea ice cover may translate into more productive fisheries in some areas: for example, the Barents Sea herring and Atlantic cod fisheries [189]. This will not, however, be the case for all fish stocks and cannot be counted on until the effects of complex interactions through the food web are better understood (see Box 6 on Bering Sea pollock).

Northern bottom-dwelling species, including Greenland halibut, appear to be sensitive to environmental changes related to climate—but the role of sea ice is not clear [199, 200].

Changes in sea ice also affect access to fish. Reduced sea ice, both in winter and in summer, is opening new areas to potential commercial fishing [201, 202], with major implications for ocean governance and fisheries management regimes [203, 204].

The predictable and relatively smooth sea ice surface in fjords in the eastern Canadian Arctic led to the initiation of a small ice-based long-line fishery for Greenland halibut in Cumberland Sound, Baffin Island, in 1987. Annual harvests varied from 4 to 430 tonnes. Over the years, from 6 to 115 people from the Inuit community of Pangnirtung were involved as fishers, and the fishery employed additional people in a processing plant. Changes in the nature of the sea ice (rougher) and its formation (later, less predictable, and no longer over ideal fishing locations) contributed to the initial decline of the fishery [205]. This decline was compounded by factors that influenced fishers' participation, such as loss of gear in a major storm and financial capacity, and possibly by factors that affected the halibut catch but were not associated with sea ice, such as scavenging of hooked halibut by Greenland sharks and changes to the marine environment associated with the North Atlantic Oscillation [206].

Catching Greenland halibut. Photo: vtluvbug79, Flickr

3e. Seabirds

Birds use sea ice principally as a resting platform. While a few species, such as gulls and jaegers, hunt or scavenge food on pack ice, most ice-associated seabirds feed in the water. They mainly use the marginal ice zone or pack ice that has areas with open water, such as polynyas and flaw leads, because that is where their food is concentrated (Box 7).

Resting on ice can have a significant effect on seabirds' energy budgets. For example, Lovvorn et al. [215] estimated that spectacled eiders expend about 50% more energy if they are floating on water rather than resting on ice. As eiders spend a lot of their time resting, the presence of ice could be critical in determining survival in years of low food supply.

Changes in sea ice have direct impacts on distribution and timing of these preferred resting and feeding areas. Changes in ice can also affect marine birds indirectly through impacts on important ice-associated prey, such as polar cod and ice amphipods.

Seabirds most associated with sea ice are species of:

Gulls and terns, including ivory gull, Ross's gull, glaucous gull, black-legged kittiwake and Arctic tern. Eat mainly fish; some scavenge marine mammal carcasses. Nest in colonies on cliffs and islands. Often associated with polynyas.

Auks, including murres, guillemots, and the little auk. Most nest in large colonies on rocky cliffs. Dive for fish and crustaceans.

Sea ducks, especially eiders. Nest on the ground on islands, coastal areas, and tundra. Winter at sea, diving for clams and other invertebrates.

Other seabirds are in the Arctic, mainly in summer, on the tundra, along the coast, and sometimes well out to sea. These include jaegers, skuas, fulmars, and shearwaters, as well as other types of ducks and geese.

Overall, climate warming may ultimately make a positive contribution to energy budgets for marine birds through increased primary production [116]. However, the transition from ice to open water will almost certainly have a negative impact for some species.

Use of multi-year ice

The best candidate for an all-season ice-dependent species is the ivory gull. Most of the worldwide population remains in ice-covered waters throughout the year [216]. Nesting mainly takes place on islands in areas with multi-year ice, or, in Canada, on nunataks (rocky peaks protruding from glaciers). Some ivory gulls in Greenland breed on ice floes [217]. Breeding birds feed in the marginal ice zone and venture far into the multi-year ice of the Arctic Ocean to areas with drift ice, polynyas, and ice edges [218, 219]. Close to 90% of the world's population breeds in the western Russian islands [220], and all ivory gulls winter along ice edges in either the northern Bering Sea, southeast Greenland, or Davis Strait [218].

In Canada, the range of the ivory gull, which shifts colony sites frequently, has contracted over the past 30 years. Colony surveys show population declines of over 70% from the early 1980s to 2009 [221]. Although the cause of the decline is unknown, most of the Canadian population has retreated northward, suggesting that the remaining birds are concentrated in areas of prolonged summer ice cover. The current nesting population of ivory gulls in Russia is estimated at 11 to 13 thousand pairs with no apparent trend [222]. Warmer springs with less ice cover in some of their breeding range may favor the gulls (Figure 27).

The Ross's gull, which breeds mainly on the Arctic coast of eastern Siberia, spends the non-breeding season in regions of heavy pack ice [223, 224]. Non-breeding Ross's gulls are also common in summer in the heavy, multi-year pack ice zones of the Arctic Ocean [225–227]. Small numbers of these gulls breed in close association with ice edges and polynyas in the multi-year ice, as observed in North Greenland [228] and the Canadian high Arctic [229].

Little auks breeding in East Greenland and Svalbard use the marginal ice zone of multi-year ice to feed on ice-associated amphipods [230–232]. The little auks nesting on Svalbard islands make excursions of over 100 kilometers to reach these highly productive feeding zones [232].

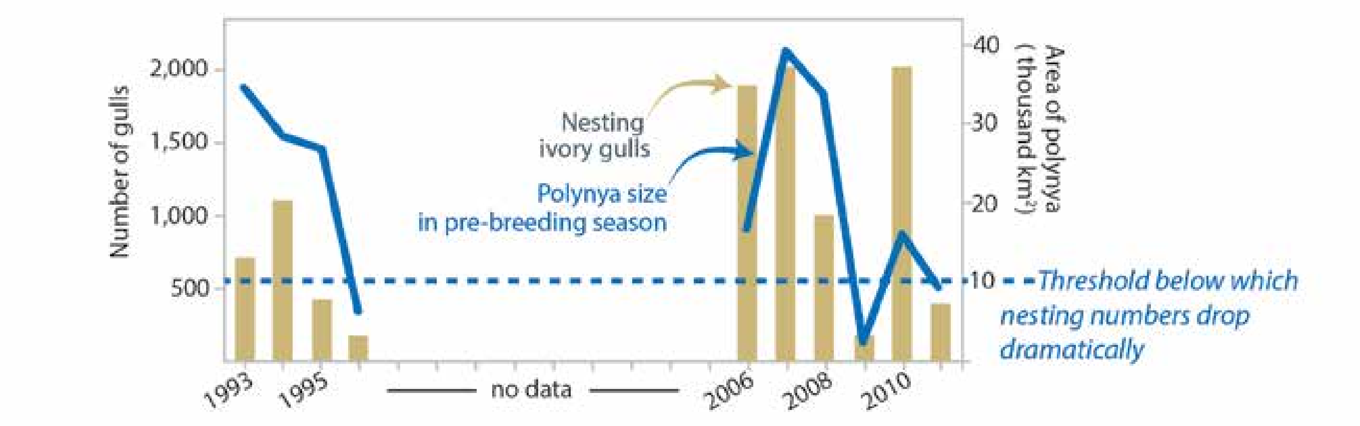


Figure 27. Number of nesting ivory gulls and area of the nearby polynya they are assumed to feed in during pre-breeding season, Severnaya Zemlya, Kara Sea, Russia, 1993 to 1996 and 2006 to 2011
The bars show survey results at the world's largest ivory gull nesting colony on Domashny Island. Numbers of nesting ivory gulls fluctuate from year to year depending on environmental conditions in the pre-breeding season (mid-May). In the northeastern Kara Sea, where wildlife is limited by the harsh ice conditions, polynyas are important for foraging [255]. More gulls are able to build up enough fat resources for egg-laying when there is more open water in a large nearby polynya prior to nesting. If the area of the polynya remains below a threshold of about 10,000 square kilometers (dashed line) by mid-May, dramatically fewer gulls nest at the colony, as occurred in 1996, 2009 and 2011.
From Gavrilo 2011 [222]

Shifts in ranges

With decreasing summer ice cover, population expansion of ice-associated bird species in the northernmost parts of their range, along with reductions and range contractions at the southern edge, are likely. Some shifts have already been detected, including for ivory gulls, as noted above. Small but significant reductions have also been documented for glaucous gull populations in several parts of their low Arctic range (CAFF Seabird Group, unpublished). Although there is limited scope for high Arctic species to expand to the north, the decrease in the area of multi-year ice may increase access to open water in some areas. Sea ice north of Greenland and the northeast Canadian archipelago is the thickest and densest in the Polar Basin and, historically, used by only a few seabirds. The most likely candidates to take advantage of less multi-year ice in these areas are eiders, black guillemot, Ross's gull, little auk, and thick-billed murre.

In recent years the common eider has expanded its range more than 300 kilometers northward in Greenland, suggesting that it is taking advantage of access to new foraging grounds [233]. Seabird breeding colonies along the east coast of Greenland are associated with polynyas within the multi-year drift ice. The coastline in between these polynyas supports very few breeding seabirds. Ice in this region has decreased in recent years [234] and may open the way for range expansions along the coast and for population increases among seabirds. The same could happen among Canada's Queen Elizabeth Islands.

At the same time more southerly species are expanding northward into formerly ice-dominated waters. For example, great black-backed gulls and razorbills have expanded to Hudson Bay [235], horned puffins to the Beaufort Sea [236], and great skuas to Svalbard [237]. The extent to which competition from sub-Arctic species will affect Arctic species is unknown, but negative impacts are likely [238].

Box 7. Eiders and polynyas

Polynyas are important to sea ducks, especially eiders, which require a mix of sea ice and open water for their daily cycle of resting and feeding [256, 257]. Several eider populations have developed patterns of local movements back and forth from polynyas, where they can be certain of finding open water at any time, to ephemeral flaw lead systems that open and close unpredictably, depending on wind direction and currents [256, 258, 259]. The eiders roost at night in the permanently open polynyas, which are usually in areas where local bottom topography causes very high current speeds that keep the water from freezing. At dawn they make exploratory flights in search of feeding areas. If no flaw leads are available they may fall back on feeding in the polynyas, where food supplies are often depleted. In exceptionally cold winters, when even some normally permanent polynyas freeze over, mass die-offs of eiders may occur [256].

Spectacled eider in flight. Photo: Casey Setash/USFWS

The entire world population of over 300,000 spectacled eiders overwinters in polynyas and flaw lead systems south of St Lawrence Island in the northern Bering Sea [260, 261]. They feed on three species of clams, one of which has undergone a sharp decline since the 1980s. This decline is attributed to warmer water and an increase in variability of the timing of sea ice melt [158]. Future reduction in ice cover is likely to affect the eiders through reduction in food and reduced opportunity to rest on ice floes. Commercial fisheries enabled by reduced ice could also have a negative impact on this population by disturbing the ocean bottom, the source of the eiders' food [215].

Spectacled eiders in a polynya in the northern Bering Sea. Photo: Bill Larned

Capacity to adapt to changing ice conditions

Many Arctic seabirds, including murres and northern fulmars, habitually return each year to the breeding colonies where they were reared. Hence, changes in breeding range are likely to be slow for colonial seabirds. The founding of new colonies may take decades and, in the meantime, birds continue to attempt breeding where conditions are sub-optimal. This happened, for example, with Atlantic puffins in the Lofoten Islands, Norway, where no successful reproduction took place over more than a decade [239]. Birds that do not breed in colonies (for example, jaegers) tend to be more flexible about breeding locations [221]. Range adjustment for these species may be more rapid.

Outside of the breeding season, several marine bird species are known to make major changes in their distribution from year to year [240]. Rapid adjustment to changing ice conditions would seem likely for most species. For example, the post-breeding movements of thick-billed murres in Hudson Bay appear to be determined by the speed and extent of freeze-up in a given year [241]. A recent study, however, demonstrated that common eiders in the northern Bering Sea do not readily alter their wintering locations in response to ice conditions, at least not on a year-to-year basis [42].

Impacts through the food web

Meltwater near the receding ice edge reliably supports blooms of phytoplankton, which in turn support high concentrations of the fish and invertebrates that are eaten by seabirds and fed to their chicks. As the Arctic Ocean switches to an environment with less ice during the breeding season, this pattern is expected to break down (see section on Changes in timing). Blooms of primary production will become less predictable and more diffuse, accompanied by a reduction in ice-associated prey. This could lower reproductive success of seabirds that need dense concentrations of prey, or prey of a particular size range, during the critical chick-rearing period. For instance, comparison of spring ice conditions and murre colony sizes along a north–south gradient in Greenland indicates that sites with less ice-edge habitat are able to support fewer breeding murres [242] (Box 8). The same changes in conditions, however, could benefit other species, such as the northern fulmar, that forage over large areas and rear a single chick over a longer period [243].

Thick-billed murre colony, Svalbard. Photo: ajmatthehiddenhouse, Flickr

Box 8. Sea ice conditions, primary production, and colony size of Greenland seabirds

A study of thick-billed murre nesting colonies along a 1,700 kilometer north-to-south gradient on the west coast of Greenland [242] illustrates how important the receding spring ice edge is for seabirds. Northern nesting locations, with higher sea ice concentrations during the breeding season, faster rates of ice melt, and greater predictability of ice conditions, supported the largest colonies (Figure 28). At more southerly locations, with less ice and more erratic melt patterns, the more diffuse primary production supported smaller numbers of birds.

With the current and predicted trends towards earlier break-up and reduction of sea ice cover, the food availability at these northern murre colonies will likely decline, as may the number of birds that each colony can support.

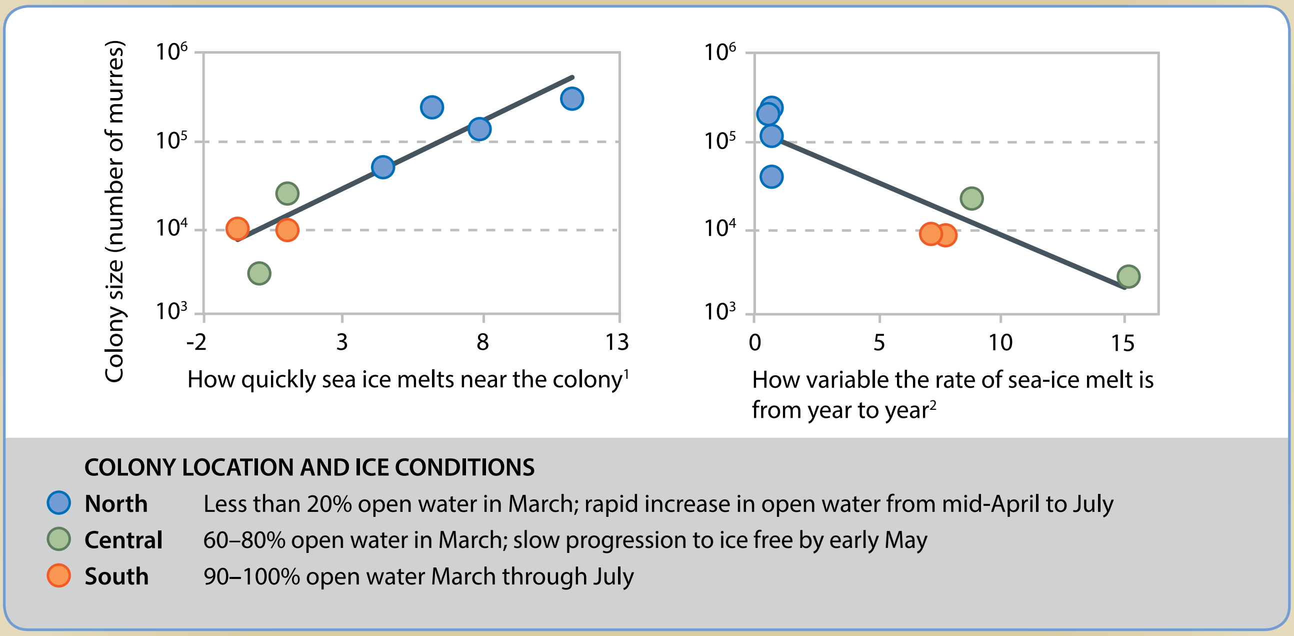


Figure 28. Thick-billed murre colony size in relation to spring sea ice conditions, West Greenland
Based on analyses of data from areas around 46 murre colonies, grouped into regions. Colony sizes are historical maximum estimates of numbers of birds (representing carrying capacity) rather than current population sizes. This approach avoids the confounding factor of overharvest in some areas in recent decades. Sea ice conditions are based on satellite measurements, 1979 to 2004.

[1] Rate of change of fraction of open water, units X 10^{-3}

[2] Statistical measure of variability of the rate of change: residual from mean, units X 10^{-2}

Source: Laidre et al. 2008 [242]

Changes in the distribution and timing of primary production will be felt throughout the food web, but the nature of these changes for any given region is difficult to predict. Ice cover is an important determinant of primary production and also of how well the water is mixed from top to bottom [97]. These factors in turn may affect the proportion of primary production cycled through zooplankton and hence available to birds, compared to the proportion incorporated in bottom-dwelling invertebrates and hence available to birds only in shallow water. A trend towards greater ocean-bottom production, for example, is considered likely for the Barents Sea [244].

Earlier melting of seasonal ice leads to increasing sea-surface temperatures and this will also affect seabirds' food sources. Water around breeding colonies will be warmer earlier in the season. This will likely have impacts on some species of fish and invertebrates that are important food items for seabirds [245, 246]. For example, a replacement of one species of copepod that is adapted to cold waters by another, more temperate copepod species is likely to affect little auk populations [247]. Such a change, affecting the very abundant little auk, could then have consequences for terrestrial ecosystems that are enriched by their droppings [248]. It is difficult, however, to predict how severe the impacts will be, as little auks are able to adjust their foraging strategies to some extent to cope with a range of sea conditions. Little auks showed similar fitness levels across a 5° C range of sea-surface temperatures in a study in the Greenland Sea from 2005 to 2007 [249].

In addition to the bottom-up impacts (through changes to the birds' food supplies), top down impacts (through changes in predation) are likely to result from reduction of sea ice. Breeding seabirds are highly susceptible to predation by mammals while nesting [250]. Sea ice provides access even to remote islands for terrestrial predators such as Arctic foxes (Figure 29). Consequently, most Arctic-nesting seabirds breed either on cliffs or in rock crevices. Reductions in winter ice cover may prevent access by mammalian predators to previously vulnerable nesting locations, making these sites suitable for ground-nesting seabirds and shifting the competitive balance among species (for example, Birkhead and Nettleship 1995 [251]).

Figure 29. Less sea ice may lower predation on seabird nests at some locations by reducing access by Arctic foxes
Risk of predation by foxes is an important factor in choice of breeding locations for ground-nesting birds, such as eiders and gulls [262, 263]. Arctic fox predation can lead to breeding failure in years when late ice melt allows the foxes to reach island colonies during nesting, as recorded for Arctic terns in Greenland [264] and common eiders in Canada [265].
Photo: Sam Chadwick, Shutterstock.com

Detecting impacts at the population level

Many of the impacts from changes in sea ice discussed in this section are mediated through the food web and are likely to affect seabirds through incremental changes, rather than immediately reducing or increasing population abundance. Seabird abundance is also affected by other factors, including harvest pressure and conditions on seasonal ranges outside of the Arctic.


Little auks
Photo: Incredible Arctic, Shutterstock.com

Indicators such as changes in reproductive success or locations of breeding and wintering areas will provide early warning of ecosystem changes that may later be translated into increases or declines in seabird populations. For example, populations of thick-billed murres have increased during periods of moderate climate warming and declined in periods of greater warming [238]. Trends vary around the Arctic [221, 252, 253]. A 20-year study on murre colonies in Canada found a significant, ongoing decline in amount and quality of food provided to nestlings and concluded that this was related to changes in sea ice [254] (see Changes in timing topic). This early warning of negative impacts has not yet translated into measurable declines in reproductive success or abundance of murres in the region, but is likely to do so in the future [254].

3f. Marine mammals

Changes to seasonal sea ice extent are already having negative impacts on some species of Arctic marine mammals. The accelerating ice loss that has become evident in the past few years may represent a significant threat to Arctic marine mammal biodiversity [55]. Reduced seasonal sea ice has the potential to alter the distribution, abundance, and movements of Arctic marine mammals, and to affect interactions among species [266].

Multi-year sea ice, which is now being replaced by seasonal sea ice, influences both the distribution and the abundance of Arctic marine mammals. It can act as a barrier to movement for beluga and bowhead whales and narwhals [266]. Six of the eleven ice-associated marine mammals are known to use multi-year sea ice (Table 1), but only two of these, the ringed seal and polar bear, are distributed throughout the circumpolar Arctic in association with multi-year ice [266]. The densities of both these species, however, are generally low in areas dominated by multi-year ice [267, 268]. Researchers attribute the low density to low primary production associated with multi-year ice. The relatively thick multi-year ice reduces the light available for photosynthesis.

In the short term, increases in primary production under the thinner seasonal sea ice might benefit some populations of ringed seals and polar bears. How much this would enhance their habitat, however, depends on aspects of the physical environment and the ecosystem. Much of the Arctic basin over which multi-year ice is melting is very deep. Increases in primary production will not necessarily transform these areas into feeding zones equivalent in value to the shallow shelf regions that support communities of algae, invertebrates, and fish in the water column and on the ocean bottom [269].

Arctic marine primary production has increased over the past decade due to sea ice decline [116], and this trend is projected to continue [270]. The result might be higher concentrations of zooplankton, to the benefit of some marine mammals, such as bowhead whales [134]. However, the loss of prey species that depend on ice, especially polar cod and amphipods [208], is expected to have negative impacts on other marine mammals, particularly ringed seals [134].

While less sea ice will likely lead to smaller ranges for some species, loss of ice removes a barrier to range expansion for others, especially whales. Humpback, minke, and fin whales and harp, hooded, spotted, and ribbon seals, are among the marine mammal species likely to expand their ranges northward as the ice recedes [271].

Ice as habitat

Narwhal, beluga, and bowhead whales are associated with sea ice year-round. It structures their habitat and feeding opportunities (see case study on narwhal below). Ecosystem changes do not appear to have affected beluga and bowhead whale populations in the Bering, Chukchi, and Beaufort seas. Belugas are not as specialized in their feeding as narwhals and may be more resilient to change. Bowhead whales in this region may have benefited from an increase in zooplankton along the Beaufort Sea shelf due to changes in the ocean caused by sea ice retreat [55, 272].

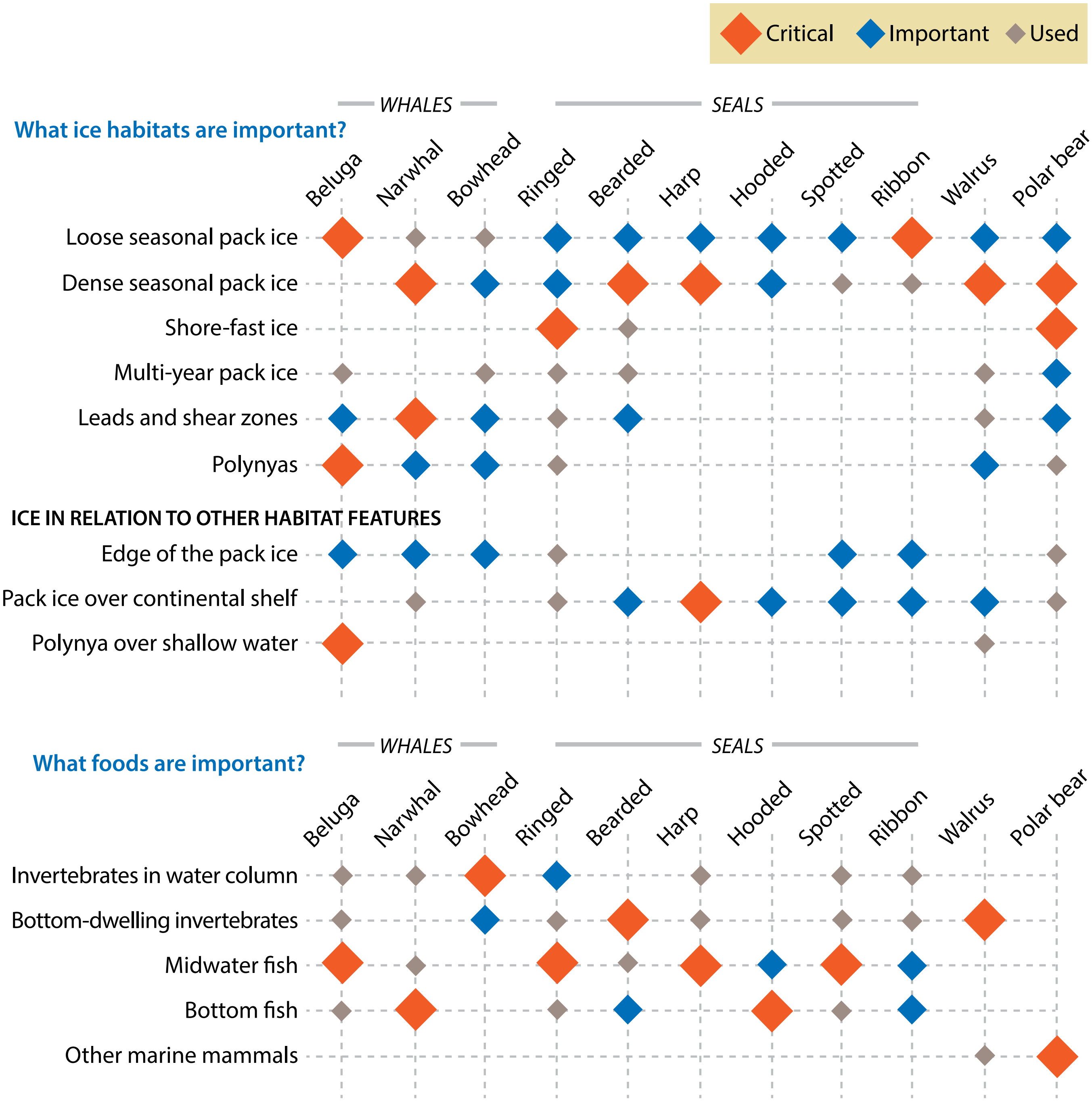
Ringed and bearded seals also live with sea ice throughout the year, and all aspects of their lives are adapted to it. **Ribbon, spotted, harp, and hooded seals** use open-water areas for much of the year but breed on pack ice. They need to have stable ice available in early spring close to food supplies for their pups [55]. Many seal populations are not monitored or have not been monitored for long enough periods to distinguish trends due to changes in sea ice from natural variation. Declines in abundance or reproduction attributed to changes in sea ice have been documented for hooded seals in the northeast Atlantic and harp seals in the White Sea [55]. Ringed seals in Hudson Bay, which were declining in the 1990s, apparently in relation to ice conditions, have increased in abundance in the 2000s [273].

Walruses give birth and mate on sea ice. They also use sea ice as a "haul-out" for resting offshore. This gives them access to feeding grounds that otherwise would not be accessible, permitting greater overall abundance [55]. In recent years, Pacific walruses have been forced onto land, and calves have been found abandoned at sea when ice suitable for haul-outs melted early (Box 9). This raises concerns about whether female walruses will have difficulty nourishing themselves and caring for their young [55, 274]. Atlantic walruses might be more resilient to changes in summer ice as they do not venture as far offshore for feeding in summer and make more use of land haul-out sites [55, 275].

Polar bears use ice for travel and access to the ice-associated seals, especially ringed seals, that they feed on [55]. When they are on land during the ice-free period, they mainly fast. While they may eat vegetation, bird eggs, and even berries, they cannot live without the high energy content of the fat that they acquire from seals hunted from the ice [269, 276]. Reduced populations, poorer body condition, and changes in distribution and behavior are now apparent, especially for populations at the more southerly extent of their range [277–279] (Box 10).

Bearded seal. Photo: BMJ, Shutterstock.com

Table 1. Arctic marine mammals rely on a diversity of ice habitats and prey items



🔶 Critical 🔷 Important ◆ Used

What ice habitats are important?

	WHALES			SEALS						
	Beluga	Narwhal	Bowhead	Ringed	Bearded	Harp	Hooded	Spotted	Ribbon	Walrus	Polar bear
Loose seasonal pack ice	🔶	◆	◆	🔷	🔷	🔷	🔷	🔷	🔶	🔷	🔷
Dense seasonal pack ice		🔶	🔷	🔷	🔶	🔶	🔷	◆	◆	🔶	🔶
Shore-fast ice				🔶	◆						🔶
Multi-year pack ice	◆		◆	◆	◆					◆	🔷
Leads and shear zones	🔷	🔶	🔷	◆	🔷					◆	🔷
Polynyas	🔶	🔷	🔷	◆						🔷	◆
ICE IN RELATION TO OTHER HABITAT FEATURES											
Edge of the pack ice	🔷	🔷	🔷	◆				🔷	🔷		◆
Pack ice over continental shelf		◆		◆	🔷	🔶	🔷	🔷	🔷	🔷	◆
Polynya over shallow water	🔶									◆	

What foods are important?

	WHALES			SEALS						
	Beluga	Narwhal	Bowhead	Ringed	Bearded	Harp	Hooded	Spotted	Ribbon	Walrus	Polar bear
Invertebrates in water column	◆	◆	🔶	🔷		◆		◆	◆		
Bottom-dwelling invertebrates	◆		🔷	◆	🔶	◆		◆	◆	🔶	
Midwater fish	🔶	◆		🔶	◆	🔶	🔷	🔶	🔷		
Bottom fish	◆	🔶		◆	🔷		🔶	◆	🔷		
Other marine mammals										◆	🔶

Based on Laidre et al. 2008 [266], revisions based on Stirling 1980 [40], Gilchrist and Robertson 2000 [256] for polar bear habitats; Stirling 1980 [40], Laidre and Heide-Jorgensen 2011 [281], Laidre et al. 2004 [302] for narwhal habitats and diet; Loseto et al. 2009 [303] for beluga diet; Lawson and Hobson 2000 [304], Hammill et al. 2005 [305] for harp seal diet

Box 9. Ice melt drives Pacific walruses onto land

Pacific walruses in the Bering and Chukchi seas move from the ice to coastal haul-outs if the receding ice edge moves too far north for them to feed. They need enough ice cover for haul-out sites over the shallow waters of the continental shelf in order to feed. In the Chukchi Sea, the edge of the ice in late summer has receded north of the continental shelf most years since the previous ice low of 2007.

Some land haul-out sites on the US and Russian coasts of the Chukchi Sea have seen ten-fold increases in walrus numbers since 2000, with an estimated 97,000 walruses at one location in Chukotka, Russia in 2010 [295]. New haul-out sites have been established—for example, at Point Lay, Alaska, where over 20,000 walruses first appeared in 2010.

Cape Kojevnikova 2009. Photo: Varvara Semenova/ MMC

Walruses are feeding less and are in poorer condition, young animals are crushed in the crowd, and the animals are vulnerable to human disturbance. Other major recent changes, including to migration timing and routes, have been observed by Chukchi Sea walrus hunters.

Sources: MacCracken 2012 [296], Garlich-Miller 2012 [297], Boltunov et al. 2012 [298]

Assessing vulnerability to sea ice decline

Arctic marine mammals use several specific types of ice habitat and feed on a range of types of prey (Table 1). The sensitivity to loss of sea ice for each mammal species depends both on how its habitat and prey are affected and how well it can adapt to these changes.

Species with small populations, small ranges, or those that depend on particular locations or habitat types are likely to be more vulnerable. Each species also has innate limitations on how fast its population can grow and recover from setbacks. This maximum growth rate, due to such characteristics as age to maturity and the number of young produced each year, is lower for polar bears and whales than for seals [55, 266, 280].

Sensitivity to climate change was analyzed for the 11 ice-associated marine mammal species listed in Table 1 by Laidre et al. 2008 [266]. All but the three whale species were rated as highly sensitive to direct impacts from changes in their sea ice habitats. Polar bears were considered highly sensitive to changes affecting their prey, with narwhal, bowhead, and spotted, ribbon, and hooded seals being rated as moderately sensitive.

There were three types of sensitive species: 1) narrowly distributed species that are specialized feeders (for example, narwhal and walrus); 2) seasonally ice-dependent species that use the marginal ice zone (for example, hooded seal and harp seal); and, 3) species that rely mainly on annual sea ice over the continental shelf and areas toward the southern extent of the ice for foraging (for example, the polar bear).

Overall, the polar bear, narwhal and hooded seal were considered to be the most vulnerable species due to their reliance on particular sea ice habitats and their specialized feeding habits.

Box 10. Declines in polar bear body condition

In areas where sea ice melts completely in the summer polar bears may be forced onto land. Earlier sea ice break-up in these areas reduces the amount of time bears have for hunting seals on the ice. In some areas where this is occurring, bears are becoming thinner, resulting in decreases in survival and reproduction.

Changes in sea ice over the past two decades have led to significant declines in physical condition of bears in the western Hudson Bay [277, 299], southern Hudson Bay [300], and Baffin Bay populations [279]. Regehr et al. 2007 [278] showed that survival decreased in association with earlier sea ice break-up and that this contributed to a 22% decline in the size of the western Hudson Bay polar bear population between 1987 and 2004. Reduced survivorship in relation to sea ice conditions has also been demonstrated in the southern Beaufort Sea polar bear population [301].

For the western Hudson Bay population, the body condition of bears measured during the ice-free period declined from 1980 to 2007, as did the average weight of female polar bears in the fall (Figure 30). The female bears weighed were suspected to be pregnant.

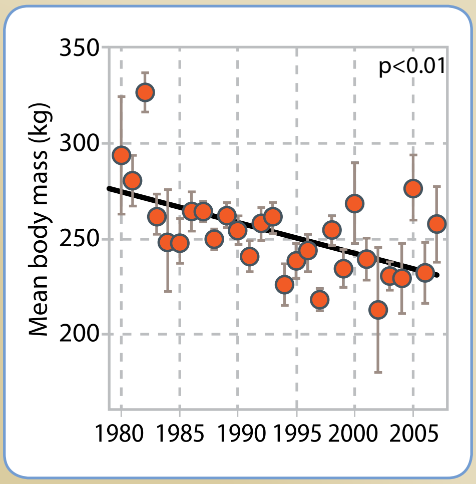


Figure 30. Declining fall weights of female polar bears, western Hudson Bay, 1980 to 2007
Body weights were estimated for females on their own, and thus likely to be pregnant.
Source: Stirling and Derocher 2012 [269]

For the Baffin Bay population, the decline in body condition since the early 1990s is associated with deteriorating ice conditions [279]. Polar bears were in significantly worse condition in years with less summer sea ice cover, starting in the 1990s when ice in these regions began its sharp decline (Table 2).

Table 2. Trends in body condition for the Baffin Bay polar bear subpopulation and relationship with sea ice conditions, 1977 to 2010

	Overall trend in body condition ↓ Decline ↑ Improvement			Relationship between sea ice and body condition + Means body condition was better in years with more sea ice		
SAMPLING PERIOD	MALES	FEMALES	CUBS	MALES	FEMALES	CUBS
1978-1995 spring captures	0	↓	↑	0	0	0
1992-2010 spring captures	↓	↓	NA	+	+	NA
1991-2006 fall captures	↓	↓	↓	+	+	+

The sea ice measurement used represents sea ice habitat available to the bears mid-May to mid-October.
"0" means no trend. "NA" means not enough data to analyze.
Source: Rode et al. 2012 [279]

Case study: Vulnerability of narwhals to loss of sea ice

Narwhals may be particularly vulnerable to loss of ice [266]. They have a limited distribution: mainly in the North Atlantic part of the Arctic Ocean. They are physiologically adapted to a highly specialized life style [280], and they appear to have quite inflexible patterns of movement and behavior [281, 282].

Narwhals feed intensively in winter by diving for Greenland halibut in a few fairly small areas with heavy pack ice. Most of the world's narwhal population winters between Greenland and Baffin Island, where ice cover is shrinking and melting earlier in the spring, reducing their feeding habitat and exposing them to predation [281]. The distribution of Greenland halibut themselves may be affected in the future by changes in the marine environment related to sea ice loss: they may move to shallower waters in response to changing water temperatures [196, 283].

Narwhals. Photo: National Institute of Standards and Technology

Predation and harvest by humans are both influenced by the changes in sea ice. Narwhals migrate up to a thousand kilometers to spend the summer in bays and passages with open water. Killer whales are becoming more common along migration routes and in summering areas in the Canadian Arctic during the open-water season. Ice no longer impedes their passage. Narwhals are one of the prey items of killer whales while they are in the Arctic [284, 285].

Changes in spring and summer ice conditions have made narwhals more accessible to hunters from the Greenland coast. Harvest from the community of Siorapoluk increased after about 2002 when less ice between Greenland and Ellesmere Island made new hunting areas accessible by boat [286]. But thin ice can also hamper human hunting of narwhal. Thin sea ice in 2012, for example, made the traditional spring hunt from the ice off the northern coast of Baffin Island too dangerous, and few narwhals were harvested [287].

From 2008 to 2010 four incidences of sea ice entrapment were observed in the fall in summering areas in Canada and Greenland [288]. In each case, large groups of narwhals (between 40 and 600) were trapped by rapid ice formation in sheltered waters and died. The narwhals may have delayed their fall migration because the start of freeze-up is now two to four weeks later in their summering areas than it was 30 years ago. However, more data are needed to verify this. These particular incidences, although considered unusual, are not necessarily related to the trend in freeze-up timing—but they illustrate the vulnerability of narwhals to altered sea ice conditions [288].

The net effect so far on narwhal populations is not known, although the monitoring situation should improve as there are now estimates of abundance from recent population surveys. Local hunters helped improve narwhal survey methods and added their observations and perspectives from traditional knowledge [289–291]. Baffin Bay narwhal abundance is considered stable or increasing, while remaining lower than in the early 1990s [292, 293]. Status and trends for smaller populations remain unclear [294]. Harvest quotas are set annually for narwhals in both Greenland and Canada.

4. Topics in sea ice and biodiversity

This section examines five topics that cut across the ocean realms or provide a broader perspective on sea ice change. It starts on land, with a look at some of the links between sea ice and tundra ecosystems. Next, it looks at how snow cover on sea ice is changing and how this affects sea-ice-associated biodiversity. Third is the emerging topic of Arctic ocean acidification, its relation to sea ice, and the potentially very serious consequences for marine biota. Fourth is the recurring theme of changes in timing of ice freeze-up and melt—and the vital, associated question, how well will Arctic biota adjust? The final topic is the impacts of sea ice change on biodiversity in the context of cumulative effects.

4a. Sea ice and tundra ecosystems

The extent of sea ice cover influences the climate of tundra ecosystems. When there is less ice, air temperatures warm over land [306]. This translates into far-reaching changes in terrestrial ecology. Since the early 1980s, production of tundra vegetation has shown the greatest increases in locations adjacent to seas that have experienced the most dramatic losses of summer sea ice [307]. This "greening" of the tundra is accompanied by shifts in vegetation communities, such as an expansion of shrubs [308]. The connection works both ways: changes on land, including increased river flows, melting glaciers, and earlier loss of snow, affect coastal microclimates and freshwater input to the Arctic Ocean [1]. These changes combine with impacts from loss of sea ice to affect marine biodiversity.

Sea ice connects islands

Winter sea ice provides foxes and wolves with a means to access and colonize remote islands. A study of the genetics of Arctic foxes throughout their range showed that the occurrence of sea ice is the main factor in determining how similar fox populations are to one another: the less sea ice, the more genetically distinct are the populations [309]. If island populations become isolated due to loss of winter ice, some populations will be at risk of decline or extinction due to loss of genetic diversity and inbreeding [309, 310]. Wolf populations on Banks, Ellesmere and Devon islands in Canada have declined and been reestablished in the past through colonization over the sea ice from other islands [311]. As with foxes, wolf populations are at risk of reduction if winter ice conditions alter sufficiently to compromise movement over ice.

Arctic wolf. Photo: Cephas

Sea ice is a winter hunting zone for some terrestrial predators

Both Arctic foxes and wolves feed on marine resources during winter, travelling long distances to hunt and scavenge. Arctic foxes scavenge seals killed by polar bears [309, 312] and may also prey on ringed seal pups [313]. Wolves are also known to forage on sea ice in winter, likely scavenging seal carcasses [314]. How important feeding on sea ice is in the ecology of foxes and wolves is not known [309, 314].

Recent studies using satellite tracking show that both gyrfalcons [315] and snowy owls [316] spend substantial periods of time far offshore in winter, presumably preying on marine birds and roosting on ice floes (Figure 31). Snowy owls have been observed hunting seabirds that congregate in patches of open water in winter [256]. Changes in winter sea ice extent and polynya formation that affect seabirds could also affect the food intake of snowy owls. As owls are small-mammal predators during breeding season, changes in snowy owl populations would affect the tundra food web [316].

Figure 31. Gyrfalcons and snowy owls: terrestrial birds of prey frequenting sea ice habitat in winter
Satellite tracking of 48 gyrfalcons (left) in Greenland over three winters (2000–2004) showed that some falcons travel almost continuously during the winter and many of them spend long periods at sea. The record holder was a young female falcon that travelled over 4,500 km one winter, spending more than 100 days over the ice-covered ocean between Greenland and Iceland [315]. Satellite tracking of nine adult female snowy owls (right) in the Canadian Arctic over two winters (2007–2009) showed that most spent several weeks on the sea ice between December and April. Analysis of high-resolution satellite images showed that they spent most of their time on the ice around open-water patches frequented by seabirds [316]. Photos: Tom Reeves, Shutterstock.com (gyrfalcon), Tom Middleton, Shutterstock.com (snowy owl).

4b. Snow on ice

The current warming trend that is changing and reducing the Arctic's sea ice is also changing and reducing the snow on top of the ice. Changes in snow have impacts at the base of the food web, as well as direct impacts on animals that use snow on ice to construct birthing dens. Snow on ice is also a factor in determining the suitability of ice for travel by Arctic residents. Poor snow conditions can impede access to hunting areas, as well as make travel by snow machine among coastal and island communities difficult or impossible [317].

Much of Arctic marine diversity is driven by bottom-up processes: any change in primary production drives changes up through the food web, from the tiniest copepod to the largest whale. The interplay of light and nutrient availability, much of which is mediated by sea ice, is at the center of these changes in primary production. But it is not just thinning and melting ice that lets in more light. The snow on top of the ice blocks light penetration. Snow thickness and timing of snow melt are the main determinants of when and how much light is available for ice algae and under-ice plankton blooms [97].

Although the overall amount of winter precipitation in the Arctic is increasing, later freeze-up in the fall and more rain and warm-weather spells in the spring are reducing the snow pack on ice. Over the past three decades, spring snow extent on Arctic land has decreased by 18% per decade, faster than the rate of loss of summer sea ice cover [89] (Figure 32). This decrease is an impact of warmer springs, and the trend would also apply to the snow cover on sea ice. Modeling indicates that, as freeze-up of the ice shifts to later in the fall, the timing of freeze-up will have an increasingly significant effect on the depth of spring snow on sea ice. This is because late freeze-up reduces the period that snow accumulates [318].

While the impacts of increased under-ice light on primary production and food webs are likely to be mixed (see sections on Arctic biota), the direct effects of reduced snow are clearly negative for some species. Both polar bears, and ringed seals, their main prey, depend on spring snow on sea ice to create caves in snow drifts for birthing. Melting snow and rain in the spring can cause these birth dens to collapse or melt away, killing some or all of the occupants [269].

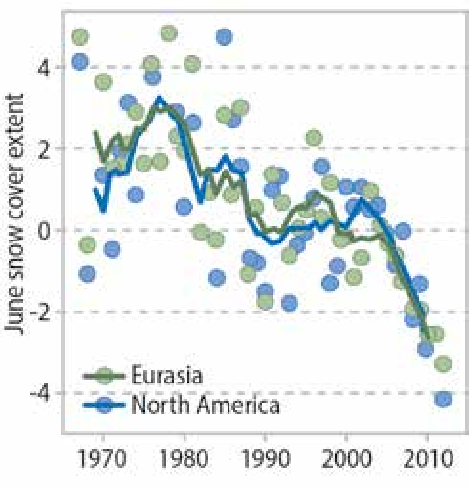


Figure 32. Trends in terrestrial spring snow cover for the Arctic, 1967–2012
Data are June averages for all Northern Hemisphere snow cover. Values are standardized anomalies with respect to the 1988–2007 mean. Solid lines are five-year running means.
From Derksen and Brown 2012 [89], data from NOAA CDR (satellite monitoring)

Studies have shown that survival of ringed seal pups declines in locations without at least 20 cm of snow on level sea ice in April [318] (Figure 33). For the whole Arctic marine environment, the extent of snow cover at or above this 20 cm threshold depth is projected to decrease by 70% by the end of the century [318].

Figure 33. Ringed seal in snow cave
Snow of 20 cm depth on flat ice is needed to form the deeper snow drifts alongside pressure ridges and hummocks. Ringed seals need at least 50–60 cm of snow for their caves [319].
Photo: B. Kelly, NSF

4c. Capacity to adjust to changes in timing

The timing of biological production is changing in the Arctic Ocean. For some Arctic species, this change may lead to problems in finding the abundant, concentrated food supplies needed for successful reproduction. For others, the extended growing period may be beneficial. Animals that travel on ice will also see impacts from changes in the timing of ice formation and melt. Over the long term, the future of Arctic biodiversity will be partly determined by each species' capacity to adjust its behavioral and reproductive patterns to minimize detrimental impacts or take advantage of beneficial ones [218].

Shifting ice-edge blooms

Spring blooms of phytoplankton and ice algae determine the timing of many annual events in Arctic marine ecosystems [81, 320, 321]. Ice-edge algal blooms usually peak within 20 days of the ice retreating from any given area [6]. Many Arctic birds and mammals take advantage of the zooplankton (especially copepods) and fish (especially polar cod) that the algal blooms support [148, 212].

This shifting zone of abundant, high quality food is ideal for meeting the energy needs of seabirds while they are nesting and feeding their young [322]. Reliance on food associated with these transient events, however, makes Arctic seabirds vulnerable to changes in the timing and location of algal blooms. Changes in the location of the ice edge during the nesting period have been linked to reduced reproductive success or declines in some seabird populations: black guillemots in the Beaufort Sea [323] and murres, kittiwakes and least auklets in the Bering Sea [324–326].

Algal blooms are occurring earlier in about 11% of the Arctic Ocean [214] (Figure 34). The change is in some areas where ice is melting earlier, creating gaps of open water that make these earlier blooms possible. This trend is likely to expand into other areas of the Arctic Ocean as multi-year ice is replaced by yearly ice that is less thick and melts more quickly [214]. The trend to earlier algal blooms has the potential to reduce availability of food for zooplankton at critical periods of their reproduction and growth [22, 214]. Earlier break-up, however, does not always lead to earlier blooms. When the ice melts before winter storms have abated, the resultant wind mixing of the water column can create conditions that delay the spring bloom, as demonstrated in the Eastern Bering Sea [212]. To what extent zooplankton will adjust their yearly cycle to track these changes is not known (see Plankton and Fish sections).

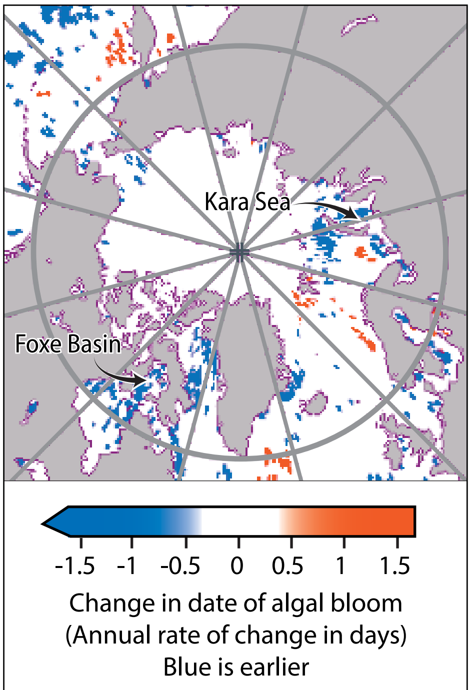


Figure 34. Trends in the timing of peak phytoplankton blooms in the Arctic Ocean, 1979–2009
The rate of change is very rapid at some locations. For example, the peak algal bloom occurred in early September in Foxe Basin and in the Kara Sea in the mid-1990s but had shifted to mid-July by 2009, a change of about 50 days.
Source: Kahru et al. 2011 [214]

Capacity to adjust to change

Fundamental ecological processes are changing too rapidly for Arctic vertebrates to adapt to through evolution [322]. There is evidence of many animal species (but not all) having the capacity to switch diets, alter migration patterns and advance their reproduction schedule in response to changing conditions [22]. It is likely, however, that the rate and extent of change will outstrip this adaptive capacity for many Arctic species [322].

An example is the case of thick-billed murres (Brünnich's guillemots) in Hudson Bay, Canada. During the 1980s, while breeding, the murres fed on polar cod associated with pack ice. When the ice melts, the cod become dispersed in the water column and hence harder to find. As the date of ice break-up advanced during the 1990s, the murres adjusted by advancing the date of egg-laying by five days from 1988 to 2007. However, the rate of ice melt near their nesting area outstripped this adaptation: the date of peak food availability is now 17 days earlier. As a consequence, the birds have turned to food sources other than polar cod and have found it more difficult to provision their nestlings, causing a slower growth rate for chicks, especially in years with a greater mismatch between the date when the chicks hatch and the date the ice melts near the colony [14, 320].

In the high Arctic, seabird populations show greater flexibility in responses to changes in the timing of ice conditions. At Prince Leopold Island in the Canadian high Arctic, early ice break-up has been associated with earlier breeding and enhanced reproductive success for black-legged kittiwakes, glaucous gulls and thick-billed murres [327]. Populations of black-legged kittiwakes are increasing in the Canadian high Arctic [328], possibly as a result of enhanced reproductive success due to earlier ice break-up.

Changes in timing of freeze-up and break-up

Another type of timing mismatch is related to ice as a platform for travel, hunting, and denning for some mammals. Changes in timing of ice formation in autumn and melting in the spring have led, in some regions, to shifts in the locations where polar bears hunt and den [55].

Pregnant polar bears den in the autumn and give birth during the winter. At Hopen Island, Svalbard, sea ice freeze-up dates have shifted, on average, from late October to early December between 1979 and 2010, limiting access to the island for denning (Figure 35). Years with later freeze-up over this period coincided with years with fewer maternity dens on the island and poorer body condition for both mothers and cubs in the spring [329].

Populations of some terrestrial mammals are adapted to the seasonal presence of sea ice for migration and hunting, including Arctic foxes [310] and caribou. The Dolphin and Union caribou herd in Canada migrates annually between calving range on Victoria Island and winter range on the adjacent mainland. The date on which sea ice formed a platform suitable for the caribou to cross fell, on average, 10 days later by 2008 than in the early 1980s, and this timing shift can be expected to increase. To what degree the caribou herd will be able to adjust their migration patterns to this rapid change is not known [330].

Melting sea Ice at Pond Inlet, Nunavut, Canada
Photo: Peter Prokosch, UNEP /GRID-Arendal

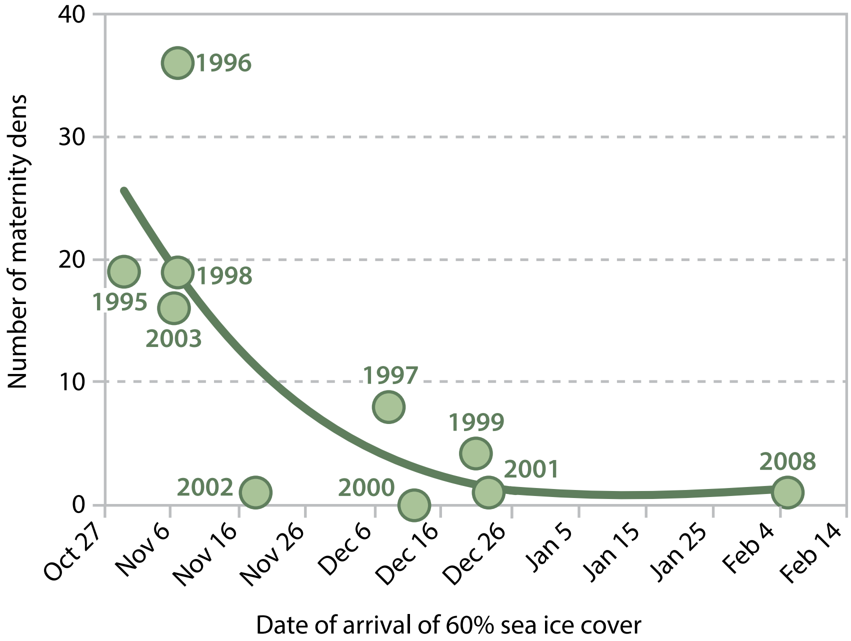


Figure 35. Number of polar bear maternity dens observed on Hopen Island in relation to the date of sea ice formation the previous autumn
Source: Derocher et al. 2011 [329]

Polar bear in snow den
Photo: Sergey Uryadnikov, Shutterstock.com

4d. Ocean acidification

The ocean has absorbed about 43% of all the carbon dioxide emitted to the atmosphere through the burning of fossil fuels during the industrial period, which began around 1750 (recent analyses reported in Arndt et al. 2012 [331]). While this has slowed the rate of climate change, it has made the ocean more acidic. This is an ongoing process and the magnitude of future acidification depends on the success of global carbon dioxide emission reduction [332, 333].

Ocean acidification interferes with the ability of marine organisms, including mollusks, crabs and crustaceans, to form shells and external skeletons, due to the chemical properties of calcium carbonate, the building material that they use. The more acidic the water, the less calcium carbonate is available to marine organisms [333] and the more energy the organisms need to expend to build and maintain their shells and exoskeletons [334]. If conditions cross a chemical threshold, calcium carbonate in shells and exoskeletons dissolves back into the water [335].

The Arctic marine environment is particularly susceptible to ocean acidification and the accompanying reduction of available calcium carbonate. The susceptibility is partly because more carbon dioxide dissolves in colder water than in warmer water (thus increasing the acidification), but also due to the chemical and biological characteristics of Arctic Ocean water. In particular, increasing amounts of sea ice meltwater may periodically deplete surface waters of the calcium carbonate ions needed to build shells and skeletons [336, 337] (Box 11).

An ecosystem shift caused by low concentrations of calcium carbonate was documented in 2008 in nearshore areas of the Canada Basin. As a consequence of extensive sea ice melt, surface waters shifted from a chemical environment in which mollusks form shells to an environment in which shells dissolve [338]. In 2009 a similar shift was recorded over large areas of surface waters in the Bering Sea for several months, as well as in bottom waters during September [339]. Researchers attribute this shift to increases in sea ice meltwater and river discharge, as well as to changes in the cycling of organic matter, all against a background of the increasing acidification of ocean waters.

Box 11. Pteropods and ocean acidification

Pteropods, tiny swimming marine snails that are important in the Arctic marine food web, may be particularly vulnerable to ocean acidification. A study based on modeling predicts ocean conditions that could drive the Arctic pteropod *Limacina helicina* to extinction by the end of this century. This common, widespread pteropod eats floating algae and small crustaceans and is in turn eaten by larger invertebrates, fish, seabirds, and the bowhead whale. Loss or severe depletion of populations of this tiny snail would have major ecological and economic implications, including negative impacts on North Pacific pink salmon fisheries.

Source: Comeau et al. 2012 [340]

The pteropod Limacina helicina
Photo: Kevin Lee

4e. Cumulative effects

This report is focused on how climate change is affecting sea-ice-associated biodiversity, primarily through loss of ice. Ultimately, however, the impacts experienced by biota and by humans in the Arctic are not neatly parceled into categories. Impacts are cumulative—experienced simultaneously from more than one stressor. They are also interactive—working together in ways that are often more (and sometimes less) than the sum of their parts [341–343]. Predicting and managing cumulative effects remains difficult and, although increasingly incorporated into policy and law, often poorly executed [342, 344].

In the present-day Arctic marine environment, most current and potential stressors of concern have some relationship to the reduction of sea ice. The increase in the time and extent of ice-free waters in the Arctic opens up new opportunities for shipping, resource extraction, commercial fishing and tourism, which will intensify existing pressures and impacts on Arctic biodiversity and add new ones. In addition, sea ice changes interact with other stressors, some caused by activities far from the Arctic and others operating on a global scale. Ocean acidification, covered as a previous topic, is one example. The issue of contaminants is another. Both the levels of contaminants deposited into the marine environment through atmospheric deposition and the manner in which they are magnified through the food web may be affected by climate change, including reduced sea ice cover [345, 346]. In addition, melting multi-year ice may release pollutants that were stored in the ice over the years [347].

Cumulative effects of multiple stressors will need to be taken into account in plans and actions aimed at the conservation of and/or the sustainable use of ice-associated biodiversity, as well as in environmental impact and risk assessments. Impacts on sea-ice-associated biodiversity, in addition to those discussed in this report, include risk of harm from spills and noise pollution from shipping and oil and gas activity, disturbance from human activities in sensitive areas and at critical times, and introduction into Arctic waters of non-native species, parasites and diseases of fish and wildlife. These impacts, in turn, affect human health and societies, cultural and spiritual integrity, and economic pursuits. The consideration of cumulative effects is one of the main pillars of ecosystem-based management [348] (see the Looking ahead section and Appendix 1).

Current and potential effects on Arctic marine biodiversity from various stressors have been assessed through Arctic Council initiatives. These initiatives form the basis for identifying needs for monitoring and research and for actions to reduce risk. Monitoring needs are incorporated into planning through the Circumpolar Biodiversity Monitoring Program [349]. Projects incorporating impact assessment include:

- Arctic Biodiversity Assessment [2];
- Arctic Climate Impact Assessment [8] and Snow, Water, Ice and Permafrost in the Arctic (SWIPA) [1];
- Arctic Ocean Review Project [350, 351];
- the Arctic Marine Shipping Assessment [352, 353]; and
- Arctic Monitoring and Assessment Programme contaminant assessments (for example, on mercury and on ocean acidification [354, 355].

Photo: Jele, Shutterstock.com

5. Human dimension

5a. Arctic peoples and sea-ice-associated biodiversity

The Arctic is home to about 4 million people, over 1.5 million of whom live in 10 cities with populations over 60,000, most located by the sea [196, 356]. The remaining 2.5 million live in medium-sized to small communities both inland and spread along coastlines. Settlement is dispersed, with many small villages in all Arctic jurisdictions (Figure 36).

Marine mammals, fish and birds provide Arctic coastal indigenous people with a diet rich in omega-3 fatty acids and selenium that affords protection against ailments such as cardiovascular diseases, diabetes, obesity and cancer [358].

Arctic coastal peoples are affected by sea ice to varying degrees, depending on their location and on the extent of their use of marine resources. The Inuit (Figure 37), Saami, Dene, Aleut, Koryak, Nenets, Dolgan, Nganasan, Entsi, Yukagir, Even and Chukchi peoples, as well as non-indigenous residents of Arctic coastal areas, make use of the Arctic marine environment for food, cultural purposes, or for small-scale economic pursuits [350]. In addition, the Arctic marine environment is a focus of larger-scale economic interests from the Arctic coastal nations and beyond. Marine food resources potentially affected by sea ice are also important to many inland Arctic dwellers. For example, salmon that spend parts of their lives in the Bering Sea are a main food source and of high cultural value to inland Arctic Athabaskan and Gwich'in communities in western North America.

Indigenous cultures have flourished around the rim of the Arctic Ocean for millennia. The success of these cultures reflects the abundance of marine resources, integral to Arctic coastal cultures and economies [8]. Sea ice has been a relatively constant presence for Arctic people, who use it as a platform for travelling to where food resources are located and for accessing those resources [357].

The prevalence of long-standing, thriving Arctic cultures is a testament to the deep knowledge that Arctic indigenous peoples hold about the movements and behaviors of the birds, mammals and fish that they relied on for their survival [8] (see Case study on the ice culture of the Bering Strait and coastal Chukchi Peninsula). Adaptability to highly variable environmental conditions and the ability to predict what effects these variations might have on their food resources have always been strengths of Arctic people [196, 359]. The scope of current warming trends and the associated rapid change in conditions is testing these skills in a significant way. For example, as marine organisms react to greater periods of open water in the summer months or to shifting dynamics of polynyas in the winter, northern hunters must adapt their methods in order to find animals that have shifted both in location and the time of year they may be accessible. These changes in environments and wildlife have implications for northern people's food security and for wildlife and habitat management, topics that are examined in more detail later in this section.

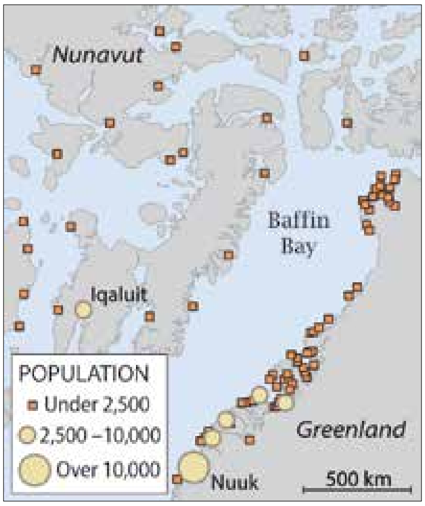


Figure 36. Settlements dot Arctic coastlines even in sparsely populated areas such as Greenland and the Canadian Arctic Archipelago
Adapted from Hovelsrud et al. 2011 [196]

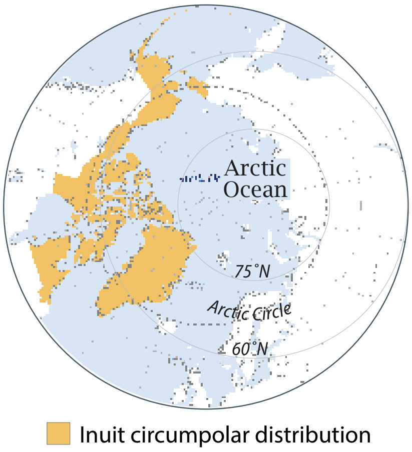


Figure 37. The circumpolar distribution of the Inuit: Canada, Alaska (US), Greenland (Denmark) and Chukotka (Russia)
From Ford 2009 [372], based on data from Makavik Cartographic Services

Case study: The ice culture of the Bering Strait and coastal Chukchi Peninsula

Based on material prepared for this report by Lyudmila Bogoslovskaya and Boris Vdovin of the Likhachev Institute of Cultural and Natural Heritage of Russia, Moscow, and Igor Krupnik of the Arctic Studies Center, Smithsonian Institution, Washington, DC.

The hunting cultures of the far north are just as closely tied to sea ice as the animals they rely on. Consider, for example, the Iñupiat Eskimo of northwestern North America, the Yupik Eskimo of Bering Strait, and the Maritime Chukchi people of Northeastern Asia—collectively known as the ice culture, or the Arctic marine mammal hunting culture. The peoples of the ice culture have made their living, generation upon generation, by hunting sea-ice-dependent mammals and using other ice-associated resources of the Bering Strait and coastal Chukchi Peninsula.

There, where two continents and two oceans meet, are the Chukchi Peninsula's productive coastal and marine ecosystems and the Bering Strait, which serves as a major migration corridor and vital breeding ground. Today, the indigenous peoples of the region still subsist on the resources the sea and ice provide: nine marine mammal species—bowhead, grey, humpback and white (beluga) whales, Pacific walrus, and ringed, bearded, spotted and ribbon seal—as well as marine and coastal birds, ocean fish and invertebrates.

Photo: A. Apalyu

Key to the survival of many of these animals is the complex icescape of the northern Bering Sea and the southern Chukchi Sea: the system of polynyas, seasonal ice leads, drifting ice fields, and expanses of shore-fast ice. Some of the polynyas are substantial and quite stable. A large polynya called the Chukchi Clearing extends up to a thousand kilometers along the outer edge of shore-fast ice and serves as the main migration throughway, as well as the key hunting and feeding area for marine mammals along the Arctic coast of Chukotka. On the southern coast of the Chukchi Peninsula, the Sireniki Polynya is a vast expanse of open water about 150 kilometers long and up to 80 kilometers wide, where marine and coastal birds often overwinter in their tens of thousands. A small group of bowhead whales overwinters and breeds in the polynya's open water, and walrus and bearded seals breed and wait out the winter months on the surrounding floating ice before migrating north in the spring.

Over the course of at least two thousand years, the peoples of the sea ice culture have developed their own rules for sustainable long-term use of the icescapes of these marine and coastal ecosystems. Yupik Eskimo and Maritime Chukchi traditional knowledge of ice formation and dynamics, local weather and climate characteristics, currents and tidal patterns, and marine animal biology is extensive and does not have analogues in scientific sources, particularly at this local scale.

Photo: A. Borovik

Unfortunately, many practices that promote oral transmission of ice-associated local ecological knowledge from older to younger generations are fading under contemporary conditions. Invaluable age-old expertise often disappears as older generations pass on. If indigenous people of today are to continue the subsistence-based life perfected by the generations of their ancestors, the traditional ecological knowledge and skills of the Arctic sea hunters must be recorded. There is a dual purpose to this: maintaining the distinctive ice culture of the Bering Strait and Chukchi Sea and improving our understanding of current changes in sea-ice-related ecosystems.

Overview of impacts on humans of changes in sea-ice-associated biodiversity

The human dimension of climate change in the Arctic is an ongoing focus of Arctic Council assessments. Impacts on human societies and economies were presented and discussed in the Arctic Climate Impact Assessment [8] and have been further explored in subsequent assessments [1, 2, 352, 360]. This overview is based mainly on these Arctic Council assessments. Main direct and indirect pathways of impacts on humans are shown in Figure 38.

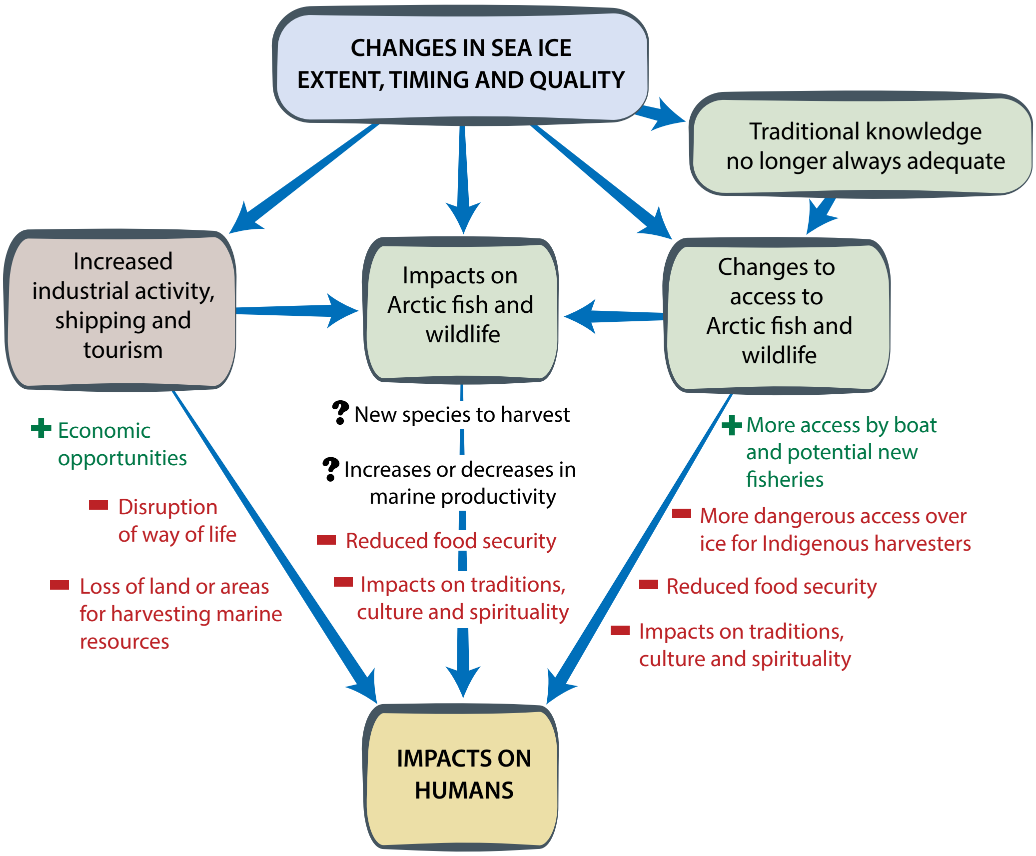


Figure 38. Pathways of impacts on Arctic humans resulting from changes in sea ice and associated changes in biodiversity

As discussed in earlier sections, decreases and changes in Arctic sea ice are currently affecting marine ecosystems and are expected to have much more significant effects as the ice continues to retreat. Many of the changes remain highly uncertain. For example, production of algae, the base of marine food webs, has recently increased overall, but is likely to be declining in amount and quality in some regions. Some animals of importance to humans, such as some fishes and seabirds, may not be greatly affected by loss of ice or may benefit from longer open-water periods. Some may be affected indirectly through food webs in ways that are hard to predict. Populations of several ice-associated marine mammals that are important in indigenous diets, cultures and economies are predicted to decline [22, 271, 361].

Changes in the duration and extent of sea ice will affect the ranges and foraging patterns of seabirds and marine mammals, which can in turn contribute to introductions of invasive species and parasites [21, 362]. Changes in ranges and foraging can have further effects through the food web. For example, killer whales, which are increasing in number in some parts of the Arctic [284], are potential competitors of human hunters of marine mammals.

Less ice leads to increasing seawater temperatures and to northward expansion of sub-Arctic species adapted to these warmer waters. As a consequence, species distribution and availability may change dramatically and in unexpected ways. For example, the appearance of capelin in Cumberland Sound, Nunavut, over the past decade has led to a switch in the diet of Arctic char, an anadromous fish that is an important food source and supports a small commercial fishery. Formerly invertebrate feeders, the char are now also eating capelin [363]. Local residents have observed that the flesh of char has become whiter, which they attribute to this change in diet. This affects the local fishery, as white-fleshed char are less marketable than those with orange flesh [364].

Most important seabirds harvested around the Arctic: auklets, murres, sea ducks (Alaska); murres and common eider (Canada), fulmar and puffin (Faroe Islands); long-tailed duck and common eider (Finland); thick-billed murre and common eider (Greenland); puffin, common murre and common eider—for down and eggs (Iceland); gulls and black guillemot (Norway); eiders, murres and other alcids, gulls, terns and cormorants (Russia) [23].

Trends towards shorter periods of winter ice cover and reductions in ice thickness can prove a challenge to hunters who find their hunting seasons shrinking. Changes in ice conditions also increase their risk of falling through the ice or becoming stranded on ice platforms that have broken free of land. Hunters' knowledge of ice conditions can mean the difference between life and death. Sea ice is becoming less predictable, leading locals to take adaptive measures, such as constructing sleds that can function as boats to cross short stretches of open water [357]. Another adaptive measure is to acquire the best possible knowledge of ice conditions (Box 12). In some regions, reduced seasonal ice is also leading to more shoreline exposure to storm waves, threatening coastal structures and restricting hunting and fishing by boat, especially late in the summer. A number of Inuit villages along the Beaufort Sea coast are facing eventual relocation to escape the advancing sea [14].

The effect of sea ice loss on indigenous communities in the Arctic goes beyond impacts on subsistence activities. Ice is at the center of the culture and spirituality of northern Arctic coastal indigenous peoples. Knowledge of sea ice is embedded in the language of the Inuit [359, 365]. For example, a seal's breathing hole, *allu*, is perceived as central to life since it allows the seal to breath and allows polar bears and people to hunt seals [365].

While changes in the ice-associated biota of the Arctic may not directly affect people living south of the Arctic, some Arctic marine species are well known and play a part in non-Arctic cultures, notably in Europe and North America. There is considerable global interest in the well-being of iconic species like beluga whales, narwhals, and walruses. Polar bears, in particular, have become symbolic throughout the world of the growing threat that climate change poses to nature [366, 367]. This global awareness of Arctic wildlife means support for the conservation of these species is widespread, offering the potential for positive impacts on biodiversity. However, the high profile of Arctic wildlife may also present a challenge to Arctic indigenous peoples when decisions or actions affect their access to traditional uses of biodiversity [368, 369].

A selection of postage stamps from around the world, reflecting the interest in sea-ice-associated animals in both Arctic and non-Arctic nations. Scans of stamps: Shutterstock.com

Box 12. Augmenting traditional knowledge to adapt to uncertain sea ice conditions

Reliable knowledge about sea ice conditions is essential for hunters [373]. As ice becomes less predictable, technology can augment the hunters' own traditional knowledge to improve the safety and efficiency of hunting on ice. A service in Canada's high Arctic provides Inuit communities with satellite image maps (Figure 39), updated three to five times a week, showing floe-edge location and ice conditions [374]. Maps are downloaded, printed and posted locally. The service started in 2003 and has expanded over the years to include harvesting areas for more communities [375]. In Alaska, weekly reports on ice conditions from several sources, both science-based and hunter-based, have been provided to walrus hunters via the internet for each hunting season since 2010 [376].

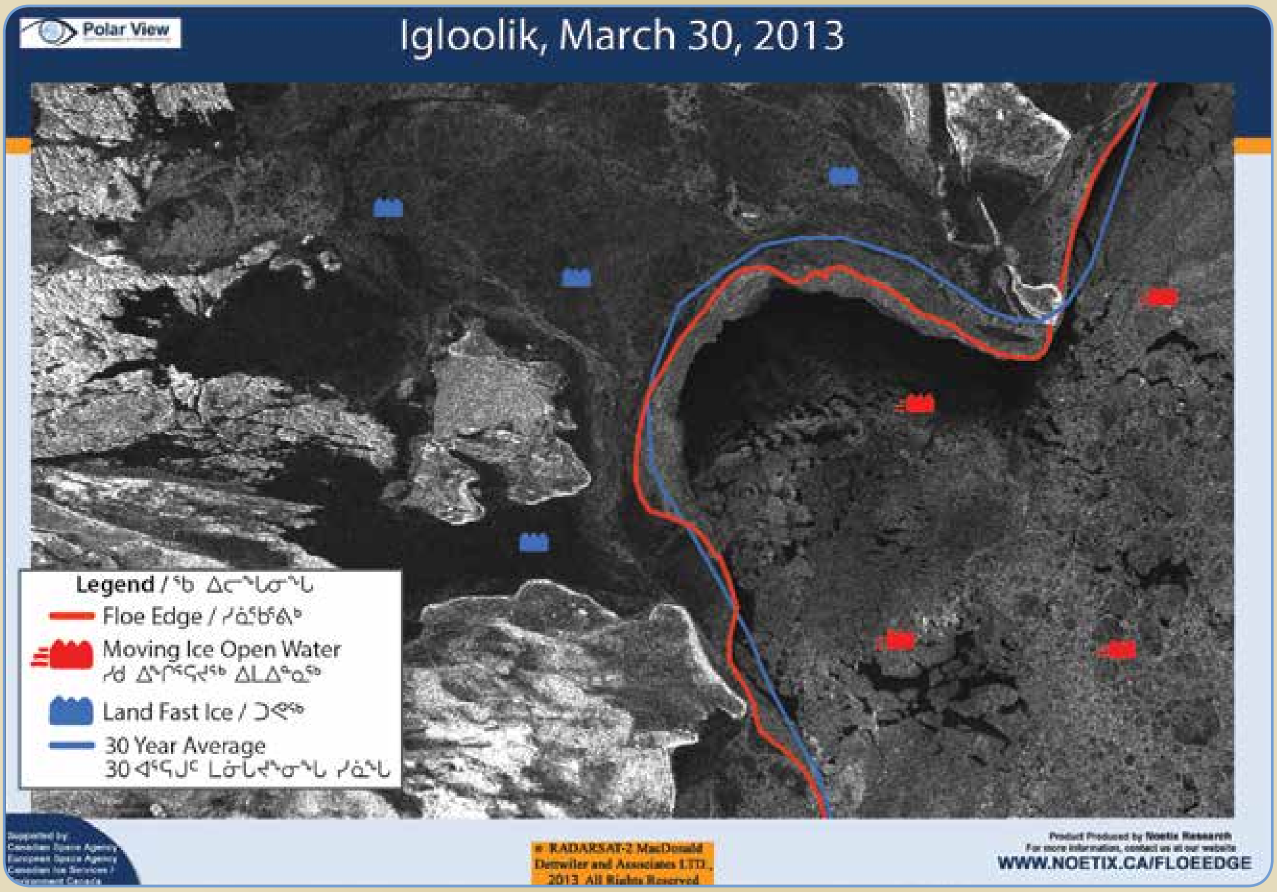


Figure 39. Sample Polar View Floe Edge Service satellite image map, March 30, 2013
Image provided by Noetix Research

Increased sea ice melt is opening up Arctic waters to industries such as shipping and tourism and is leading to increased access for non-renewable resource extraction (oil, gas and minerals) [8, 21, 196, 350]. These changes represent both opportunities and challenges for Arctic residents. For example, new job opportunities may bring cash into remote communities and remove economic barriers to harvesting, but could also reduce the time available for traditional subsistence and cultural practices [370, 371].

Industrial expansion in the Arctic marine environment also brings potential negative impacts to Arctic marine biota that are of economic and cultural importance to Arctic residents. Noise and physical disturbance along shipping routes may affect distributions of some species, as well as disrupt feeding, reproduction and, for marine mammals, underwater communication [352]. The presence of more ships increases the

Marine mammals provide not only food, but the raw materials for clothing, household goods, and for creations of spiritual and artistic significance [357].

risk of collisions with marine mammals, and spills, for which there is inadequate preparation and response capacity at present [350]. Even without accidents, more industrial activity brings greater risk of damage to fish, wildlife and habitats from pollution by discharges and other sources, such as ballast exchange, hull foul, and washing and maintaining equipment and vessels. Another heightened risk is that of introduced parasites and invasive species [352].

Increased marine traffic is a reality in Arctic waters, with an upward trend in the number of ships operating over the last 30 years. Two and a half million cruise ship passengers travelled to the Arctic in 2007, more than double the estimate for 2004 [21].

Hunters will certainly respond to the challenge of harvesting resources from an increasingly seasonally ice-free ocean. They will build on their traditional knowledge, refining new techniques and tools and including new observations of ice dynamics and how biodiversity is reacting. This new knowledge will be a critical contribution to the future management of marine resources—resources that include fish and wildlife, as well as extractive resources such as oil and gas. Development of the latter will need to be carried out in a way that minimizes impacts on species that northern communities rely on.

Hunting seals in East Greenland. Photo: Kitty Terwolbeck, Flickr

5b. Food security in a changing ice regime

Assessment of food security is a useful approach for integrating environmental, social and economic pressures. Its application to the Arctic is fairly new. Ongoing initiatives include a study on Arctic food security commissioned by the government of Canada [379] and the Arctic Council's *Arctic resilience report* [380], *Arctic human development report volume II* [381] and *Arctic Ocean review phase II* [350], all of which incorporate consideration of food security. The Inuit Circumpolar Council Alaska has undertaken a project to provide a framework for food security studies in the Arctic [382] (see the Looking ahead section).

Food security is a product of many, often interlinked, economic, social, institutional, and environmental conditions [383]. One aspect of food security is the balance between consumption of store-bought foods and traditional or country foods. This balance is associated with cultural practices, affordability, diet preferences, and many other factors [384, 385]. In the Canadian Arctic, factors as diverse as rising costs of hunting equipment, concern about contaminants in marine mammals, and decreasing numbers of full-time hunters have contributed to a decline in the use of country foods in recent decades. This has negatively affected both food security and nutrition [386].

Food security exists when "all people, at all times, have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life" [377]. The term "food insecurity" is used when these conditions are not met.

Food security is based on the stability of three components: availability of food; access to food; and use of food [378].

An interview-based study in Igloolik, an Inuit community in Nunavut, Canada [387], found that changing sea ice is one of many factors contributing to a high prevalence of episodes of food insecurity among residents. Igloolik is located on a small island. Its residents require either open water for boating or stable ice for travel by snow machine in order to hunt walrus, fish, access caribou hunting grounds, and travel to other communities. The ice season in the sea near Igloolik declined from nine to seven months between 1979 and 2008, with freeze-up moving from November to December [388]. Residents report that, even when the sea starts to freeze, it takes longer for the ice to become firm enough for safe travel. This means a longer period during which hunting is not possible. Changes in ice dynamics also mean there have been fewer walruses near Igloolik in recent years, so they are either not accessible to hunters or harvesting the walruses costs more in fuel. These ice-related changes have led, at times, to acute shortages of country foods. Traditional ways of coping with food shortages include sharing and trading food among communities (Figure 40). When travel is impeded by sea ice conditions, this system also breaks down.

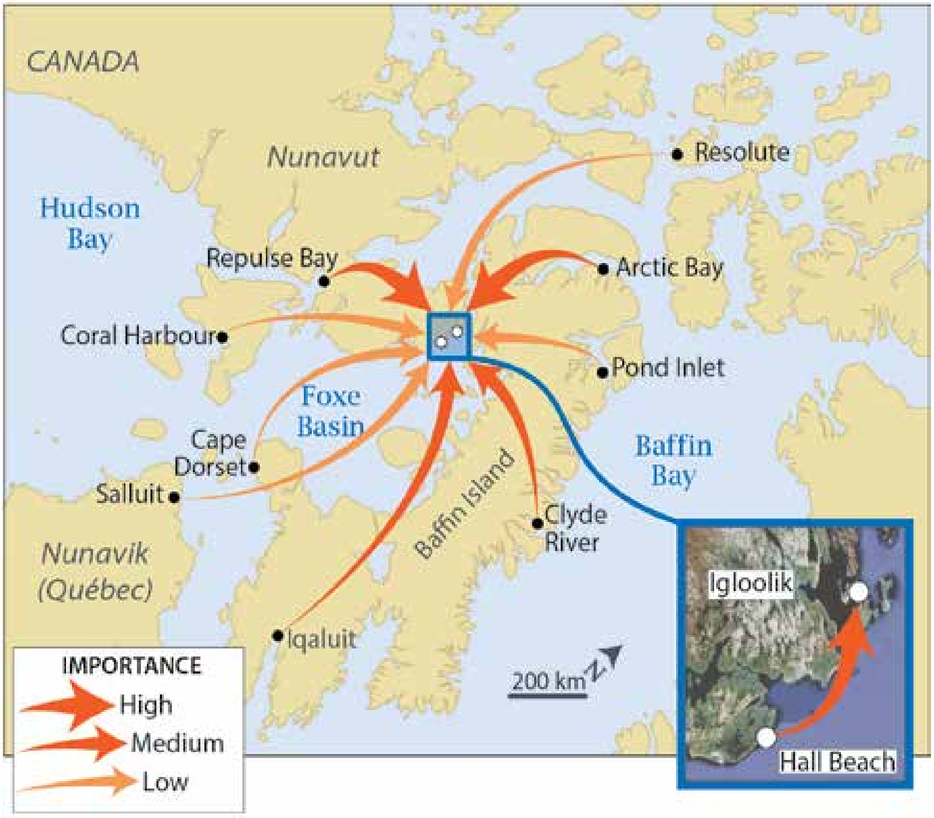


Figure 40. Inter-community sharing network for country foods: sources of food received by Igloolik in 2007
Trading and sharing foods is a powerful adaptive measure to cope with food shortages. The width of the lines reflects the importance of each pathway in this network, which is based on interviews with Igloolik residents in 2008. Adapted from Ford and Beaumier 2011 [387]; inset map from Google Earth

Not all changes in ice conditions are detrimental to food security. For example, earlier ice break-up and later freeze-up over the past decade have altered the seasonal distribution of bowhead whales in the northern Bering Sea. For the Yupik village of Savoonga, also on St. Lawrence Island, this has meant a poorer spring hunt but more favorable conditions for whaling in the winter. The village's whalers have adapted by starting a winter whaling season [389].

Fishing hole in the ice, Greenland. Photo: Lawrence Hislop, UNEP/GRID-Arendal

5c. Conservation of Arctic flora and fauna in a changing ice regime: implications for co-management

While management systems vary around the Arctic, there are common challenges in coming to grips with the rapid pace of Arctic change and the accompanying upswing in economic activity and increase in uncertainty about the cumulative impacts of these changes on biodiversity. This section explores these challenges primarily from a regional point of view—the scale at which day-to-day decisions are made, for example, about wildlife and fish harvests, management of protected areas, and prevention of habitat degradation.

Co-management arrangements in Canada, as established under modern-day land claim agreements (for example, the Inuvialuit Final Agreement [392] and the Nunavut Land Claims Agreement [393]) are formal, legally-based cooperative institutional arrangements among provincial, territorial and federal governments and Aboriginal (indigenous) authorities and local wildlife "user" communities. Collectively, these parties provide advice and make decisions regarding the conservation of wildlife, habitat and harvesting and the associated research, policies, regulations and legislation. In some Canadian jurisdictions, co-management arrangements are established as formal joint institutions; in others, they are embodied in defined relationships among "co-management partners."

In the circumpolar Arctic, environmental and wildlife management arrangements find expression through legal, formal and informal relationships often involving different levels of government, and, to varying degrees, local communities and indigenous peoples. Co-management arrangements are those that emphasize and formalize the roles of these parties in decision-making [390, 391]. The specific arrangements vary from cooperation and collaboration to shared authority for decision-making.

This section is written primarily from the perspective of co-management practitioners in Canada with input from their counterparts in Alaska. The challenges discussed, however, are illustrative of challenges faced by those concerned with wildlife and habitat management through different systems and in other Arctic nations.

In the following discussion, the term "co-management partners" is used to describe the various government agencies and community and indigenous people's organizations that play an advisory or decision-making role in co-management of fish, wildlife and habitat and related policy and research. "Co-management organizations" are boards and councils through which advice and decisions are formulated.

Co-management meeting on bears in the town of Aklavik in Canada's Western Arctic
Photo courtesy of Wildlife Management Advisory Council (North Slope)

In general, changing sea ice conditions directly or indirectly affect almost all areas in which Arctic coastal wildlife co-management organizations and partners have responsibilities. The changes will demand new approaches that involve increased planning and regulatory flexibility, heavier reliance on risk assessment, greater tolerance and care in the application of precautionary approaches, and more demand for research related to population and stock assessment. They will also require greater reliance on subsistence users, local communities and regional institutions to monitor and report ecological and sociological changes resulting from altered sea ice conditions.

The decline of sea ice, both recent and projected, directly affects managed species of fish and wildlife, altering habitat and affecting abundance and distribution of populations. The changes to ice also lead to or contribute to a broad range of additional stressors. These include increasing warming and acidification of the ocean; more storm surges, greater open-water fetch and bigger wave heights leading to greater coastal erosion and recession; new shipping, tourism and hydrocarbon activity; and growing human presence in the Arctic [14, 394].

These stressors carry with them new issues and both positive and negative impacts for managers to understand and respond to. In addition, the direction, rates and magnitude of ecosystem and socio-economic changes will vary widely within and across regions [21].

Requirement for up-to-date information and expanded knowledge on ecosystems

Rapid and variable changes to sea ice and related ecological conditions will seriously challenge the adequacy and reliability of both historical science-based and traditional-knowledge-based information about wildlife populations and habitat. In many areas, new information, including updates of fish and wildlife population information, and knowledge to aid in understanding changing ecological relationships will be required. For example, when species previously considered incidental or invasive become frequent visitors or residents, current understandings of ecosystem integrity are challenged and the functioning of Arctic marine food webs must be reassessed.

A central role of co-management organizations and partners is to gather and maintain wildlife population and fisheries stock information along with related research and traditional knowledge needed to determine conservation requirements and sustainable harvest levels. This is becoming an increasingly complex task that challenges the institutional capacity of co-management systems and has resource implications. To compound this, the increased need for science support may run counter to the trend toward austerity measures that scale back environmental science capacity.

Harvesting and traditional use

Co-management arrangements in Arctic coastal regions of Canada and the United States are heavily focused on protecting the harvesting rights of Inuit, Iñupiat and Yupik peoples and on conserving traditional uses of land and marine areas [392, 393, 395, 396]. Changes in sea ice conditions and the impacts on wildlife will affect co-management partners who are required to determine and justify sustainable harvest levels and quotas, especially when population-related trend data are uncertain and dynamic. Specifically:

- changes in the timing of migration for whales and seabirds will affect the determination of harvest seasons;
- changes in population distributions will necessitate re-evaluation of long-standing harvest allocation levels between regions and among communities; and,
- declining populations of some species will especially challenge co-management organizations that allocate quotas for subsistence, commercial and sport harvests.

Food supplies are likely to be affected by declines in some wildlife food sources, and increases in others. When preferentially harvested species become less accessible or less abundant, co-management partners will need to respond by tracking and managing the increased harvest of other species and developing new arrangements for the barter and sale of wildlife among communities and regions. For example, breeding populations of greater white-fronted geese in northern Alaska have increased recently due to vegetation changes related to warmer summers [397]. If ice-associated sea ducks decline, white-fronted geese may become more important as a food source.

Photo: Bikeriderlondon, Shutterstock.com

A shorter ice season and less stable ice conditions already affect harvesters' access to marine mammals [196]. This has led, for example, to the need to make adjustments to the length of time hunters may hold a tag for the harvest of an animal. But demands for fewer tags that are held for longer periods can be difficult to reconcile with goals of providing hunting opportunities for all harvesters. In another example, a later freeze-up in some areas has opened a fall whaling season, helping offset poorer conditions in the spring [389]. These types of changes will require, in some instances, a reassessment of longstanding regulated harvest seasons.

New and expanded fisheries

The potential increase in commercial Arctic fisheries, in particular, is likely to test the capacity of co-management organizations. Increases in some fish stocks and improved access due to a longer open-water season are leading to interest in commercializing fisheries that did not exist in the past or were limited to subsistence use [398]. The appearance in Arctic waters of new fish species, such as sockeye salmon in the Beaufort Sea [399, 400], may also lead to new demands for commercial fishing.

Establishing sustainable harvest levels for these stocks in Arctic waters will be a challenge, especially for newly arrived species and where historical data are limited. Research funds, already stretched in monitoring the status of fish stocks considered vulnerable, will have to be stretched further to accommodate additional species and the more frequent re-assessment of existing species.

Ecosystem-based management

The sustainability of stocks is important, but so is the ecological role that fish species play in the Arctic ecosystem. For example, a fishery that is sustainable in terms of the stock being harvested could still negatively affect seal populations, with consequences for polar bears and other species [401].

Often in the past, management approaches focused narrowly on the yields of individual fish stocks and wildlife populations, supported by species-centered research. A broader knowledge base is needed. For example, alterations in sea ice conditions and in the use of sea ice by polar bears [269] are leading to a recognition of the need for a broader management approach backed by more comprehensive ecological research. Some co-management bodies have responded by encouraging greater interdisciplinary collaboration among polar bear specialists, sea ice scientists and climate scientists (for example, Joint Secretariat 2011 [402]). This direction will require enhanced capacity for collaborative work among the ecological, social and physical science disciplines. New funding and support arrangements between co-management partners and Arctic states might be needed.

Historically, wildlife management has aimed to maximize sustainable harvest, subject to the requirements of conservation. In Canada, as a matter of law, recommended total allowable harvests and harvest quotas must be justified on the basis of conservation—an approach to managing species and habitat that has as its goal their long-term optimum productivity [392]. Wildlife population assessments underlie the recommendations that restrict or liberalize harvests.

Co-management that operates within an integrated and ecosystem-based management framework needs to consider the full range of stressors and impacts in determining harvest quotas and other management options, including habitat protection. Changing sea ice conditions alter and add stressors and change predator–prey relationships, increasing the difficulty of understanding the conservation requirements of Arctic species.

Shipping and oil and gas development

Among these added stressors are increased Arctic shipping and offshore oil and gas development [352, 360]. Innovative approaches are needed to address uncertainty and surprise, especially in assessing and managing actual and perceived environmental risk. Risk assessment methodologies will become important tools, especially in regard to increased Arctic offshore drilling and shipping and associated high-consequence, low-probability events, such as blow-outs and spills. These methodologies will be used to evaluate future development scenarios and resolve differences among co-management partners.

Photo: Vik01, Shutterstock.com

Habitat protection measures

As sea ice conditions change, participants in co-management will need a better understanding of how ecological impacts affect spatial planning. The result will likely be a re-appraisal of area boundaries, conservation designations and conditions applied to zones in existing marine conservation and protected areas and plans, community conservation plans and species range management plans. It can take a long time—a decade or more—to establish new habitat protection areas and habitat conservation measures (for example, Beaufort Sea Partnership 2009 [403]). The rate of change in habitat conditions might exceed the capacity of co-management institutions and partners to reassess and establish habitat area protections early enough to be effective and avoid critical tipping points [404–406].

Focus on sea-ice-associated wildlife

Ice-associated animals, such as polar bears, Pacific walrus, ringed seal, bearded seal, spectacled and king eiders, and beluga, narwhal and bowhead whales, will likely be an increasing priority of management efforts in response to public concern, population declines or, in some cases, population increases.

Changing sea ice conditions will induce effects that alter the conservation requirements of various harvested species [271, 407]. The result will likely be increasing attention and debate over the quality of the information, analysis and understanding that informs species conservation requirements and the judgments on which they are based. This will prove especially challenging in decisions affecting how these high-profile Arctic species such as polar bear, walruses, whales and seals, are dealt with under species-at-risk legislation and associated recommendations for species uplisting, downlisting and de-listing.

International forums and agreements

Uncertainty about the population status and conservation requirements of harvested Arctic species will also challenge the ability of co-management organizations to participate effectively in international forums and agreements. An example is CITES *(Convention on International Trade in Endangered Species of Wild Flora and Fauna)*, where trade-related conservation measures and their effectiveness for species such as the polar bear are already highly contentious [408, 409].

Dealing with uncertainty through a broad-scale application of the precautionary approach to Arctic wildlife harvest management can lead to conflicts, especially where indigenous harvesting rights are protected in law. Canadian co-management systems are faced with significant challenges when, for example, a general deficiency in species information is invoked to limit or restrict indigenous harvesting rights. If a decision on total allowable harvest will restrict legally protected harvesting rights, the need for that specific conservation measure must be justified at the spatial and animal population scale at which the decision is made. This highlights the importance of sound, defensible, scientific and traditional-knowledge-based information to support decisions, as well as the need for careful consideration of approaches to dealing with uncertainty.

Traditional knowledge and science in decision-making

In Canada, largely as a consequence of land claim agreements, co-management partners are generally required to give equal weight to traditional knowledge and science in recommendations and decision-making affecting wildlife management [392, 393]. In Alaska, information based on traditional and local knowledge is used in conjunction with the best available scientific information in making decisions about wildlife and fisheries research and management [410].

The standing of traditional knowledge in wildlife and conservation management, even in circumstances where it is confirmed in law, remains tenuous in the view of some scientists and co-management partners [411–413]. As a result, the potential associated with the effective use of traditional and local knowledge has not been fully realized [414, 415]. Until it is, the timely and unique insights that traditional and local knowledge can provide into changing sea ice conditions and their ecological and human consequences will be of limited value to management decisions. At worst, two bodies of knowledge and two ways of knowing—one science-based, the other user-based—will engage in an ongoing contest over the nature of changing sea ice conditions and their effects. Polar bear conservation management provides an example of how this debate can play out, both within Arctic nations and internationally [409, 416].

With the rapid change in sea ice and related ecological conditions, the dependence of co-management organizations on the observations and knowledge of local indigenous people, especially harvesters, will be greater than ever. Local knowledge incorporates observations of people engaged over their lifetimes in hunting, fishing and processing of traditional foods. Observations are interpreted within the long-term context and worldview of traditional knowledge to provide current information that can detect subtle changes in species health and ecological conditions. It takes much longer for such changes to be detected through population surveys. Recent work has focused on ways of making better use of both forms of knowledge in understanding and managing wildlife under a changing climate regime (for example, Berkes et al. 2007 [415], Henri et al. 2010 [417]). Traditional and local knowledge can be incorporated more effectively into resource management, assessment and research if it is recorded, compiled and presented in a way that makes it accessible (Box 13) [418].

Box 13. Making traditional and local knowledge more accessible for decision-making

Methods, tools and innovative approaches to improving use of local and traditional knowledge have recently been developed or are in the works. Some examples:

- A handbook on community-based monitoring developed as part of CAFF's monitoring program [421]
- Collaborative, international sea ice research and monitoring through the International Polar Year "Inuit Sea Ice Use and Occupancy Project". Ongoing work associated with this includes weather, sea ice and ecosystem monitoring through a blend of science, new technologies and traditional knowledge (see photo) [359, 422].
- Systematic documentation and archiving of traditional knowledge and community-based monitoring datasets through ELOKA (Exchange for Local Observations and Knowledge of the Arctic), a service set up through the US National Snow and Ice Data Center as part of International Polar Year [423]
- Bering Sea Sub-Network, a community-based environmental observation alliance including villages in Alaska and Russia, collaborating to monitor change in the Bering Sea [424]

Inuit forecasters equipped with generations of environmental knowledge are helping scientists understand changes in Arctic weather. Photo: Shari Gearheard/NSIDC

Bridging scales: international agreements and regional and local cooperation

Differing attitudes, knowledge, understanding and concerns among regions and countries about the ecological effects of changing sea ice conditions compound the challenges of managing wildlife, habitat and harvesting across international boundaries. Co-management arrangements provide an important means of linking local, regional, national and international interests, sharing information, and coordinating management. The value of community-level monitoring has not been fully realized. It could be greatly enhanced and contribute substantially to national and international discussions on Arctic warming and sea ice and marine-related effects.

These are lost opportunities. Arctic indigenous people who hunt and travel on ice understand ice states and conditions in ways that only a handful of traditional knowledge studies have documented to date. The observations and associated understanding of local people could be of substantial value to ice science and to the assessment of the effects of changing ice conditions, particularly on ice-dependent species.

The direct participation of co-management organizations and partners in these forums is a way to integrate environmental monitoring efforts across a broad range of geographic scales and jurisdictions. An example, in terrestrial Arctic ecology, focusing on caribou and wild reindeer, is the CircumArctic Rangifer Monitoring and Assessment Network (CARMA), a network under CAFF that includes academic, government, and co-management partners [419]. Another promising example is the relationship between co-management organizations in Canada and TRAFFIC—the wildlife trade monitoring network—with respect to the assessment of Canadian polar bear populations [420].

Playing on the ice with toy snowmobiles carrying seal meat, Pond Inlet, Canada. Photo: Peter Prokosch, UNEP/GRID-Arendal

6. Looking ahead

It is clear that changes are occurring now in sea ice ecosystems and that, with the accelerating decline of multi-year ice and vastly altered extent and timing of seasonal ice, further major changes are ahead. The nature of some of these changes remains very hard to predict. In part this is due to a lack of knowledge about some fundamental aspects of Arctic marine science, and in part it is due to the complex interplay among impacts of climate change and other stressors with the processes that control marine food webs. We know to expect the unexpected. We know there will be winners and losers, both for Arctic biota and for humans.

Looking ahead means mitigating the impacts of stressors and planning for rapid change. This section provides, first, a set of four recommendations that emerged from the preparation of this report. These are followed by an annotated compilation of selected relevant recommendations from recent Arctic Council assessments and task group reports. The section finishes with some examples of new initiatives that respond to the challenges of rapid changes in sea ice.

6a. Recommendations emerging from this report

1. **Facilitate a move to more flexible, adaptable wildlife and habitat management and marine spatial planning approaches that respond effectively to rapid changes in Arctic biodiversity.**

   Rapid reduction of sea ice shifts baselines and increases the urgency for biodiversity conservation. Planning and management systems are challenged by the pace of change and increased uncertainty. Decision-makers at local, regional, national and international levels face common challenges in anticipating and adapting to new conditions and addressing conflicting needs, all within a context of heightened global concern for Arctic biodiversity. Designing support for good decision-making should include:

   a) analysis of existing systems and how well they are equipped to conserve biodiversity impacted by change in sea ice;

   b) identification of common needs and of areas where collaboration through the Arctic Council community would be effective;

   c) preparation of resources and tools, such as guidelines and best practices.

2. **Identify measures for detecting early warnings of biodiversity change and triggering conservation actions.**

   Move towards a stronger reliance on early warnings of ecosystem change, rather than on population trends as triggers for making decisions. Aside from catastrophic die-offs and breeding failure, impacts from changes in sea ice are often incremental, such as a reduced rate of reproduction or survival, or less energy intake from prey. Impacts may take years to be detected in population trends, especially for long-lived animals. Measures such as reduced body condition or changes in ice-dependent prey species are evidence of impacts that can be acted on before declines are detected in abundance or distribution. In some cases these earlier actions will prevent or lessen population declines. Factors to consider in selecting such measures of change include long-term costs and benefits, support by research, ability to be updated, and suitability for determining thresholds for action.

3. **Make more effective use of local and traditional knowledge in Arctic Council assessments and, more broadly, in ecological management.**

   We need the best available knowledge to detect and respond to rapid Arctic ecosystem change. Local and traditional knowledge sources, by their nature, bring a depth of knowledge and understanding of ecosystems, as well as early warnings of change, that complement science-based studies. However, these knowledge sources are generally underutilized in assessment and management except at the scale of the knowledge holders' communities. Arctic Council can provide a leadership role in improving this through:

   a) developing methods or tools for more effective presentation and analysis of local and traditional knowledge sources in Arctic Council assessments, and

   b) placing a focus on this issue through Arctic Council ecosystem-based management initiatives.

4. **Target resource managers when communicating research, monitoring and assessment findings.**

    Increase efforts to communicate results of research and monitoring relevant to conservation of sea-ice-associated biodiversity. Focus particularly on meeting the information needs of those making on-the-ground wildlife conservation decisions on, for example, conditions of development permits or fish and wildlife harvest regulations. Available information, including from recent Arctic Council assessments, may be hard for managers to sift through or to know what is most relevant to them. Work in this area should engage users of the information in designing content and delivery and should consider methods beyond print media. It should take into account time and resource constraints of the users and considerations such as keeping information up to date. Communication may best be delivered at a national or regional level, but benefits and efficiencies of collaboration through Arctic Council could be explored.

Polar cod in Beaufort Sea. Photo: Hidden Ocean 2005 Expedition, NOAA Office of Exploration

6b. Arctic Council recommendations

Arctic Council has recently released several assessments and experts group reports that address or are relevant to sea-ice-associated biodiversity. Review of these reports reveals a high degree of congruence in themes and content of the recommendations. All the assessment recommendations emphasize the need to improve Arctic monitoring. As a whole, the recommendations provide comprehensive guidance on priorities and actions of particular relevance to conservation of sea-ice-associated ecosystems. An annotated summary of relevant recommendations from these recent Arctic Council reports is presented in Appendix 1.

6c. New directions in policy

This section features four diverse policy-related initiatives that respond to recent and projected rapid changes in sea ice and associated biodiversity. Each project is led by a different sector of the broader Arctic Council community: the first by a Permanent Participant organization, the second by an Observer organization, the third by Arctic Council through several of the working groups, and the fourth by CAFF in partnership with the international science community.

The first initiative is an Inuit-led project that explores food security from an indigenous perspective, first for Alaska and then for consideration for wider application. Its outcomes include a policy framework for food security in the Arctic and identification of priority information needs. The second initiative, led by an international non-government organization, builds knowledge and explores options for the conservation of ice-dependent species in the not-so-distant future when most of the multi-year ice has gone. The third initiative is not a single project, but a discussion of work ongoing through Arctic Council on facilitation and coordination of marine protected area development. New directions and opportunities are highlighted. The fourth initiative tackles the problem of inadequate ecological information for decision-making by focusing on the efficiency and effectiveness of monitoring, data distribution, analysis and reporting.

Walrus cows resting on sea ice south of Nunivak Island, Alaska, while nursing their calves. Photo:Brad Benter, USFWS

An Inuit perspective on food security in the Alaskan Arctic: Building a framework on how to assess change in the Arctic

Lead: Inuit Circumpolar Council Alaska

With the many changes happening in Arctic ecosystems, mainly due to climate change and industrialization, food security is becoming a central topic of conversation.

In response to the need to address the security of traditional food sources within a changing Arctic, the Inuit Circumpolar Council Alaska (ICC-AK) is building a conceptual framework on how to assess food security from an Inuit perspective. The Inuit-led project will contribute to our understanding of the pressures on traditional food resources and communities that are resulting from climate changes, increased human presence and development in the Arctic. The framework will also be a tool to enhance the ability of Inuit communities and scientists to work together to holistically understand changes occurring within the Arctic. It will provide elected leaders and policy makers with an understanding of what food security means in the Arctic, what the drivers are and what will need to be monitored in order to create action plans.

Food security, from an Inuit perspective, relies on cultural and environmental systems that interlink and support each other. Inuit traditional Arctic foods include berries, greens, sea ducks, fish, whales, seals and walrus. They provide food, clothing, shelter, medicines, energy, nutrients, and spirituality. Understanding the interlinking of these systems will ultimately provide a tool to identify vulnerabilities throughout the ecosystem.

Through literature reviews, community meetings, interviews and gathering of traditional knowledge, this project will identify the baselines needed to assess the vulnerabilities of food security. These baselines will recognize Inuit priorities in assessing food security and where vulnerabilities lie. Preliminary examples of the types of baselines that may be included are 1) full understanding of ice coverage needed to understand food web dynamics; 2) more use of traditional knowledge on under-ice currents needed to gain a better understanding of salmon distribution; or, 3) more effort to be applied to establishing food web models that consider more than energy transfer by incorporating physical characteristics and/or the human dimension—for example, food web models interlinking sea ice, Inuit communities, aquatic primary producers and terrestrial vegetation.

The project is scheduled for completion in the spring of 2015, with the conceptual framework ready for distribution in the fall of 2014. Results will be shared with the Arctic Council, along with encouragement to expand the assessment to the entire Arctic using the resources and knowledge of the Arctic Council working groups.

Fish drying in Kaktovik, Alaska. Photo: J. Slein

Maintaining ecosystem and cultural values in "The Last Ice Area"

Lead: WWF

WWF is one of the organizations trying to work out what risks the ice loss poses for the future of ice dependent life. Its new project, called "The Last Ice Area", focuses on the area where summer sea ice is projected to persist the longest: North Greenland and the Canadian high Arctic islands [17] (shown in Figure 4). The goal of the study is to help identify places in and around this core of summer sea ice that will be important to maintaining the ecological and cultural values associated with the sea ice.

On a parallel track, WWF scientists are engaging with Inuit and governments in the region to begin discussion on potential future management of the area in a fashion that will encourage resilience of ice-dependent life. The aim is to ensure that future important conservation opportunities are not foreclosed by management decisions that may not have taken into account the likely future state of the area.

The research through the Last Ice Area project is grouped around these central questions:

Where and when will the ice loss be?

An ice modeling team will attempt to bring better spatial and temporal resolution into the discussion of sea ice loss. Better information on likely quantities, locations and types of sea ice at particular places and particular times in the future should help in projecting how species are likely to use the habitat.

How will ice-dependent life react to the ice loss?

To answer this question, we need better information on the current status and behavior of ice-dependent life [55]. WWF is contributing to efforts in this area by putting money into surveys of polar bear subpopulations and polar bear denning locations, by helping to track narwhal populations, and by funding a survey of traditional Inuit knowledge of the Last Ice Area. Given the size, difficulty and complexity of the task of determining even current population sizes for the various forms of ice-dependent life, this task could easily stretch beyond the time at which the knowledge it provides could be most useful.

An Al Jazeera TV crew accompanied WWF on a voyage to the Last Ice Area in the summer of 2012. Photo: C. Tesar, WWF

Arctic Council and international initiatives on protected areas

Lead: Arctic Council

Protected areas have long been used to maintain and conserve Arctic biodiversity and landscapes. However, with sea ice waning and the pressure for human access to Arctic waters growing, the Arctic Council has recognized that a new approach will be needed to maintain the functions of Arctic marine ecosystems.

In the face of climate change and increasing disturbance, will existing networks of protected areas be sufficient to ensure conservation? Or will we be faced with a situation where what is desirable to protect today is changed or lost as ecosystems alter, species shift their ranges and previously inaccessible regions become open to exploitation? These questions are especially critical in the marine environment, where the extent of protected areas remains very small in comparison with the terrestrial environment.

In response, the Arctic Council and the World Conservation Union (IUCN) have worked in recent years to identify marine areas of heightened ecological and cultural significance. The results of these efforts [425, 426] are feeding into a process in which Arctic states will be asked to consider how protection of such areas can be implemented: for example, through the use of tools such as "Special Areas" or "Particularly Sensitive Sea Areas" designated through the International Maritime Organisation. The United Nations Convention on Biological Diversity has added to the growing pressure to address protection in the Arctic marine environment and recently adopted resolutions encouraging the identification of Ecologically or Biologically Significant Marine Areas in the Arctic [427].

The results of these initiatives are also contributing to the Arctic Council's ongoing work in identifying best practices and advancing a common understanding of ecosystem-based management and Arctic resilience. Such initiatives will help foster a management approach for the Arctic and its marine ecosystems that addresses local concerns and, at the same time, links the Arctic into the wider global context.

Inukshuk, Baffin Island, Canada. Photo: City Escapes Nature Photography, Shutterstock.com

Directions in ecological monitoring: The Circumpolar Biodiversity Monitoring Program and the *Arctic marine biodiversity monitoring plan*

Lead: CAFF

Achieving success in conserving Arctic biodiversity while allowing for economic development requires comprehensive baseline data on status and trends of Arctic biodiversity, habitats and ecosystem health [2]. The unprecedented changes being experienced in the Arctic make it particularly important to deliver this information to decision-makers in a timely manner. To do so requires coordinated and consistent monitoring, easily accessible, comprehensive data, and up-to-date assessments of trends. CAFF is working to improve the quality of monitoring and the accessibility of data, and to shorten the time between detection of changes and effective policy responses.

A key component in this process is the Circumpolar Biodiversity Monitoring Program (CBMP), an international network of scientists, government agencies, indigenous organizations and conservation groups working to harmonize and integrate efforts to monitor the Arctic's living resources [349]. A key objective of the CBMP is to create a publicly accessible platform for collecting and disseminating information on the status of, and trends in, Arctic biodiversity. Towards this objective, the CBMP has developed the Arctic Biodiversity Data Service, an online platform for discovering and accessing data on the Arctic's biodiversity [428]. This service aims not only to make biodiversity data more accessible for multiple purposes but also to make it available earlier. For example, up-to-date data on distribution and abundance of seabird species across the Arctic are available on the data service and can be used for environmental assessments, emergency response and to develop research into drivers of biodiversity change.

Figure 41. Eight Arctic Marine Areas around which monitoring is being coordinated
Adapted from Gill et al. 2011 [429]

The *Arctic marine biodiversity monitoring plan* [429] is the first of four pan-Arctic biodiversity monitoring plans developed by the CBMP to improve the ability to detect and understand the causes of long-term change in the composition, structure and function of Arctic ecosystems. The plan, which is currently being implemented, uses existing monitoring capacity and enhanced coordination and integration to improve monitoring and make it more cost-effective.

Common parameters, sampling approaches and indicators are being implemented across eight Arctic marine areas (Figure 41). Data sources and formats vary widely across the Arctic and it is challenging to access, aggregate, and depict this diverse range of data. A related challenge lies in synthesizing this information and examining how biodiversity data are related to data on physical and chemical environmental conditions. This type of synthesis and analysis is needed to improve understanding of what is driving biodiversity trends at various scales, from regional to global, and thereby facilitate management responses and research.

It is critical to deliver this information in effective and flexible reporting formats that will meet the needs of decision makers at local to international scales. The first *State of Arctic marine biodiversity report* is scheduled for completion in 2016 and will be repeated every five years. Data collected through the marine plan will be accessible through the Arctic Biodiversity Data Service, providing policy and decision-makers with ongoing access to the information they need. As well, a suite of environmental indicators will be reported on every two years. These products will be supplemented by regular scientific publications, performance reports and other communications material. Already, pan-Arctic datasets have been compiled and analyzed, offering insights into potential drivers of biodiversity change (for example, Eamer et al. 2012 [430]).

Taking ice samples off the side of the Amundsen
Photo: Marine Productivity Laboratory, Fisheries and Oceans Canada

7. Appendices

Appendix 1. Annotated summary of recommendations from related Arctic Council assessments and task groups

This section summarizes recommendations of particular importance to conservation and management of sea-ice-associated biodiversity from the following reports:

- ABA: *Arctic biodiversity assessment. Status and trends in Arctic biodiversity* [2, 431]
- SWIPA: *Snow, water, ice and permafrost in the Arctic: Climate change and the cryosphere* [1]
- AOR: *The Arctic Ocean Review Project, final report (phase II 2011–2013)* [350]
- EBM: *Ecosystem-based management in the Arctic* [348]
- AMSA: *Arctic marine shipping assessment* [352]
- AOA: *Arctic Ocean acidification assessment* [355]

Recommendations are grouped under the following themes:

1. Climate change mitigation
2. Peoples and culture
3. Adaptation and management
4. Protected areas
5. Preventing damage to ecosystems
6. Fisheries in international waters
7. Harvest
8. Communication
9. Knowledge

Annotations (*in italics*) are based on this report and the two experts' workshops on sea-ice-associated biodiversity organized by CAFF as part of this project (Vancouver, Canada and St Petersburg, Russia). A synthesis of discussion on recommendations from the workshops is available as supplementary material to this report [3].

Only selected recommendations are presented here, and many are summarized. The original documents (referenced in parentheses following each recommendation) should be consulted for exact wording and more detail. Many recommendations that are more broadly focused, but still relevant to sea-ice-associated biodiversity, are not included. For example, the *Arctic biodiversity assessment*'s recommendations on contaminants and invasive species are relevant to sea-ice-associated biodiversity, but have been omitted from this presentation.

1. Climate change mitigation

- International negotiations to reduce global greenhouse gas emissions should be pursued as a matter of urgency. Member States of the Arctic Council should increase their leadership role in this process. (SWIPA Executive Summary)
- Actively support international efforts addressing climate change as an urgent measure. Flagged as of specific importance are efforts to reduce greenhouse gas emissions and to reduce emissions of black carbon, methane and tropospheric ozone precursors. (ABA Recommendation 1)
- Arctic states should reaffirm the importance of their engagement in the UNFCC to reduce global greenhouse gas emissions as a matter of urgency. (AOR Recommendation 19)
- It is recommended that the Arctic Council urge its Member States, Observer countries and the global society to reduce the emission of CO^2 as a matter of urgency. (AOA Recommendation 1)

Addresses the root cause of threats to ice-associated biodiversity by slowing the rate of climate change.

2. Peoples and culture

- The Arctic states in cooperation with the Arctic Council should assist, as appropriate, the Permanent Participants with the documentation of current and historical a) timing and geographical extent of local uses of the marine environment, and b) levels of traditional marine resources harvests, taking into account the differing documentation needs and capacities of Arctic states. (AOR Recommendation 1)
  This recommendation is of particular relevance to use and governance of marine mammals, seabirds and fish that are ice-associated as these species are under pressure from climate change, are highly valued for traditional local use, and are of high profile at international scales. Related to this report's recommendation 1.
- Promote the active involvement of indigenous peoples in the management and sustainable use of protected areas. (ABA Recommendation 5c)

3. Adaptation and management

3.1. Adapting to rapid change in ice

- Develop and implement Arctic adaptation strategies. (SWIPA Executive Summary)
- Ensure that standards for environmental management are in place, or can be adapted, to take account of cryospheric change. (SWIPA Executive Summary)
- Actively support international efforts addressing climate change, including implementing adaptation measures, as an urgent matter. (ABA Recommendation 1)

3.2. Conserving endemic species

- Concerted international efforts should be undertaken to preserve endemic Arctic flora and fauna. (SWIPA, Biological impacts of changes in sea ice in the Arctic, section 9.3)

3.3. Ecosystem-based management

- Propose that Arctic Council adopt a policy commitment to ecosystem-based management (EBM), a common definition of EBM, and a set of EBM principles. Taken together, these present the framework for implementing EBM in the Arctic. This includes supporting ecosystem resilience to maintain ecological functions and services, and recognizing that humans are an integral part of ecosystems and that sustainable use is central to management objectives. This framework also lays out the role of EBM in addressing cumulative effects and the importance of incorporating and reflecting knowledge drawn from science and from traditional and local experts. It stresses the inclusive nature of EBM, the need for broad participation at all stages, and the value of transboundary perspectives and partnerships. Of particular note is the recognition of the need for flexible and adaptive measures in light of the rapid changes occurring in the Arctic. (EBM Recommendations 1–3)
- Advance and advocate ecosystem-based management as a framework for cooperation, planning and development across the Arctic, including consideration of cumulative effects. Further details support the above recommendation from the EBM Experts' Group. (ABA Recommendation 2)

Some specific, practical recommendations for successful implementation of EBM in sea ice ecosystems:

- Develop and adopt a policy and best practices for incorporating traditional knowledge into EBM activities as appropriate. (EBM Recommendation 4: Arctic Council activities, policy and implementation)
- Encourage the use of the revised map of 17 Large Marine Ecosystems to inform EBM implementation. (EBM, Recommendation 4: Arctic Council activities, science and information)

4. Protected areas

4.1. Refuge for ice-associated species when most multi-year ice has been lost

See also the description of the related WWF project "The Last Ice Area" in the Looking ahead section.

- Canada and Greenland should consider creating a World Heritage Site in Northwest Greenland/Northeast Canadian Archipelago as refuge for ice-associated species. (SWIPA, Biological impacts of changes in sea ice in the Arctic, section 9.3)
- Develop and implement mechanisms that safeguard Arctic biodiversity under changing environmental conditions, such as loss of sea ice: safeguard areas in the northern parts of the Arctic where high Arctic species have a relatively greater chance to survive for climatic or geographical reasons, as a refuge for unique biodiversity. (ABA Recommendation 7)

4.2. Policy and mechanisms for protected areas (and sensitive and significant areas)

- Explore need for internationally designated Arctic marine areas for purpose of environmental protection. (AMSA, Recommendation II.D., Protecting Arctic people and the environment)
- Explore ways in which Arctic States can cooperate to advance conservation and management of biologically, ecologically and culturally significant areas. (EBM, Recommendation 4: Arctic Council activities, policy and implementation)
- Identify biologically, ecologically and culturally significant areas in the coastal, marine and terrestrial environments, and consider EBM-related needs for these areas. Identify areas most vulnerable to human impacts. (EBM, Recommendation 4, Arctic Council activities, science and information)
- Advance the protection of large areas of ecologically important marine habitats, taking into account ecological resilience in a changing climate. For marine protected areas, build on existing processes to complete the identification of areas and implement conservation measures. (ABA Recommendation 5)

5. Preventing damage to ecosystems

5.1. Reducing threats and enhancing capacity to respond to pollution events

These measures are important for protection of sea-ice-associated biodiversity from impacts including spills, pollution, under-water noise, disturbance and introduction of alien invasive species.

- Reduce the threat of pollutants to biodiversity by supporting development of prevention and clean-up measures and technologies for oil spills, especially in ice-filled waters, such that they are ready for implementation in advance of major oil and gas developments. (ABA Recommendation 11)
- Finalize and implement the Polar Code (international shipping regulations) and support other international work that leads to safe shipping practices in the Arctic, including training requirements for ship personnel, ship routing and reporting measures, ballast water management, and enhancing and sharing of information needed for navigation. (AOR Recommendation 3)
- Encourage development of international standards relevant to Arctic oil and gas operations; move toward circumpolar policy harmonization in sectors such as environmental monitoring and pollution prevention practices; and, promote interactions with international treaty bodies that address issues such as spill preparedness and response. (AOR Recommendations 14, 15 and 16)
- Increased collaboration between Arctic Council and international organizations is recommended to protect whales from ship-related impacts such as ocean noise and ship strikes. (AOR Recommendation 11)

5.2. Proactive steps to prevent damage to sensitive areas

Focuses effort on increasing protection for sea-ice-associated biota at critical times and places, for example, whales at summer feeding locations and nesting birds. Also protection of areas important for indigenous people for fishing and harvest of marine mammals and birds.

- Identify areas of heightened ecological and cultural significance and consider protection measures related to impacts from shipping. (AMSA Recommendation II.C. Protecting Arctic people and the environment) *Identification portion complete in 2013* [425]
- Safeguard areas critical for sensitive life stages of Arctic species, including polynyas; to accomplish this, develop guidelines and implement spatial and temporal measures to reduce disturbance outside of protected areas. (ABA Recommendation 6)

6. Fisheries in international waters

- Support efforts to plan and manage commercial fisheries in international waters under common objectives that ensure long-term sustainability of species and ecosystems. Encourage precautionary, science-based management of fisheries in these waters in accordance with international law. (ABA Recommendation 10c, AOR Recommendation 10)
  An important recommendation in relation to sea ice and biodiversity, as changes in ice extent and timing are making new marine regions accessible to fishing while at the same time leading to changes in ocean productivity, food webs and distribution of fish species.

7. Harvest

- Consider genetic viability of species and adaptation to climate change as guiding principles in determining and managing sustainable harvest levels. (ABA Recommendation 10b)
  Particularly important for ice-dependent species as they experience range contractions and a vastly altered environment.
- Improve the use and integration of traditional ecological knowledge and community-based monitoring in managing harvests. (ABA Recommendation 10a)
  Increasingly important as sea ice changes alter the habitat for harvested species, as well as accessibility of harvesting areas, at regional and local scales (see Human dimension section)

8. Communication

The importance of building awareness of threats to sea ice ecosystems and of delivering targeted materials to decision-makers was stressed at the expert workshops, leading to this report's recommendation #3.

- Develop communication and outreach tools and methodologies to better convey the importance of Arctic biodiversity and the changes it is undergoing. (ABA Recommendation 17)

9. Knowledge

Knowledge gaps and priorities were discussed at the expert workshops held in the development of this report. See the supplementary material to this report for more details [3]. Summary:

> *Priority knowledge gaps for sea-ice-associated biodiversity: understanding how changes at the lower trophic levels affect ecosystem structure and function; timing and spatial mismatch; filling knowledge gaps on species distribution; winter processes; knowledge about functioning of the central Arctic Ocean.*
>
> *Points on methods, approaches and processes: enhance capacity for research on lower trophic levels; improve baseline modeling of sea ice changes; put more effort into involving Arctic residents in research and monitoring; focus on coordinated circumpolar monitoring; develop remote sensing measures relevant to biodiversity change and for tracking trends in key features like polynyas.*

Specific recommendations on research and monitoring priorities are in the chapters of SWIPA, AOR, and the ABA. Selected recommendations from these reports particularly relevant to sea-ice-associated biodiversity:

- Research and monitor individual and cumulative effects of stressors and drivers of relevance to biodiversity, with a focus on stressors that are expected to have rapid and significant impacts and issues where knowledge is lacking. This should include, but not be limited to, modeling potential future species range changes as a result of these stressors; developing knowledge of and identifying tipping points, thresholds and cumulative effects for Arctic biodiversity; and developing robust quantitative indicators for stressors through the Circumpolar Biodiversity Monitoring Program. (ABA Recommendation 16)
  This recommendation is of particular relevance for the conservation of sea-ice-associated biodiversity because of the rapid rate of change and the consequent potential for unexpected and sudden shifts in ocean regimes.
- Improve and expand systematic, comprehensive surface-based monitoring of the cryosphere. (SWIPA Executive Summary)
- Regional scientific assessments and monitoring of biological community components across the Arctic, using standardized methodologies among areas, are highly recommended. (SWIPA, Biological impacts of changes in sea ice in the Arctic, section 9.3)

- Develop and enhance systems to observe the cascading effects of cryospheric change on ecosystems and human society. (SWIPA Executive Summary)
- Increase and focus inventory, long-term monitoring and research efforts to address key gaps in scientific knowledge, including knowledge about invertebrates, microbes, parasites, and pathogens. (ABA Recommendation 13)
- Monitor and assess combined effects from multiple stressors. (AOR Recommendation 18)
- Involve Arctic peoples and their knowledge in the survey, monitoring and analysis of Arctic biodiversity. (ABA Recommendation 14)
- Maintain and support development of remote sensing methods for observing the cryosphere. (SWIPA Executive Summary)

Photo: Denis Burdin

Appendix 2. Common and scientific names of species

This reference list includes species or groups of species that are referred to by common names in the report.

Common name	Scientific name
A–C	
Arctic char	*Salvelinus alpinus*
Arctic fox	*Alopex lagopus*
Arctic tern	*Sterna paradisaea*
Arrow worms	Phylum Chatognatha
Atlantic cod	*Gadus morhua*
Atlantic puffin	*Fratercula arctica*
Atlantic salmon	*Salmo salar*
Auks and auklets	Seabirds of the family Alcidae
Bearded seal	*Erignathus barbatus*
Beluga	*Delphinapterus leucas*
Black guillemot	*Cepphus grille*
Black-legged kittiwake	*Rissa tridactyla*
Blue mussel	*Mytilus edulis*
Bowhead	*Balaena mysticetus*
Brittle stars	Class Ophiuroidea
Brown bear	*Ursus arctos*
Capelin	*Mallotus villosus*
Caribou	*Rangifer tarandus*
Centric diatoms	Order Centrales
Common eider	*Somateria mollissima*
D–F	
Fin whale	*Balaenoptera physalus*
Flatworms	Phylum Platyhelminthes
Fulmar (or northern fulmar)	*Fulmarus glacialis*
G–I	
Glaucous gull	*Larus hyperboreus*
Gray whale	*Eschrichtius robustus*
Great black-backed gull	*Larus marinus*
Great skua	*Stercorarius skua*
Greater white-fronted goose	*Anser albifrons frontalis*
Greenland halibut (Greenland turbot)	*Reinhardtius hippoglossoides*
Greenland shark	*Somniosus microcephalus*
Guillemots	*Cephus spp.*
Gyrfalcon	*Falco rusticolus*
Harp seal	*Pagophilus groenlandicus*
Herring	*Clupea harengus*
Herring gull	*Larus argentatus*
Hooded seal	*Cystophora cristata*
Horned puffin	*Fratercula corniculata*
Hudson Bay common eider	*Somateria mollissima sedentaria*
Human	*Homo sapiens*
Humpback whale	*Megaptera novaeangliae*
Ice cod (also known as polar cod)	*Arctogadus glacialis*
Iceland gull	*Larus glaucoides*
Ivory gull	*Pagophila eburnea*
J–L	
Jaegers	*Stercorarius spp.*
Killer whale (Orca)	*Orcinus orca*
Kittiwakes	*Rissa spp.*
Least auklet	*Aethia pusilla*
Little auk	*Alle alle*
Long-tailed duck	*Clangula hyemalis*
M–O	
Minke whales	*Balaenoptera spp.*
Murres	*Uria spp.*
Narwhal	*Monodon monoceras*
Nematodes	Phylum Nematoda
P–R	
Pacific cod	*Gadus macrocephalus*
Pacific salmon	Salmon of genus *Oncorhynchus*
Pennate diatoms	Order Pennales
Pink salmon	*Oncorhynchus gorbuscha*
Polar bear	*Ursus maritimus*
Polar cod (known in N. America as Arctic cod)	*Boreogadus saida*
Pteropods	Sea butterflies in the clade Thecosomata
Puffin (Atlantic)	*Fratercula arctica*
Raven	*Corvus corax*
Razorbill	*Alca torda*
Ribbon seal	*Histriophoca fasciata*

Ringed seal	*Pusa hispida*
Ross's gull	*Rhodostethia rosea*
S–U	
Sandlances	Family Ammodytidae
Sculpins	Family Cottidae
Sea anemones	Order *Actiniaria*
Sea cucumbers	Class *Holothuroidea*
Sea lilies	Members of the class Crinoidea
Sea stars	Class *Asteroidea*
Sea urchins	Class *Echinoidea*
Shearwaters	Several species of genus *Puffinus*
Snow crab	*Chionoecetes spp.*

Snowy owl	*Bubo scandiaca*
Sockeye salmon	*Oncorhynchus nerka*
Spectacled eider	*Somateria fischeri*
Spotted seal	*Phoca largha*
Thayer's gull	*Larus thayeri*
Thick-billed murre (Brünnich's guillemot)	*Uria lomvia*
V–Z	
Walleye pollock	*Theragra chalcogramma*
Walrus	*Odobenus rosmarus*
Whitefishes	*Coregonus spp.*
Wolf	*Canis lupus*

Appendix 3. Glossary

Anadromous fishes	Fishes that spend part of their life cycle in marine environments and part in freshwater.
Arctic	There are many definitions in use. The CAFF definition is shown on the map on the inside cover. For the purposes of this report, the Arctic marine area is that which is directly influenced by sea ice. For terrestrial ecosystems, high Arctic and low Arctic are defined using vegetation zones. Both are tundra, with low Arctic having denser vegetation cover. In the marine environment, the division between high Arctic and low Arctic is not as clear and reflects general perceptions of the different zones, approximately extending the terrestrial zone divisions to the marine environment (see Figure 3 in Christensen et al. 2011 [432]).
Arctic Ocean	In this report, we use the term to include the central basin of the Arctic Ocean and the adjacent seas that are wholly or in part ice-covered at least seasonally.
Benthos	The flora and fauna at the bottom of the sea (the benthic realm).
Brine channels	Tiny channels in sea ice filled with high-salt-content water. As sea ice forms, droplets of salty water form and these join into narrow brine channels that riddle the ice and drain to the surrounding sea. The salt-saturated water in the channels remains liquid at low temperatures, and brine channels provide year-round habitat for microorganisms in sea ice.
Food chain	Organisms related through their feeding habits. Food chains follow a single pathway as animals eat plants and each other.
Food web	Organisms related through their feeding habits. Food webs trace how plants, animals and microbes are interconnected by different pathways.
High Arctic	See Arctic
Lead	Stretch of open water in sea ice, often transient. Flaw leads are situated between land-fast ice (also called fast ice) and pack ice and occur annually.
Low Arctic	See Arctic
Marginal ice zone	The transition area from pack ice to open water.
Pelagic organism	Organism living in the water column (the pelagic realm).
Photosynthesize	Using the energy of sunlight to produce carbohydrates from carbon dioxide and water.
Phytoplankton	Tiny, single-celled algae.
Plankton	Organisms that drift with the currents as opposed to other pelagic organisms like squid, fish and whales, that propel themselves.
Polynya	Area of permanently or frequently open water surrounded by sea ice.
Sub-Arctic	The northern part of the boreal or temperate zone (south of the Arctic).
Trophic level	A position on a food chain. Primary producers are the lowest trophic level. In the Arctic, marine mammals and humans are at the top.
Upwelling	The process of deep, often nutrient-rich water rising to the surface due to wind or currents.
Water mass	A body of ocean water with a common history of formation, giving it distinct physical properties that distinguish it from the waters around it.
Zooplankton	The animals of the plankton world: mainly small crustaceans and other invertebrates that feed on phytoplankton or particles of organic matter.

Appendix 4. Workshop participants

Vancouver workshop, March 22–24, 2011

Hussein Alidina, World Wildlife Fund – Arctic; Tom Barry, CAFF Secretariat; Larry Carpenter, Wildlife Management Advisory Council (NWT); Stanislav Belikov, All-Russian Research Institute for Nature Protection; David Boertmann, Danish National Environmental Research Institute; Cindy Dickson, Arctic Athabascan Council; Garry Donaldson, Environment Canada; Peter Ewins, World Wildlife Fund – Arctic; Stephen Ferguson, Fisheries and Oceans Canada; Jérôme Fort, Danish National Environmental Research Institute; Tony Gaston, Environment Canada; Kristen Gorman, Association of Early Polar Career Scientists; Sarah Hardy; Trish Hayes, Environment Canada; Janet Hohn, US Fish and Wildlife Service; Andy Majewski, Fisheries and Oceans Canada; Igor Melnikov, P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences; Ilya Mordvintsev, A.N. Severtsov Institute of the Ecology and Evolution, Russian Academy of Sciences; Gabriel Nirlungayuk, Nunavut Tunggavik Inc.; Michel Poulin, Canadian Museum of Nature; Jim Reist, Fisheries and Oceans Canada; Dominique Robert, Québec-Océan; Duane Smith, Inuit Circumpolar Council; Evan Richardson, Environment Canada; Amy Thompson, Gwich'in Council International; Tomas Tomascik, Parks Canada; Jill Watkins, Fisheries and Oceans Canada

St. Petersburg workshop, March 5–6, 2012

Tom Barry, CAFF Secretariat; Stanislav Belikov, All-Russian Research Institute for Nature Protection; Malin Daase, Norwegian Polar Institute; Stanislav Denisenko, Zoological Institute, Russian Academy of Sciences; Garry Donaldson, Environment Canada; Maria Gavrilo, Arctic Antarctic Institute, St. Petersburg; Trish Hayes, Environment Canada; Janet Hohn, US Fish and Wildlife Service; Ksenia Kosobokova, P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences; Igor Melnikov, P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences; Andrey Popov, Arctic Antarctic Institute, St. Petersburg; Igor Smirnov, Zoological Institute, Russian Academy of Sciences; Vasiliy Lappo Smolyanitsky, Arctic Antarctic Institute, St. Petersburg; Evgeny Syroechkovsky, CAFF/Institute for Nature Conservation; Irina Trukhanova, Saint-Petersburg State University; Boris Vdovin, Russian Institute for Natural and Cultural Heritage; Elmira Zaingutdinova, Saint-Petersburg State University

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