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Arctic marine biodiversity

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Chapter 36G. Arctic Ocean

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1. Introduction

1.1 State

The Central Arctic Ocean and the marginal seas such as the Chukchi, East Siberian, Laptev, Kara, White, Greenland, Beaufort, and Bering Seas, Baffin Bay and the Canadian Archipelago (Figure 1) are among the least-known basins and bodies of water in the world ocean, because of their remoteness, hostile weather, and the multi-year (i.e., perennial) or seasonal ice cover. Even the well-studied Barents and Norwegian Seas are partly ice covered during winter and information during this period is sparse or lacking. The Arctic has warmed at twice the global rate, with sea-ice loss accelerating (Figure 2, ACIA, 2004; Stroeve et al., 2012, Chapter 46 in this report), especially along the coasts of Russia, Alaska, and the Canadian Archipelago (Post et al., 2013). Changes in ice cover, ocean warming, altered salt stratification, alterations in water circulation and fronts, and shifts in advection patterns show that oceans within the Arctic are subjected to significant change, and may face even more change in future (Wassmann, 2011 and references within). The Central Arctic Ocean and the marginal seas are home to a diverse array of algae and animals, some iconic (e.g., polar bear), some obscure, and many yet to be discovered. Physical characteristics of the Arctic, important for structuring biodiversity, include extreme seasonality resulting in short growing seasons and annual to multi-annual ice cover. The Central Arctic Ocean has a deep central basin (>4000 m depth) surrounded by the most extensive shelves of all the world's oceans, and is characterized by extensive (albeit declining) ice cover for much of the year. This offers a vast number of different habitats created by the shape of the seabed, latitude, history of glaciations, proximity to the coastline and rivers, oceanic currents, and both the seabed and the ice as a substrate. Barriers for dispersal, such as the ice plug in the Canadian High Arctic, effectively separate stocks of some marine mammals (Dyke et al., 1996). Polynyas, which are open water areas surrounded by ice, provide important foraging and refuge areas and contribute to Arctic biodiversity. Differences in ice cover, mixing between warm- and cold-water currents, or currents with different nutrient content, create a mosaic of nutrient-poor areas which is reflected in species diversity (ABA, 2014, Figure 3). Despite this heterogeneity, the Arctic is less diverse than lower-latitude areas for several taxa, including mammals and birds, but equal to, or higher than those areas for bottom animals (Renaud et al., 2009; Piepenburg et al., 2011), marine crustaceans and phytoplankton (algae

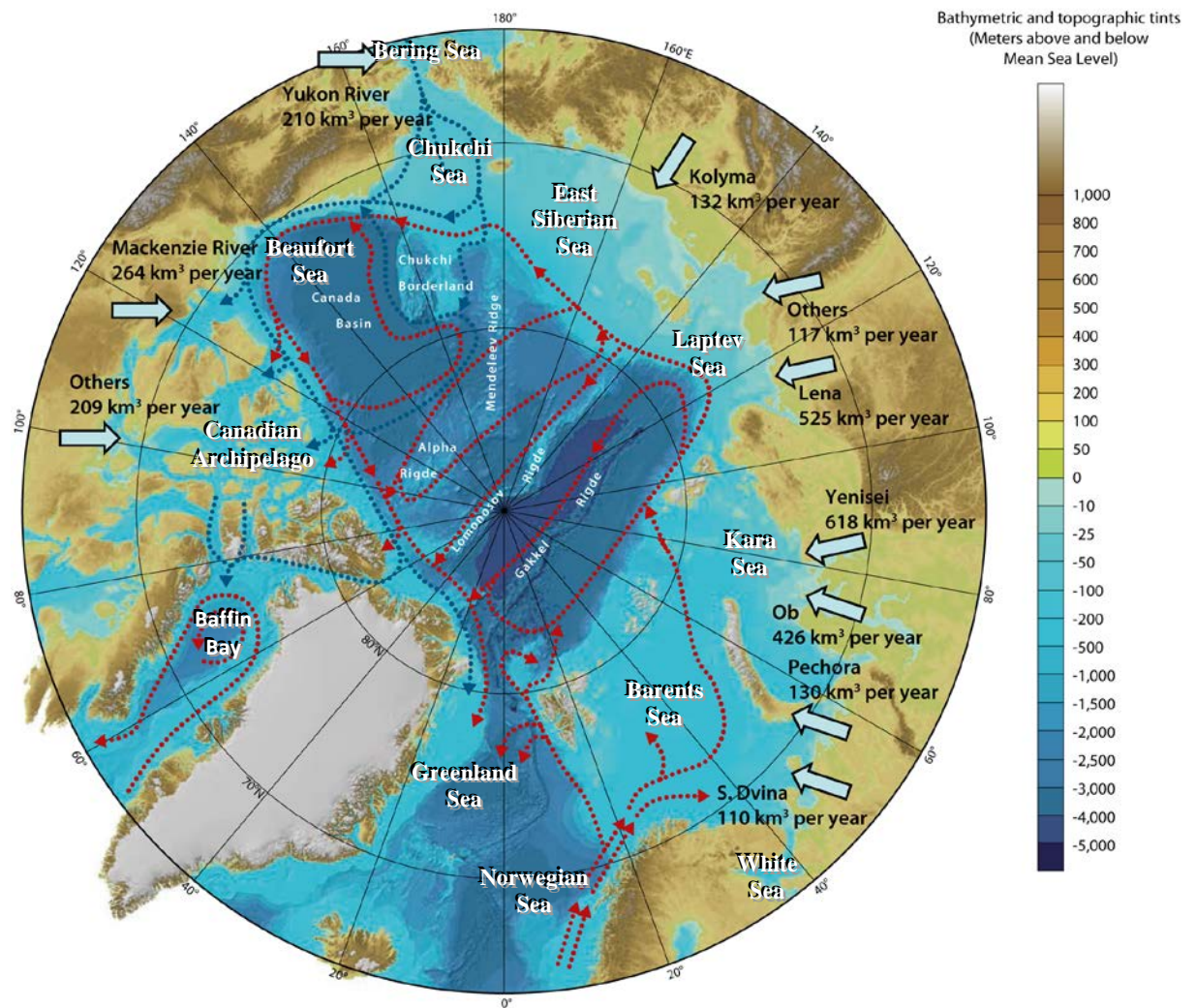
plankton) (Archambault et al., 2010). The marine areas in the Arctic support species of algae, plankton, nekton, fish, benthos, mammals, and birds (see sections below) but also thousands of species of fungi, endoparasites and microorganisms (Figure 3, see also ABA 2014 for more information). Due to mixing of sub-Arctic and Arctic fauna, the biodiversity is high in the vicinity of the Arctic Gateways of the North Atlantic and Pacific Oceans (ABA, 2014). The Red List of the International Union for Conservation of Nature (IUCN) includes 13 Arctic or seasonal mammalian inhabitants and 21 Arctic or Arctic-breeding seabirds as threatened species (IUCN, 2012), and eight targeted fish stocks and five Arctic fish species are evaluated according to the IUCN red list criteria (Christiansen et al., 2014, <http://www.iucnredlist.org/technical-documents/categories-and-criteria>). Humans in the Arctic lead lives based on traditional hunting, fishing and gathering of marine resources or commercial fishing and other economic and recreational activities. Along the coast and on islands, the marine environment plays a central role in food, housing, settlement patterns, and cultural practices and boundaries.

1.2 Trends and Pressures

Climatically, ecologically, culturally and economically, the Arctic is changing, with implications throughout the region (ABA, 2014). Primary producers, such as sea-ice algae and sub-ice phytoplankton, have lost over 2 million km² of Arctic ice since the end of the last century (Figure 2, Kinnard et al., 2011), representing a loss of habitat. The largest changes will take place in the northern sections of today's seasonal ice zones, which will expand and eventually cover the entire Arctic Ocean while the multi-year ice will be declining (Wassmann, 2011). The seasonal timing of the ice-algal bloom, driven by light penetration through thinning sea ice, is critical to reproduction of some zooplankton, and the subsequent algal bloom is critical for the survival of zooplankton offspring (Søreide et al., 2010). The annual zoo- and phytoplanktonic pulses of productivity fuel the Arctic marine food web (Darnis et al., 2012) affecting zooplankton production and the Arctic cod that feed on them (Ji et al., 2013), as well as their seabird and marine mammalian predators (Post et al., 2013). It also affects the underlying benthic communities such as bivalves, crabs, sea urchins, which are in turn key prey for seabottom feeding specialists, such as diving sea ducks, bearded seals, walrus, and gray whales (Grebmeier and Barry, 2007). Vertebrate species are also directly affected and walrus and polar bears are moving their habitats from the diminishing sea ice to land (Fischbach et al., 2009). Arctic warming and sea-ice loss will facilitate invasion by new species, hosts, harmful microorganisms, and diseases (Post et al., 2013).

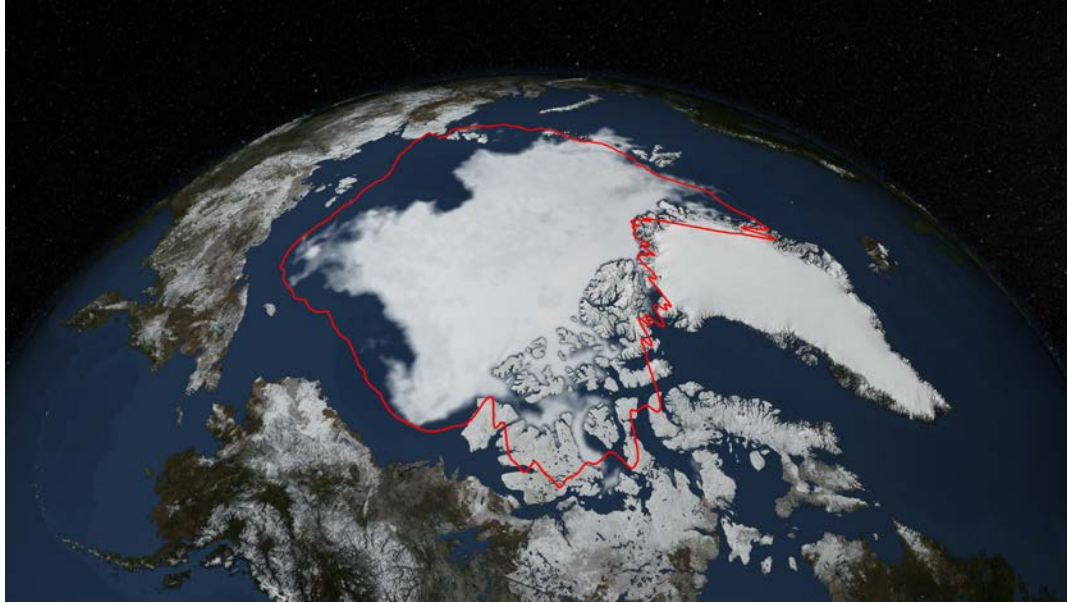
As sea ice retreats (see also chapter 46) and living commercial resources migrate northward, shipping (AMSA, 2009), fishing, petroleum activities, tourists, and consequently the risks of oil spills, noise, pollution and disturbances follow. These risks are often found where fish and marine mammals are abundant (AMSA IIc, 2013). Some of the largest populations of seabirds in the northern hemisphere are intersected by major shipping routes. Boreal fish stocks may move into unexploited parts of the Arctic, depending on the sensitivity and adaptive capacity of the affected species (Hollowed et al. 2013). New Arctic and sub-Arctic species have recently been reported from the Canadian Beaufort Sea and harvested Atlantic species have

moved poleward into Arctic Seas. These patterns likely represent both altered distributions resulting from climate change and previously occurring but unsampled species. (Mueter et al., 2013). As targeted boreal stocks move into as yet unexploited parts of the seas, Arctic fish species turn up as unprecedented by-catch and could be vulnerable to large-scale industrial fisheries (Christiansen et al., 2014, ABA 2014). Bottom-dwelling fisheries harvest near the seabed and they reshape bottom morphology and impoverish, perturb and change the functional composition of benthic communities (Puig et al., 2012). Cold-water coral, sponges and sea pens, which form a more complex habitat, are protected species (Fuller et al. 2008, FAO 2009) and areas potentially inhabited by these vulnerable taxonomic groups are mainly found north of 80°N in the Barents Sea, the Greenland Sea, and North of Greenland (Jørgensen et al, 2015; Jørgensen et al 2013; Boertmann and Mosbech 2011; Tendal et al 2013; Klitgaard and Tendal, 2004). Bans on industrial fisheries in the Chukchi and Beaufort Seas are currently in place in the USA (<http://alaskafisheries.noaa.gov>), along with restrictions on new commercial fishing operations in the Canadian Beaufort (<http://news.gc.ca/web/article-en.do?mthd=index&crtr.page=1&nid=894639>) and "protected areas" (those regions with reduced or strictly controlled fishing) are debated for the Arctic region (Barry and Price, 2012). Competition for use of marine space might increase in the Arctic, together with increased demand for products from the sea (food, minerals, recreation, etc). Climate-induced changes in the severity of storms and intensity of extreme events might pose challenges to the exploitation of resources in the Arctic. Arctic oil and gas fields provide a substantial part of the world's supply at present, and many fields have yet to be developed. There might be a threat of oil spills and introduction of invasive species (AMAP, 2009). Contaminants are present in organisms at the base of the food web, and they accumulate from one level of the food web (trophic level) to the next (AMAP, 2011). In addition to coastal wave erosion and changes in wildlife movement patterns and cycles, managers also face increases in ocean acidity due to increased CO₂ concentrations. The oceans within the Arctic are especially vulnerable to ocean acidification and Arctic marine ecosystems are highly likely to undergo significant change due to ocean acidification (AMAP 2013). The suite of stressors experienced by species living in the Arctic today is novel, making past periods of climate change an imperfect analogue for the challenges now facing biodiversity in the Arctic (ABA 2014). Global climate change threatens to alter the population dynamics of many species for which rates of demographic change and estimates of population size are imprecise or lacking. There is an urgent need to continuously monitor their distribution and occurrence as significant changes occur in the ecosystem. At present, scientists are unable to provide valid answers to questions about safe and sustainable operations. The availability of solid interdisciplinary baseline data is rare but crucial, and it is clear that ongoing and future changes can only be detected through long-term monitoring of key species, communities and processes, providing adequate seasonal coverage in key regions of the Arctic, utilizing new technologies, and making existing historical data accessible to the international research community. Up-to-date knowledge is needed and gaps in knowledge and key mechanisms driving change must be identified in order to secure Arctic biodiversity.



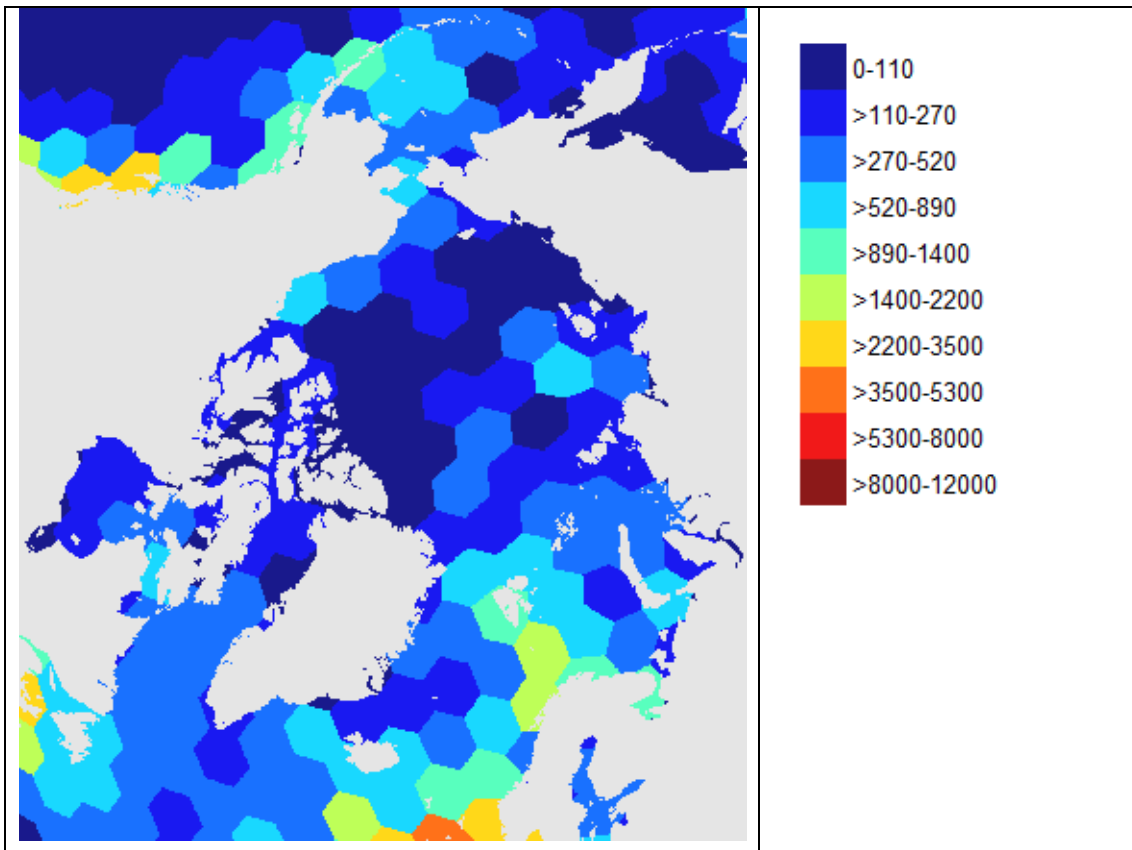
The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

Figure 1. The deep Central Arctic Ocean and the marginal seas such as the Chukchi, East Siberian, Laptev, Kara, White, Greenland, Beaufort, Barents, Norwegian and Bering Seas, Baffin Bay and the Canadian Archipelago. Blue arrows show freshwater inflow, red arrows water circulation. (adapted from CAFF 2013, Arctic Biodiversity Assessment, figure 14.1).



The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

Figure 2. Sea ice acts as an air conditioner for the planet, reflecting energy from the Sun. On September 17, the Arctic sea ice reached its minimum extent for 2014 — at 1.94 million square miles (5.02 million square kilometres) the sixth lowest extent of the satellite record. With warmer temperatures and thinner, less resilient ice, the Arctic sea ice is on a downward trend. The red line in the still image indicates the average ice extent over the 30 year period between 1981 and 2011. NASA/Goddard Scientific Visualization Studio, 2014. Printed with permission from NASA's Earth Science News Team patrick.lynch@nasa.gov.



The boundaries and names shown and the designations used on this map do not imply official endorsement or acceptance by the United Nations.

Figure 3. Pan-Arctic map showing the number of marine species from the OBIS database in a gridded view of hexagonal cells (OBIS, 2015).

2. Primary producers

General information on primary producers

Primary producers (algae) in Arctic marine waters are dominated by small, solitary photosynthetic cells containing different types of pigments, and reproducing by the formation of spores and gametes (Daniëls et al., 2013). They consist of numerous heterogeneous and evolutionarily different groups (Adl et al., 2012) and include both single-celled organisms (microalgae) and multicellular organisms (macroalgae). In addition, the prokaryotic Cyanobacteria also occur throughout the ocean. Microalgae occur as solitary cells or form colonies with different shape and structure. The size varies between 0.2 and 200 μm , a few up to 400 μm (pico: < 2 μm , nano: 2-20 μm , micro: 20-200 μm). Macroalgae are seaweeds that are visible to the naked eye, take a wide range of forms, and range from simple crusts, foliose and filamentous forms with simple branching structures, to more complex forms with highly specialized structures for light capture, reproduction, support, flotation, and

attachment (Diaz-Pulido and McCook, 2008).

2.1 Introduction

Arctic microalgae can be divided by function (e.g., ice algae and phytoplankton). Phytoplankton live suspended in the upper layer of the water column, but ice algae live attached to ice crystals, in the interstitial water between crystals, or associated with the under-surface of the ice (Horner et al., 1988).

2.2 Status

The study of phytoplankton, ice algae and macroalgae of Arctic seas dates back more than one hundred years (e.g., Ehrenberg, 1841; Cleve, 1873; Kjellmann, 1883; Rosenvinge, 1898). Early studies concentrated on diversity and on temporal changes in species composition or distribution relative to oceanographic structure, and were of local or regional character. Poulin et al. (2010) reported 2,016 taxa with 1,874 phytoplankton and 1,027 sympagic (ice algae) taxa in Arctic waters. Daniëls et al. (2013) concluded that few biodiversity assessments of benthic microalgae exist across the Arctic, but estimate ca. 215 seaweed species. Most of the algal species in the Arctic are cold water or temperate species, although some are distributed globally and a few are warm water species (Hasle and Syvertsen, 1996; von Quillfeldt, 1996). The species composition in different Arctic areas is often comparable, which is likely to be due to advection (horizontal transportation) of cells by the currents in the Arctic (Carmack and Swift, 1990; Abelman, 1992). Differences occur on a smaller scale, often as a result of local environmental conditions (Cota et al., 1991; von Quillfeldt, 2000). Prominent forcing factors on species diversity in the Arctic include the extreme seasonality of light, combined with sea-ice distribution (Bluhm et al., 2011), but the result (increase/decrease) depends on season and locality. However, a suite of environmental variables (e.g., nutrients, light, water stratification, salinity, temperature) determines abundance, biomass and taxonomic composition over time (Poulin et al., 2010). Many species have a wide environmental tolerance (Degerlund and Eilertsen, 2009).

The composition of the phytoplankton varies seasonally (von Quillfeldt, 2000; Lovejoy et al., 2002; Ratkova and Wassmann, 2002; Wassmann et al., 2006; Sukhanova et al., 2009). Most species can be characterized as winter, spring, summer or autumn species, but a few are seasonally independent. Several decades ago, few Arctic areas had been sampled during winter, but the importance of flagellates during winter had been suggested (Schandelmeier and Alexander, 1981; Horner and Schrader, 1982; Rey, 1986). Recently the importance of extremely small (< 20 µm) forms in Arctic waters throughout the year has been confirmed (e.g., Vørs, 1993; Lovejoy and Potvin, 2011; Niemi et al., 2011; Sørensen et al., 2012; Terrado et al., 2012; Kiliyas et al., 2013).

Ice communities are widespread throughout the Arctic (e.g., Apollonio, 1965; Meguro et al., 1967; Grainger, 1977; Hsiao, 1980; Horner et al., 1988, Horner et al., 1992, Syvertsen 1991), but the different types of communities are characterized by specific species (von Quillfeldt, 1997; Gradinger, 1999; Melnikov et al., 2002; Zheng et al., 2011). Solitary diatoms (a type of microalga) are common in interstitial

communities or sometimes in older ice, whereas the majority of colonial algae, except for *Melosira arctica*, are most common in sub-ice communities of one-year-old ice and in more offshore areas (Dunbar and Acreman, 1980; De Sève and Dunbar, 1990; von Quillfeldt, 1996; von Quillfeldt et al., 2003). Irradiance is the most important factor in determining abundance of ice algae. Snow depth and ice thickness control light in sea ice and thereby algal abundance, as does the ice structure (Gosselin et al., 1997; Robineau et al., 1997; Krembs et al., 2000). Ice algae are distributed throughout the ice during winter and become concentrated at the bottom in spring as a result of brine drainage and active migration of cells through brine channels (Hsiao, 1980; Horner, 1985). Furthermore, a south-north spatial gradient similar to the seasonally dependent gradient in the species composition is often observed. The oldest and most specialized ice community occurs in the far north (Syvertsen, 1991).

Lüning (1990) divided Arctic seaweeds into flora with a distinct vegetation structure; many species are distributed throughout the Arctic, and a few are found only within the Arctic Basin. Macroalgal (multi celled algae attached to the seabed) diversity decreases with increasing latitude and from the Atlantic to the Pacific sector (Pedersen, 2011). Temperature is a primary factor in macroalgal distribution (Lüning, 1990). Wulff et al. (2011) emphasized that macroalgae can be of either Atlantic or Pacific origin, but more macroalgae are of Pacific origin than previously thought. Substratum characteristics are important for the distribution of benthic algae (Zacher et al., 2011.) Along the Russian Arctic coast are areas where a soft substratum prevails and macroalgae are absent (Lüning, 1990). Areas exposed to mechanical effects of sea ice or icebergs will also be devoid of macroalgae (Gutt, 2001; Wulff et al., 2011). The Arctic is also strongly affected by marked changes in surface salinity due to melting of sea ice and freshwater input from rivers. Thus, macroalgae must be able to withstand large variations in salinity over the year. Fricke et al. (2008) described the succession of macroalgal communities in the Arctic and the effect of disturbances on communities of different ages and their changes with depth.

2.3 Trends

Daniëls et al. (2013) comment that it is difficult to estimate trends in Arctic phytoplankton, sea-ice algae and benthic algae due to the relatively poor knowledge of algal distributions prior to the period of rapid environmental changes. Baseline data are generally lacking, and it is challenging to distinguish between natural variations and changes in assemblages due to anthropogenic modification. The high variability in the number of single-celled algae across the Arctic can be related to sampling effort in time and space, rather than actual differences, and a strong bias towards large cells (Poulin et al., 2010) and sampling in coastal areas has been observed. Knowledge of the biodiversity improved recently as a result of improved sampling techniques, advanced microscopic and molecular methods, electronic databases and gene libraries, and increased international cooperation (Daniëls et al., 2013), as well as increased sampling in the central basins (e.g., Melnikov, 1997; Katsuki et al., 2009; Joo et al., 2012; Tonkes, 2012).

Some surveys indicate that climate-mediated changes appear to be occurring, but geographical differences are also found. For example, less sea ice and an increase in atmospheric low-pressure systems that generate stronger winds (and deeper mixing of the upper ocean), as well as a warming and freshening of the surface layer are likely to favour smaller species (Sakshaug, 2004; Li et al., 2009; Tremblay et al., 2012). However, Terrado et al. (2012) found that some small-celled phytoplankton species were specifically adapted to colder waters, and are likely to be vulnerable to ongoing effects of surface-layer warming. Altered discharge rates of rivers and accompanying changes of composition will also affect the composition of the phytoplankton (Kraberg et al., 2013). *Emiliana huxleyi*, a prymnesiophyte, has become increasingly important: blooms of this species have occurred in the Atlantic, presumably related to changing climate conditions (Sagen and Dalpadado, 2004; Hegseth and Sundfjord, 2008). The reappearance of the North Pacific planktonic diatom *Neodenticula seminae* may also be a consequence of regional climate warming (Poulin et al., 2010). Harrison et al. (2013) predict that northward movement of Atlantic waters will replace cold-water phytoplankton with temperate species and shift transition zones farther north. Increased amounts of annual sea ice relative to multi-year ice will influence ice-algal composition (Poulin et al., 2010). Warming could alter benthic algal distribution and favour invasion by temperate species (Campana et al., 2009). Models suggest that some macroalgal species will shift northwards and that the geographic changes will be most pronounced in the southern Arctic and the southern temperate provinces (Jueterbock et al., 2013). Reduced sea-ice cover and retreating glaciers will continue to alter light, salinity, sedimentation and disturbance processes (Campana et al., 2009).

3. Zooplankton

General information on zooplankton

Plankton are animals drifting in the sea. Many are microscopic, but some (such as jellyfish, medusa and comb jellies) are visible with the naked eye. Multicellular zooplankton, such as the copepods are called the ocean's "grass and grazers". In addition to copepods, amphipods, another group of small crustaceans are important. Larvaceans are solitary, free-swimming tunicates and live in the pelagic zone. They are transparent, planktonic animals with a tail. Chaetognaths (arrow worms) are transparent dart-shaped animals, while pteropod molluscs are pelagic snails.

3.1 Status

The zooplankton community structure in coastal and continental shelf waters of the Arctic is largely controlled by proximity to rivers and the areas of influx from the

Atlantic and Pacific. This community has been studied in a few restricted areas (e.g., Walkusz et al., 2010), but it has not been comprehensively reviewed. Many species known from the Atlantic and Pacific and reported from the neritic (shallow marine environment extending from mean low water down to 200m depths) Arctic are found only as advanced developmental stages, and therefore probably are non-reproductive expatriates. However, evidence is increasing that some North Atlantic species are reproducing in the polar Arctic.

Kosobokova et al. (2011) recently reviewed what is known about multicellular zooplankton in the central Arctic based largely on depth-stratified net collections from multiple projects during 1975-2007. They reported 174 oceanic species, of which 70 per cent were crustaceans. Although large copepods are very important in this assemblage, including *Calanus* species (Copepod) typical of the North Atlantic, as well as Arctic endemics (prevalent in or limited to a particular region), the abundance of this fauna is strongly dominated by small copepods. In addition to copepods, amphipods are important crustaceans, again including Arctic endemics, as well as Atlantic species; other important taxonomic groups include larvaceans (pelagic tunicates), chaetognaths (arrow worms), and pteropod molluscs (pelagic snails) (Gradinger et al., 2010). Relative to the westerlies and trade-wind regions, polar systems are relatively enriched with copepods and pteropods, and reduced in species with jelly-like bodies (Longhurst, 2007).

Despite “Thorson’s Rule” that the proportion of species with planktonic larvae decreases at high latitudes, many benthic invertebrates of the Arctic, North Atlantic, and North Pacific develop through planktonic stages. These species contribute seasonally to the diversity of the endemic assemblage, as well as to the many non-native species carried by currents into the Arctic from the Atlantic and Pacific Oceans, at times reaching abundances similar to those of the holoplankton (Hopcroft et al., 2010).

Vertical stratification of the zooplankton community in the central Arctic basins is strongly influenced by water-mass distribution and advective input of low-salinity surface water and layering of Pacific and Atlantic intrusions at mid-depths. Whereas the surface waters and waters below the surface layer are considered to be “well-characterized” (Gradinger et al., 2010), the large percentage of species in the very deep waters of the bathypelagic (i.e., open waters >1000 m depth) zone that are either new to science or previously unknown from the Arctic indicate that much remains to be learned about the truly deep pelagic fauna. The evidence to date indicates that little difference among the deep basins exists in the bathypelagic (depth generally between 1000-4000 m) zooplankton.

In-situ observations by remotely operated vehicles, as well as net collections, have shown that gelatinous megaplankton can be important in the central Arctic (Raskoff et al., 2010). This assemblage is dominated by “true” jellyfishes (medusae) and other, similar forms. Similarly to the net-collected mesozooplankton (planktonic animals in the size range 0.2-20 mm), the vertical structure of this assemblage is strongly associated with the vertical distribution of water masses. The overall abundance of gelatinous megaplankton, especially medusae, decreased dramatically over shallow slope, ridge and plateau areas relative to that found in the central basin, whereas the abundance of ctenophores (comb jellies), which are typically

present in the surface layer, remained high in these shallower areas (Raskoff et al., 2010).

In addition to water-mass dynamics, vertical distribution of zooplankton is strongly linked to the penetration of solar radiation and the availability of food. Although the seasonal irradiance signal is extreme in the Arctic, diel variability exists and may act as a physiological cue for diel vertical migration (Rabindranath et al., 2011). However, the major irradiance patterns in the Arctic are seasonal, with continuous darkness in winter and 24-h photoperiods in summer. In winter, many species reside deeper in the water column for a diapause, or resting, phase in their life cycle. Winter diapause is not universal; some species are reproductively active under the winter ice (Hirche and Kosobokova, 2011). Additional variability in summer results from breakup of sea ice. When present, ice cover strongly limits irradiance penetration and the seasonal melt further controls both the phytoplankton bloom and the release of ice algae, important factors for the timing of zooplankton life-cycle events and their vertical distribution. In deeper water the vertical linkage between phytoplankton and zooplankton becomes progressively weaker (Longhurst and Harrison, 1989).

Kosobokova et al. (2011) categorized 6 per cent of Arctic zooplankton species as ice-associated (“cryopelagic”). Grading et al. (2010) listed 39 invertebrate species as being ice-associated, although the division between cryopelagic and cryobenthic (or sympagic) is not clear. The association between the animals and the sea ice can be based on physical substrate or on the food web based on ice algae (Hop et al., 2011). Furthermore, the association may extend throughout the life cycle or just include a portion (e.g., dependence of a larval copepod stage on ice algae).

Where polynyas maintain open-water conditions in areas surrounded by solid ice cover, the zooplankton community is more similar to the open-water community rather than that found under ice. The pelagic food web of the polynya contributes to transfer of resources to the benthos (Deibel and Daly, 2007).

3.2 *Trends and pressures*

Limited long-term comparisons within the central Arctic indicate that species inventories, other than newly discovered species, seem to be unchanged. Whereas Pacific species on the shelves are probably non-reproducing populations transported from native waters of the North Pacific, at least some species typical of the Atlantic are found on Arctic shelves and seem to be reproducing successfully. Recent evidence (e.g., Kraft et al., 2013) indicates increasing reproductive success of Atlantic species. Therefore although the diversity inventory has not changed, physiological effects related to climate change appear to be shifting functions in the ecosystem. This “Atlantification” could have several possible results affecting the pelagic food web and transfer of energy to the benthos, in addition to the structure of the zooplankton community. Examples of such possible effects include differences in lipid-storage dynamics and timing of zooplankton reproduction relative to blooms of primary producers failing to provide adequate food to Arctic predators of zooplankton and changes in the production of “marine snow” (including faecal

pellets, moults, discarded mucus-feeding structures), which is important for transport of surface productivity necessary to feed the deep benthic communities.

3.3 *Climate Change and Oceanographic Drivers Affecting Zooplankton.*

Climate-induced changes in the timing and extent of sea-ice melt and breakup could have far-reaching effects on zooplankton structure and function within the pelagic food web, including coupling with the benthos and air-breathing vertebrates. The end of dormancy and initiation of feeding for lipid storage to fuel reproduction in the large Arctic copepods is linked to the ice-edge bloom. Because lipid dynamics differ in North Atlantic congeners, the “Atlantification” of the Arctic may be favoured by early and extensive breakup of the ice. The Atlantic species, which do not build up lipid reserves extensively prior to spawning, as do the Arctic endemics, may not provide adequate food for predators.

Increased ultra-violet (UV) radiation may have extensive effects on epipelagic species. This UV radiation can have substantial impacts on all plankton and can be lethal for zooplankton, especially eggs. Acidification can have a variety of effects, especially on species for which calcification is important, either for formation of exoskeletons (e.g., molluscs and crustaceans) or of sensory organs (e.g., otoliths of fish larvae and statoliths of cephalopods). Particular sensitivity can be expected in the abundant pteropod (swimming snail) species *Limacina helicina*, in which the aragonitic shell is even more vulnerable to dissolution than are calcite structures (see ocean acidification in chapter 5). Climate change impacts in the Arctic are expected to be significant and to be expressed earlier than in other oceanic realms due to the modification of the ice cover currently being observed (Stammerjohn et al., 2012).

4. Benthos

General information on the Benthos

The benthos, an important component of the ocean system, is the scientific term for the community of organisms that inhabit the seabed, ranging from the tidal coastal zone to the abyssal depths of the deep sea. The seabed environment includes a great variety of physically diverse habitats that differ from each other in terms of depth (intertidal to abyssal), temperature, light availability, and type of substratum (ranging from hard through soft, muddy bottoms). It encompasses organisms from a wide variety of taxa, sizes, life forms and ecological niches. Benthic animals, seaweeds (phytobenthos, incl. microalgae, macroalgae, seagrass), bacteria and protists (microbenthos), account for 98 per cent of the marine biodiversity in terms of species; the remaining 2 per cent are pelagic. Furthermore, some benthic fauna live in the sediment (endobenthos or infauna), attached to the seafloor (epibenthos or epifauna) or living above it (suprabenthos). Hyperbenthic (or suprabenthic) animals do not live directly on or in the seabed but very close above the seafloor in

the near-bottom part of the water column. The benthic fauna are typically classified into size categories. Microbenthic organisms are bacteria and protists smaller than 0.1 mm. Meiobenthos consists of tiny benthic organisms that are less than 0.5 mm but greater than 0.1 mm in size, mostly inhabiting the interstitial space between the sediment grains. By far the best-studied is the macrobenthos, encompassing forms larger than 0.5 mm that are visible to the naked eye, mostly polychaete worms, bivalves, crustaceans, anthozoans, echinoderms, sponges, and ascidians. Finally, the term megabenthos has been operationally defined as including large, often mobile benthic animals, mostly fish and crustaceans that are big enough to be visible in seabed images or to be caught by towed sampling gear.

4.1 *Status*

The current knowledge on the biodiversity of the benthic fauna in coastal, shelf and deep-sea regions has been summarized in three papers (Weslawski et al., 2011; Piepenburg et al., 2011; Bluhm et al., 2011a). These large-scale studies were conducted as contributions to the Arctic Ocean Diversity (ArcOD) project (<http://www.arcodiv.org>; Bluhm et al., 2011b), which in turn was part of the Census of Marine Life (<http://www.coml.org>; Snelgrove, 2010) and the International Polar Year 2007/2008. It aimed at coordinating research efforts examining the diversity in each of the three major realms (sea ice, water column, and sea floor) of Arctic marine ecosystems to consolidate what is known and fill gaps in our knowledge.

4.2 *Coasts*

Weslawski et al. (2011) reviewed the pattern of occurrence and recent changes in the distribution of macrobenthic organisms in fjords and coastal (nearshore) Arctic waters. In addition, likely future changes were hypothesized. The biodiversity patterns observed were demonstrated to differ among regions and habitat types. The North Atlantic Current along Scandinavia to Svalbard and the Bering Strait was shown to be a major area of biotic advection, where larvae and adult invertebrates are transported from the sub-Arctic areas to Arctic areas. There, increased temperature associated with increased advection in recent decades has favoured the immigration of more boreal-sub Arctic species, increasing the local biodiversity when local cold-water species may be suppressed. On the opposite side, in the Canadian Archipelago, the Nares Strait (between Greenland and Ellesmere Island), Lancaster Sound, Barrow Strait and M'Clure Strait are conduits for cold Arctic water flowing to the North Atlantic. Other large coastal areas, such as the Siberian shores, were shown to be little influenced by advected waters.

4.3 *Shelf seas (30 to 500 m)*

The knowledge of Arctic shelf seas has increased in the past decade, but benthic diversity was investigated at regional scales only. Piepenburg et al. (2011) presented a first pan-Arctic account of the species diversity of the macro- and megabenthic fauna inhabiting Arctic shelves. It was based on an analysis of 25 published and

unpublished species-level data sets, together encompassing 14 of the 19 marine Arctic shelf regions and comprising 2,636 species, including 847 Arthropoda, 668 Annelida (669 if we include the new species described by Olivier et al., 2013), 392 Mollusca, 228 Echinodermata, and 501 species of other phyla. Furthermore, gross estimates of the expected species numbers of the major four phyla were computed on a regional scale. Some areas, such as the Canadian Archipelagos, we have not compiled because of the lack of data. Extrapolating to the entire fauna and study area leads to a conservative estimate: 3,900-4,700 macro- and megabenthic species can be expected to occur on the Arctic shelves. These numbers are smaller than analogous estimates for the Antarctic shelf, but the difference is on the order of about two and thus is less pronounced than previously assumed. On a global scale, the Arctic shelves are apparently characterized by intermediate numbers of macro- and megabenthic species. This preliminary pan-Arctic inventory provided an urgently needed assessment of current diversity patterns that will be used by future investigations for evaluating the effects of climate change and anthropogenic activities in the Arctic.

4.4 *Central Arctic Ocean*

Bluhm et al. (2011a) compiled a benthic species inventory of 1,125 taxa from various sources for the central Arctic deeper than 500 m, and bounded towards the Atlantic by the Fram Strait. An additional 115 taxa were added from the Greenland–Iceland–Norwegian Seas (GIN). The inventory was dominated by taxa of Arthropoda (366), Foraminifera (197), Annelida (194), and Nematoda (140). A large overlap in taxa with Arctic shelf species supported previous findings that part of the deep-sea fauna originates from shelf species. Macrofaunal abundance, meiofaunal abundance and macrofaunal biomass decreased significantly with water depth. Species evenness increased with depth and latitude. No mid-depth peak in species richness was observed. Multivariate analysis of the Eurasian, Amerasian and GIN Seas polychaete occurrences revealed a strong Atlantic influence, the absence of modern Pacific fauna, and the lack of a barrier effect by mid-Arctic ridges. Regional differences are apparently moderate on the species level and minor on the family level, although the analysis was confounded by a lack of methodological standardization and inconsistent taxonomic resolution. Bluhm et al. (2011a) concluded that more consistent methods to observe temporal trends should be used in future efforts to help fill the largest sampling gaps (e.g., eastern Canada Basin, depths >3,000 m, megafauna). This is necessary to be able to adequately address how ocean warming, and the shrinking of the perennial ice cover, will alter deep-sea communities. The findings of Boetius et al. (2013) indicated that the benthic-pelagic coupling is more intense in the Arctic deep sea than expected and suggested strong alteration of this area in the future.

4.5 *Trends and pressures*

In a recent manuscript, Wassmann et al. (2011) reviewed the evidence reported in the scientific literature as of mid-2009 on whether – and how – climate change has already caused clearly discernible changes in marine Arctic ecosystems. In general,

they found that most reports concerned marine mammals, particularly polar bears, and fish, whereas the number of well-documented changes in planktonic and benthic systems was surprisingly low. Quantitative data on abundance and distribution are still generally lacking, and particularly few footprints of climate change have been reported from particularly remote and difficult-to-access regions, such as the wide Siberian shelf and the central Arctic Ocean, due to the limited research effort made in these environments. Wassmann et al. (2011) concluded that despite the alarming nature of climate change and its strong potential effects in the Arctic Ocean, the amount of reliable data on – as well as the research effort evaluating – the impacts of climate change in this region is rather limited. However, during a 30-year period (1980–2010), featuring a gradually increasing seawater temperature and decreasing sea-ice cover in Svalbard, Kortsch et al. (2012) documented rapid and extensive structural changes in the rocky-bottom communities of two Arctic fjords. They observed a reorganization of the benthic communities, led by an abrupt increase in macroalgal cover.

Because data on the effects of climate change on Arctic benthic fauna are limited, it is not yet possible to make sound predictions on trends and pressures on a quantitative level. However, some reports exist on general trends related to climate-change effects. Based on the available evidence of recent and on-going changes in Arctic systems, Wassmann et al. (2011) forecast that the ecological responses to climate change will encompass range shifts and changes in abundance, growth/condition, behaviour/phenology, as well as community/regime shifts, all of which will inevitably have a strong influence on regional and temporal patterns in diversity. In their attempt to predict possible changes in the diversity patterns of coastal benthic fauna in response to climate change, Weslawski et al. (2011) hypothesized that, in areas that are little influenced by advected waters, such as the Siberian shores and the coasts of the Canadian Archipelago, the local Arctic communities are exposed to increasing ocean temperature, decreasing salinity and a reduction in ice cover, with unpredictable effects on biodiversity. On the one hand, benthic species in Arctic fjords are exposed to increasing siltation from glacial meltwater and to decreasing salinities, which together may lead to habitat homogenization and a subsequent decrease in biodiversity. On the other hand, the innermost basins of Arctic fjords are able to maintain pockets of very cold, dense, saline water and thus may act as refugia for cold-water species.

Furthermore, all the current and anticipated climate-related changes in the Arctic are accompanied by an increase of anthropogenic activities, such as fisheries. These are known to impact marine ecosystems worldwide and have become an important environmental issue (Pauly et al. 1998; Link et al. 2010; Zhou et al. 2010). Particularly bottom trawling is assumed to be one of the most destructive fishing methods, causing severe damage to seafloor structure and benthic communities due to the passage of fishing gears and frequent by-catch (Jones 1992; Tillin et al. 2006; Thurstan et al. 2010). Using trawls is only feasible in largely ice-free areas, which are becoming more abundant. Trawling has recurrently been demonstrated to severely modify benthic communities (Watling and Norse 1998; Collie et al. 2000) and fish habitats (Auster 1998; Kaiser et al., 1999, Collie et al. 2000; Lindholm et al., 2001; Thrush et al., 2002; Moritz et al., 2015), primarily because of the reduction of

bottom complexity through the smoothening of sediments and removal of biogenic structures (Collie et al., 1997; Collie et al., 2000; Thrush et al., 1995; Thrush et al., 1998; Hall-Spencer and Moore, 2000). A number of field studies (Auster et al., 1995; Tupper and Boutillier, 1995a; Tupper and Boutillier, 1995b; Kaiser et al., 1999; Lindholm et al., 1999; Anderson and Gregory, 2000; Linehan, 2001; Stoner and Titgen, 2003) have related habitat complexity to survival of juvenile fishes. Cold-water corals, sponges and sea pens form biogenic structures that provide complex habitats for a diverse associated fauna. Although they are protected marine species (Fuller et al., 2008; FAO 2009), they are most vulnerable to the first passing of trawls. Areas protected from bottom trawling due to ice cover, thus remaining pristine and potentially inhabited by these vulnerable taxonomic groups, are mainly found north of 80° N in the Barents Sea, the Greenland Sea, and off northern Greenland (Jørgensen et al., accepted; Jørgensen et al., 2013; Boertmann and Mosbech, 2011; Tendal et al., 2013; Klitgaard and Tendal, 2004). Exploratory trawling fisheries will be carried out in a number of areas of the Canadian Arctic, such as Hudson Strait and northern Hudson Bay. Furthermore, there are shrimp pot fisheries, which are less damaging to benthic habitats, in Baffin Bay. There are currently no commercial fisheries in the Beaufort Sea. The United States has adopted a precautionary approach and placed a moratorium on fishing in the United States EEZ of the Arctic Ocean until further scientific information is available (Wilson and Ormseth, 2009). A similar strategy was recently adopted in the western Canadian Arctic with the signing of the Beaufort Sea Integrated Fisheries Management Framework (<http://news.gc.ca/web/article-en.do?nid=894639>), which outlines an agreement between the Government of Canada and Inuvialuit to co-manage marine mammal and fish resources in the Canadian Beaufort Sea.

5. Nekton (including demersal and holopelagic vertebrates and invertebrates)

General information on the Nekton

The nekton includes the bony fishes and the cartilaginous fishes (sharks and skate). Demersal fish species live and feed on or near the bottom, while pelagic fish live in open water. Brackish areas are usually inhabited by freshwater and anadromous fishes (whitefish, char, etc.). Cephalopod (a molluscan group consisting of, for example, octopus, squid, and cuttlefish) and shrimp species are also part of the nekton.

5.1 Status

Arctic fishes include two main groups – typically marine species which are confined to the marine environment, and anadromous species (fish migrating from salt water to spawn in fresh water such as salmonids and coregonids) which occur in freshwater and coastal areas, such as bays, inlets and estuaries, ascending rivers

from the sea for breeding. Depending on how widely the Arctic region is defined, total fish diversity ranges from 242 to 633 marine fish species (from 106 families) and 18-49 freshwater species that occur in marine/brackish waters (Chernova, 2011; Mecklenburg et al., 2011; Christiansen et al., 2013). Marine species comprise 88-90 per cent of total fish diversity. Species numbers in the Arctic are rather low, for both marine and freshwater species compared to the total number of fish species globally (approximately 16 and 12 thousand, respectively); 92 per cent of Arctic species are bony fishes; cartilaginous fishes (sharks and skate) comprise only 8 per cent. Most Arctic species are teleost (fishes with bony skeletons) fishes (92 per cent); cartilaginous (having a skeleton composed either entirely or mainly of cartilage) fishes (sharks and skates) comprise only 8 per cent (Lynghammar et al., 2013).

Fish diversity declines from the Arctic gateway regions near the Atlantic and Pacific Oceans, such as the Norwegian and Barents Seas (Atlantic) and Bering and Chukchi Seas (Pacific) to the farthest and most strictly Arctic seas. This diversity gradient is driven primarily by the presence of many boreal species in the Arctic gateway seas; such species cannot reproduce under the consistently colder conditions of the high Arctic. This spatial pattern holds in both the Eurasian and North American shelf seas (Karamushko, 2012; Christensen and Reist, 2013; Coad and Reist, 2004).

From a zoogeographic point of view, only 10.6 per cent of the bony fishes are considered as being strictly Arctic, and able to reproduce in waters below 0°C, whereas 72.2 per cent are boreal or Arctic-boreal species. Demersal fish species prevail in the group of strictly Arctic species (which includes 64 species or 14 per cent of the global marine fish fauna) (Chernova, 2011; Christensen and Reist, 2013).

Species composition and structure of fish communities vary in different depth zones and regions. Coastal brackish areas are usually inhabited by freshwater and anadromous fishes (whitefish, char, etc.). Fjords provide important habitats for fishes in some areas of the Arctic Seas, particularly along steep, bedrock-dominated coasts, such as are found in Greenland, Spitsbergen/Svalbard, Northern Norway, and the eastern parts of the Canadian Arctic Archipelago. Fjord fish faunas tend to be dominated numerically by the cryopelagic (of cold, deep oceanic waters) species (polar cod, Arctic cod), and by anadromous species. Fjord fish faunas include a wide cross-section of Arctic bottom-living (demersal) fishes (Christiansen et al., 2012), including diverse sculpins (Cottidae) and eelpouts (Zoarcidae) on sills and along fjord walls, as found in rocky areas of the continental shelves, and flatfish (Pleuronectidae) on sand and mud bottoms in fjord basins (Haedrich and Gagnon, 1991).

Fish communities of shelf seas are composed of common abundant pelagic (herring, capelin, polar cod, etc.) and demersal (gadoids, flatfish, sculpins, eelpouts, etc.) fishes.

Fish species composition in deeper waters in the Arctic Basin, as well as in many parts of the outer shelf regions, remains poorly investigated. Species richness is lower compared to coastal areas and especially shelf seas; the most abundant fishes are cryopelagic (e.g., polar cod, Arctic cod) (Andriashev et al., 1980; Melnikov and Chernova, 2013) or deepwater (e.g., snailfish) (Tsinovsky and Melnikov, 1980) fish. Cryopelagic species, which are ecologically dependent on sea ice, including the circumpolar polar cod *Boreogadus* and the ice cod *Arctogadus*, are important prey

species for many larger fish and marine mammals. Although the most abundant species are widely distributed in the Arctic and adjacent waters, the demersal fauna of the Arctic pseudo-abyss (the zone from 200 to 500–1,000 m in different parts of the ocean; characterized by a mixture of fauna) is represented mainly by endemic species (Chernova, 2011).

Commercial fisheries in the Arctic are located mainly in shelf seas where boreal species dominate. The most important areas are the Norwegian and Barents Sea in the Northeast Atlantic, Baffin Bay in the Northwest Atlantic, and in the Bering Sea in Pacific (Christiansen et al., 2014). In total 59 stocks are target species and 60 stocks are by-catch species taken by fisheries in Arctic and sub-Arctic areas. Most of the targeted species (50) are boreal species, six species are Arcto-boreal and three species are Arctic. The dominant families exploited in fisheries are herring (Clupeidae), capelin (Osmeridae), cod (Gadidae), flatfish (Pleuronectidae), and rockfish (called redfish in the Atlantic, Scorpaenidae). Wolf-fish (Anarhichadidae, an endemic Holarctic marine family) and grenadiers (Macrouridae) are important target species in the Eurasian Arctic, but in North America the effects of fisheries on these fish are dominantly through bycatch. High-latitude species in both families are considered to be endangered (Kearley, 2012). The landlocked Atlantic cod (*Gadus morhua*), found in meromictic (stratified lakes that consist of two layers that do not completely mix) Arctic lakes (Hardie and Hutchings, 2011), is considered to be of special concern.

The diversity of invertebrate nekton is much less than that of the fish, although some species are important prey for high-level predators (Gardiner and Dick, 2010). None are cryopelagic or estuarine, although some may be found in fjords. Nesis (2001) considered only seven cephalopod (a molluscan group consisting of, for example, octopus, squid, and cuttlefish) species to be resident in the Arctic. Although Arctic records of many other cephalopod species were added by Gardiner and Dick (2010) and Golikov et al. (2012), the only species that may be Arctic endemics are poorly known benthic octopods in the Bering and Chukchi Seas. Even fewer shrimp species are known from the Arctic and almost all have been reported from the North Atlantic, North Pacific, or both. One species, *Hymenodora glacialis*, is a major component of the pelagic biomass in the deep basins (Auel and Hagen, 2002).

5.2 Trends and pressures

Fisheries affect mainly the traditional marine target fish in the shelf seas located in the narrow Arctic to boreal regions of the Atlantic and Pacific Oceans (e.g., the Barents Sea and Bering Sea), and their effects are generally lower in other seas (e.g., the Laptev Sea and East Siberian Sea). But with further warming, fisheries areas are expected to shift into previously unfished Arctic regions where they will affect strictly Arctic fish communities (Christiansen et al., 2014). In coastal areas a few species, predominantly freshwater and anadromous, are harvested by indigenous peoples, but these catches are generally much lower than those of commercial fisheries. Furthermore, fisheries for anadromous species rarely involve mobile gear, which poses the greatest risk of causing extensive habitat damage in previously

unfished areas if used in ways that contact habitat features (e.g., Anderson and Clarke, 2003; Rice et al., 2006).

Under continuous ocean warming conditions, shifts of native species and new appearances of warm-water species may result in changes to fish community structure and subsequently to trophic pathways, depending on the sensitivity and adaptive capacity of the affected species (Hollowed et al. 2013). Higher water temperatures may cause an increase in the abundance and proportion of boreal species in the Arctic community. The deep Central Basin will probably be affected less than the shallower shelf seas of the Arctic, as most abundant boreal species are demersal or neritic (the relatively shallow part of the ocean above the drop-off of the continental shelf, approximately 200 m in depth) and such species are not likely to be found in areas deeper than 800-1000 m (Dolgov and Karsakov, 2011).

Occasional appearances of new species have been observed in the Arctic for decades, but these are apparently becoming more frequent. In 1950s, pink salmon was introduced from the Pacific to the Barents and White Seas (Atlas of Russian freshwater fishes, 2002). Norwegian pollock *Theragra finnmarchica* has been known in the Barents Sea since the 1950s (Christiansen et al., 2005; Privalikhin and Norvillo, 2010), but it is now considered to be a junior synonym of the Pacific walleye pollock *Gadus chalcogrammus* (Ursvik et al., 2007; Byrkjedal et al., 2008), reflecting the possibility of recent connections between Pacific and Atlantic waters across the Arctic. Range expansion of boreal species into the Arctic as ocean temperatures rise, has been observed both in the Eurasian Arctic (Christiansen et al. 2013) and in the North American Arctic, specifically in the Canadian Beaufort Sea (Mueter et al. 2013). If commercial fishing activities expand northward following these species, more bycatch may occur of endemic Arctic fish species that were previously unexploited and relatively unperturbed. In southern Newfoundland and Norwegian fjords, mesopelagic fish, especially the Myctophid (Lanternfish) *Benthoosema glaciale* and the sternoptychid (small deep-sea ray-finned fish of the stomiiform family Sternoptychidae) *Maurolicus muelleri*, are important elements. These cold-water fish, in places very abundant on the high seas, are very likely to move from the sub-Arctic to the full Arctic as ice retreats.

Although some high-latitude areas have high planktonic productivity and high fish production, e.g., the Barents Sea and Bering Sea, many strictly Arctic Seas have limited primary productivity due to ice cover, lack of nutrient replenishment, etc. Most Arctic fish, similar to deep-sea fish, have adapted to these low-productivity conditions with life-history characteristics that cause them to be readily overfished, either as directly targeted species or as by-catch (Koslow et al., 2000; Roberts, 2002; Baker et al., 2009). The risk of rapid overexploitation is high for Arctic fish populations, as it already seems to be for Greenland halibut (*Reinhardtius hippoglossoides*) in the Western Atlantic. By contrast, the Barents Sea stock has grown over the last decade, when the fishery was closed completely at first but later reopened at a low intensity.

As with many other groups, evidence exists that invertebrate nekton species are spreading into the Arctic from lower latitudes, especially the North Atlantic. Indeed, Hamilton et al. (2003) reported that fisheries in western Greenland have shifted to the northern shrimp, *Pandalis borealis*, a North Atlantic species also fished in the

Barents Sea (Standal, 2003). Furthermore, the presence of foraging schools of ommastrephid squid (Golikov et al., 2012) could indicate an important shift in the pelagic food web of the Arctic.

6. Mammals

General information on the marine mammals

Seals, together with toothed (killer whales, sperm whales, dolphins) and baleen (bowheads, blue whale) whales are part of the marine mammals.

6.1 Status

Thirty-five species of marine mammals are known to be present in Arctic waters. Seven of these (narwhal, beluga, bowhead whale, ringed seal, bearded seal, walrus, and polar bear) inhabit the Arctic year-round and are dependent upon sea ice for at least part of the year. Four additional species (spotted seal, ribbon seal, harp seal, and hooded seal) use sea ice for pupping in the winter and spring, but range widely in open waters of the Arctic and sub-Arctic the rest of the year. These eleven species of marine mammals are ice-dependent for at least some of their annual cycle; their reproduction, moulting, resting and/or feeding behaviour are closely linked to the presence of sea ice.

Another 24 marine mammal species occur in low Arctic waters or seasonally migrate to the Arctic to feed, including four species of pinnipeds, nineteen species of cetaceans, and a carnivore, the sea otter. The northern fur seal and Steller sea lion are found in the Okhotsk and Bering Seas; the gray seal is found in the Atlantic Arctic, and the harbour seal in Arctic waters of both the Atlantic and Pacific. Nineteen species of cetaceans use Arctic waters seasonally, including: the North Pacific right whale and gray whale that are confined to the Pacific Arctic; the North Atlantic right whale in Arctic waters near Greenland; the blue whale, fin whale, sei whale, minke whale, and humpback whale in both Pacific and Atlantic Arctic waters during summer; the sperm whale in low Arctic waters; Baird's beaked whale, Stejneger's beaked whale and Cuvier's beaked whale in the low Arctic waters of the Pacific; and the northern bottlenose whale in the low Arctic waters of the Atlantic. Delphinids that are present in the Arctic during summer include: killer whale, white-beaked dolphin, long-finned pilot whale and Atlantic white-sided dolphin. Dall's porpoise occur in low Arctic waters of the Pacific, and harbour porpoise in low Arctic waters of both the Atlantic and Pacific. These species occur in Arctic waters primarily to feed, based on the high seasonal productivity.

6.2 Trends

There is a history spanning several centuries of commercial whaling and seal hunting in the Arctic. In some cases, over-harvesting has reduced Arctic marine mammal populations to low numbers and contracted their ranges. Two of the three hooded seal populations were subjected to intense commercial hunting over the past two centuries. In the East Greenland Sea a substantial decrease in hooded seal abundance took place between the 1940s and 1980s (ICES, 2008), and recent surveys suggest that a downward trend continues. Regulation of commercial harvests has led to stabilization or recovery of some other marine mammal populations. All bowhead whale populations were severely depleted by commercial whaling, which began in the Atlantic in the 17th century (Ross, 1993). The global bowhead population now appears to be increasing, and the Bering-Chukchi-Beaufort subpopulation has recovered to close to its pre-whaling level. Indigenous harvesting of Arctic marine mammals also has a long history, and indigenous peoples have strong cultural and economic ties to marine mammals. In most cases the subsistence harvest is not a factor affecting marine mammal populations; however, a sharp decline of the Cook Inlet beluga population occurred in the 1990s and is attributed to subsistence overharvesting (Mahoney and Shelden, 2000); and they remain critically endangered.

Assessing Arctic marine mammal populations is challenging because of the difficulty of working in this region and the large seasonal ranges of many of these animals. Documenting changes in the abundance and distribution of marine mammals requires study on long time-scales. For the eleven ice-dependent marine mammal species, population trends are discussed here to illustrate the state of our knowledge. Trends in abundance are unavailable for most beluga sub-populations, but three subpopulations are known to be declining: the Cook Inlet (Hobbs et al., 2012), the eastern Hudson Bay (Gosselin et al., 2009), and the White Sea (Burdin et al., 2009). Although population estimates are available for most narwhal stocks (Heide-Jørgensen et al., 2010; Richard et al., 2010), they are not adequate to establish population trends. The Bering-Chukchi-Beaufort population of bowhead whales has increased since the late 1970s (George et al., 2004), and bowhead whales in West Greenland have increased since 2000 (Wiig et al., 2011), whereas trends in the bowhead subpopulations in the Svalbard-Barents Sea and the Sea of Okhotsk are unknown. Population trends for ringed seals are unknown, yet ringed seal density estimates in western Hudson Bay show an approximate 10-year cycle of fluctuation (Ferguson and Young, 2011). Walrus populations in West Greenland and the North Water have been in steady decline, whereas the population in East Greenland has been increasing (Witting and Born, 2005). Walrus numbers at Svalbard have increased slowly during 1993-2006 (Lydersen et al., 2008). Pacific Walrus populations recovered from a depleted state to historical high levels in the 1980s (Fay et al., 1997). Data are insufficient to estimate trends for spotted seals, ribbon seals and bearded seals. Harp seal birth rates in the White Sea stock have experienced significant declines since 2004 (Chernook and Boltnev, 2008). Recent models (ICES, 2008) revealed that since about 1970, the population of harp seals in East Greenland increased in size from its earlier depleted state. There was a moderate increase in the NW Atlantic hooded seal population between the mid-

1980s and 2005 (Hammill and Stenson, 2007), but the NE Atlantic hooded seal population has declined by 85-90 per cent over the last 40-60 years (Øigård et al., 2010). For nineteen polar bear subpopulations, seven are declining, four are stable, one is increasing, and insufficient data are available to determine a trend for seven subpopulations (Obbard et al., 2010). The sea otter is believed to have undergone a population decline exceeding 50 per cent over the past 30 years (Estes et al., 2005).

6.3 Pressures

Reductions in sea ice represent an on-going threat to marine mammals in the Arctic. Recent sea ice declines are well documented (Stroeve et al., 2012), and modelling predicts that the Arctic may be ice-free in summer within three decades (Wang and Overland, 2012). These reductions in sea ice are forcing ice-dependent marine mammals, such as polar bears, seals and walrus, to modify their feeding, reproduction and resting behaviour and locations. Pacific walrus have begun hauling out on land in the summer due to loss of annual Arctic sea ice and the summer retreat of the pack ice beyond the continental shelf (Garlich-Miller et al., 2011). Early sea-ice melt and longer open-water periods cause increased primary production in the Arctic (Arrigo and van Dijken, 2011), but are likely to decrease nutrient fluxes to the seafloor. As a result, walrus, bearded seals, and other marine mammals specializing in benthic feeding may experience reductions in prey availability (Bluhm and Gradinger, 2008).

The Arctic is also experiencing more human maritime activity, primarily related to hydrocarbon and mineral development and the opening of shipping routes. These changes bring risks for marine mammals of direct mortality, displacement from critical habitats, noise disturbance, and increased exposure to hunting. Arctic marine mammals also have high levels of contaminants (Norstrom and Muir, 1994), notably organo-chlorines (an organic compound containing at least one covalently bounded atom of chlorine) and heavy metals, as a result of the presence of these substances in the Arctic food web. Little evidence exists of demographic effects in wild marine mammals, but the need is growing to understand the origins of pollutants, and to coordinate efforts to reduce them at their source.

7. Marine birds

General information on the marine birds

Marine birds are adapted for the marine environment. Most species nest in colonies. Many undertake long annual migrations. Ducks, goose, auks (such as guillemots), loon, gulls, scoters, jaegers/skuas, terns, are all part of the marine birds.

7.1 Status

Arctic waters are host in summer to many millions of marine birds which come to nest. Unlike many animal groups, marine birds are more diverse and abundant in cold seas than they are in warm ones (Gaston, 2004). In the Northern Hemisphere, the highest breeding densities of seabirds occur in Arctic waters (Cairns et al., 2008). Forty-four species of seabirds, ten sea ducks (eiders and scoters) and one marine goose (brant) are listed by Ganter and Gaston (2013) as breeding in the Arctic, of which 23 species of seabirds, seven sea ducks and the brant occur in the high Arctic, with most being endemic to the region. The majority of Arctic marine birds are members of the order Charadriiformes (34 species), including four endemic genera, all containing only one immediately subordinate taxon (little auk, ivory gull, Sabine's gull, Ross's gull). Nineteen species are circumpolar, breeding in Canada, Alaska and over most of the Russian Arctic, whereas 11 occur only in the Atlantic basin (East Canada-Svalbard) and 14 in the Pacific basin (East Siberia-Yukon). Four species of sea ducks, one loon, one gull and one auk are considered to be vulnerable, near-threatened or endangered by Birdlife/IUCN (IUCN, 2012).

Most Arctic marine birds are migrants, occurring in Arctic waters only in summer, and moving to boreal or warmer waters, or in some cases to the Southern Hemisphere, in winter (Newton, 2007). Only two species of gull (Ross's and ivory), two auks (black guillemot and thick-billed murre/Brunnich's guillemot) and the four species of eider occur in Arctic waters throughout the year. The extent of migratory behaviour means that the population sizes and trends of many Arctic marine birds are potentially affected by events on their wintering ranges outside the Arctic (Ganter and Gaston, 2013).

Scoters, jaegers/skuas, some terns and some gulls occur mainly in terrestrial or freshwater habitats while breeding, but make use of marine waters while in passage, and, in the case of scoters, while moulting. Other marine birds, although feeding at sea, must all visit land to breed, so that all have a presence in the coastal zone in summer. The vast majority feed in shelf waters, although some may also feed away from the continental shelf. The most numerous birds making use of Arctic marine waters in summer are the northern fulmar, black-legged kittiwake, thick-billed murre, and little auk, all of which have world populations centred in the Arctic and numbering more than 10 million individuals (Ganter and Gaston, 2013). All these species make use of pelagic habitats. The number of seabirds making use of the central Arctic Ocean is small, although this is a major post-breeding dispersal area for Ross's Gull (Hjort et al., 1997).

Some Arctic marine bird populations provide valuable subsistence resources in the Arctic. Eiders, or their eggs and down, are harvested throughout the region and they are important for traditional food and lifestyle, not only in many Arctic communities, but also in SE Canada and the Baltic region (Merkel and Barry, 2008). In some countries, especially Iceland, down-feather collection constitutes a significant commercial industry (Bédard et al., 2008). Auks are also harvested by native peoples in Alaska and Canada.

7.2 Trends

Most Arctic seabird populations for which reliable information is available have shown negative trends in recent years. These current trends are superimposed on a situation where several important populations were substantially depressed by anthropogenic mortality, compared with numbers in the first half of the 20th century (Ganter and Gaston, 2013).

Some evidence exists for the recent northward spread of predominantly temperate or low Arctic species: e.g., glaucous-winged gull (Winker et al., 2002) in the Bering Sea, horned puffin in the Beaufort Sea (Moline et al., 2008), great skua in Svalbard (Anker-Nilssen et al., 2000; Krasnov and Lorentsen, 2000) and lesser black-backed gull in Greenland (Boertmann, 2008). At the same time, evidence exists of a retreat for at least one high Arctic species: the range of the ivory gull has contracted in Canada; most colonies in the southern part of the Canadian range are deserted, whereas numbers have remained stable farther north (Environment Canada, 2010). Southern colonies of ivory gull are also decreasing in Greenland (Gilg et al., 2009b).

Black-legged kittiwake, an abundant species throughout circumpolar Arctic waters, has shown significant population declines throughout almost the entire Atlantic sector of the Arctic, especially around the Barents Sea (Barrett et al., 2006), in Iceland (Garðarsson, 2006) and in West Greenland (Labansen et al., 2010). Thick-billed murre populations have shown downward trends over much of their range in the past thirty years. The population of thick-billed murres in central West Greenland is much lower than it was in the early 20th century, as a result of heavy harvesting of adults at colonies (Evans and Kampp, 1991; Kampp et al., 1994) and shows no sign of recovery (K. Kampp and F. Merkel, pers. comm.). Similarly, numbers in Novaya Zemlya are considerably lower than in the early 20th century: down from two million to one million birds (Bakken and Pokrovskaya, 2000). In Svalbard, numbers of thick-billed murres were thought to be stable up to the 1990s, but they have since decreased, especially in the southern part of the archipelago (CAFF Circumpolar Seabird Working Group, unpubl.). In Iceland, numbers of thick-billed murres decreased at 7 per cent per year between 1983 and 1985 and 2005-2008, whereas numbers of common murres and Atlantic puffins decreased between 1999-2005 after modest increases earlier (Garðarsson, 2006; Garðarsson, 2009).

7.3 Pressures

Eider populations declined in the 1980s and 1990s in Alaska, Canada, Greenland and Russia; in some cases because of human disturbances, excessive harvest of eggs and birds, together with severe climatic events (Robertson and Gilchrist, 1998; Suydam et al., 2000; Merkel 2004a). The current trend of common eider populations varies, but at least some populations in Alaska, Canada and Greenland are now recovering with improved harvest management (Chaulk et al., 2005; Gilliland et al., 2009; Merkel, 2010). Breeding populations in the Barents Sea region appear stable (Bustnes and Tertitski, 2000). A recent outbreak (2005-present) of avian cholera in the East Canadian Arctic reversed a population increase and reduced the population of a large colony by 30 per cent in just three years (Buttler, 2009). Bycatch in

fisheries gillnets is also a significant problem in some areas (Bustnes and Tertitski, 2000; Merkel, 2004b; Merkel, 2011) and may be a more widespread concern.

Some recent changes in the status of Arctic seabirds have been linked with climate changes, mostly ascribed to causes operating through the food chain (Durant et al., 2004; Durant et al., 2006; Sandvik et al., 2005; Irons et al., 2008), but direct effects have been documented in a few cases: White et al. (2011) showed that expansion of the great cormorant population in central West Greenland may be related to increased sea-surface temperature. Several potential causes of the decline of ivory gulls in Canada have been identified: mortality from hunting of adults in Greenland (Stenhouse et al., 2004), high levels of mercury in eggs (Braune et al., 2006) and changes in ice conditions (Gilchrist et al., 2008; Environment Canada, 2010). In Hudson Bay in recent years a combination of warm summer weather and earlier emergence by mosquitoes caused the death or reproductive failure among thick-billed murres (Gaston et al., 2002). In addition, polar bears, coming ashore earlier than usual, ate many eggs, chicks and adults of murres and common eiders, leading to complete reproductive failure at some colonies (Gaston and Elliott, 2013; Iverson et al., 2014). Such mortality has increased sharply over the past three decades.

Substantial research has been carried out on concentrations and trends of contaminants in Arctic marine birds, especially organohaline compounds and heavy metals (Braune et al., 2001; Helgason et al., 2008; Letcher et al., 2010). Very high levels of mercury have been found in the eggs of ivory gulls from Canada (Braune et al., 2006) and high levels of organohaline compounds in those from Svalbard (Miljeteig et al., 2009). High organohaline concentrations occur also in glaucous gulls from Svalbard (Bustnes et al., 2003; Bustnes et al., 2004), perhaps causing mortality in some cases (Gabrielsen et al., 1995; Sagerup et al., 2009). These species scavenge marine mammal carcasses, which places them high up the food chain and hence they become subjected to an increasing concentration of a substance, such as a toxic chemical, in the tissues of organisms at successively higher levels in a food chain (biomagnifications). As a result of biomagnification, organisms at the top of the food chain generally suffer greater harm from a persistent toxin or pollutant than those at lower levels. The extension of offshore oil and gas exploitation and transport in and through Arctic waters poses a potential threat to all marine birds (Meltofte et al., 2013), especially auks and sea ducks, which are among the birds most vulnerable to mortality from oil spills (Clark, 1984). These two groups, along with cormorants, are also very susceptible to drowning in gill nets (Tasker et al., 2000). If, as expected, a general retreat of Arctic sea ice allows an extension of hydrocarbon exploitation, shipping and fisheries in Arctic waters, then special care will be required to safeguard populations of these birds. Moreover, changes in the timing of the open-water season are affecting the timing of seasonal events in marine ecosystems, and this is affecting the optimal timing of breeding for marine birds, especially in low Arctic areas (Gaston et al., 2009). Changes in the distributions of predators and parasites have also been noted, and these may have important consequences for Arctic seabirds (Gaston and Elliott, 2013). Because of the number of Arctic endemic marine bird taxa, the decline of Arctic marine birds presages a significant loss of global biodiversity.

8. Socioeconomic Aspects

8.1 *Biodiversity and ecosystem services in the Arctic*

Biodiversity, whether it is functional, genetic or species-based, plays a role in fundamental processes of nature, i.e., so-called ecosystem processes or intermediate ecosystem services¹, which feed into all final ecosystem services, whether these are provisioning, regulating or cultural services. These latter services contribute directly to human wellbeing, and these benefits can often be valued in economic terms.

Although the ecosystem processes/intermediate services of biodiversity may be essential for most final services, their values as such cannot be added to the value of benefits from final services, as this would imply a double counting. However, it is important to ascertain the significance of biodiversity as an intermediate service in order to ensure that human actions do not limit these services to such a degree that a loss in final services occurs, and that the value of this loss exceeds the value from the human actions that led to them. And despite the remote nature of the Arctic, ecosystem processes related to biodiversity taking place there may provide important services far removed in space and time.

Biodiversity may also be a final service and, for example, it may be included in cultural services, in the sense that humans value biodiversity directly. The Arctic is a sparsely populated part of the world, but indigenous and commercial uses related to Arctic biodiversity are nevertheless present. Furthermore, humans who may never set foot in the Arctic may value the existence of Arctic biodiversity, hence the services in the Arctic may have greater importance than what immediately meets the eye.

In the following we focus on ecosystem services from Arctic biodiversity being affected by climate change pressures, where these involve services to the ecosystem (i.e., ecosystem processes or intermediate services) and services to humans (provisioning, regulating or cultural services).

8.2 *Services to ecosystems being affected*

Climate change will make species of boreal ecosystems move into what are now sub-Arctic areas, transforming these into boreal ecosystems, whereas sub-Arctic ecosystems will move into more Arctic areas. Consequently, Arctic ecosystems will remain in smaller and possibly more fragmented areas such as cold, dense, saline water basins (inner fjords and the abyss) and may thus act as important refugia for cold-water species.

¹ The Millennium Ecosystem Assessment (2005) coined the expression *Supporting services*, which was later referred to as *Ecosystem processes or Intermediate services* by the UK National Ecosystem Assessment (2011) and others.

In a spatial context, Arctic biodiversity will therefore decline. In some areas, Arctic biodiversity will disappear, but species of boreal ecosystems will increasingly move northwards, increasing boreal biodiversity in these areas. However, the absolute biodiversity may increase, decrease or remain unchanged, due to the combination of extinction and immigration. Increased biodiversity may especially be the case in the shallow marginal seas of the Arctic, but also in a presumed interim period, where both Arctic and boreal species co-exist. This may temporarily affect ecosystem processes/intermediate services. The biodiversity dynamics depend on a number of factors, such as immigration, extinctions, possible hybridization, competitive pressures and new pathogens/parasites, as well as human pressures (harvesting, bycatch of Arctic species in targeted harvests of boreal species, bioaccumulation of pollution, stress from ship traffic and oil exploitation, harvesting of eggs and birds, ocean acidification).

As the ice cover declines, the Arctic biodiversity comes under pressure, and some ecosystem services may be lost due to smaller and possibly fragmented suitable areas. This is particularly the case for species that have parts of their life cycle/history strategy dependent on ice (e.g., seals nursing on ice). A loss of ecosystem processes/intermediate services involving failures in reproduction, predator-prey interactions and habitat composition is then likely.

8.3 Services to humans being affected

On current sub-Arctic shelf areas, where boreal species will become more prominent, ecosystem services, such as those related to fisheries, may increase. This may be advantageous for human coastal communities, indigenous and otherwise, by increasing or securing values connected to benefits of cultural and provisioning services from fisheries. Off-shelf areas may not give increased ecosystem services, despite ice-cover decline, due to stratification inhibiting the mixing of the water masses and thereby limiting the nutrients needed for productive ecosystems (Wassmann, 2011). However, great uncertainty remains regarding these future processes.

Ice decline will have consequences for Arctic biodiversity. This is particularly the case for species that spend part of their life cycle on land and part on ice (e.g., polar bears, seals and walrus). These species supply provisioning and cultural services for commercial and indigenous users in the Arctic, and cultural services for people worldwide due to existence values.

IPCC (2014) identifies a number of climatic change effects that are expected to affect directly the way of life of Arctic indigenous peoples. The indirect effects via marine biodiversity change are more uncertain. Yet as mentioned above, both positive effects regarding fisheries and negative effects in relation to marine mammals may be possible. Where, how, what, and when changes may arise are unsure, and point towards significant knowledge gaps with regard to socio-economic consequences of climate change for indigenous peoples.

8.4 Management

The loss or reduction of services from Arctic ecosystems points to the need to protect the remaining Arctic and Arctic ice areas against activities that might reduce biodiversity (pollution, diseases/parasites, physical and vocal stress); e.g., securing protection in relation to activities of exploitation (fish, oil, minerals, tourism) in ice areas, and transport routes through the Arctic and Arctic ice.

The final service losses likewise point to the need for adaptive and ecosystem based management efforts to limit negative effects of existing and potential human use. This involves sustainable management of current use of resources, and restrictions on aggregating anthropogenic effects in relation to vulnerable Arctic ecosystems and species. It is clear that we will discover and develop ecosystem services in the future that we are not aware of today. Option values related to these services, for example from bioprospecting, underline the need to secure ecosystem services for the future.

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