



Last Ice Area Biophysical Reader



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1. Introduction

This is one of a series of research resources commissioned by WWF to help inform future management of the Area we call the Last Ice Area. We call it that because the title refers to the area of summer sea ice in the Arctic that is projected to last. As climate change eats away at the rest of the Arctic's summer sea ice, climate and ice modellers believe that the ice will remain above Canada's High Arctic Islands, and above Northern Greenland for many more decades.

Much life has evolved together with the ice. Creatures from tiny single celled animals to seals and walrus, polar bears and whales, depend to some extent on the presence of ice. This means the areas where sea ice remains may become very important to this ice-adapted life in future.

One of my colleagues suggested we should have called the project the *Lasting* Ice Area. I agree, although it's a bit late to change the name now, that name better conveys what we want to talk about. While much is changing, and is likely to change around the Arctic, this is the place that is likely to change the least. That is also meaningful for the people who live around the fringes of this area – while people in other parts of the Arctic may be forced to change and adapt as summer sea ice shrinks, the people around the LIA may not have to change as much.

As a conservation organization, WWF does not oppose all change. Our goal is to help maintain important parts of the natural world, parts that are important just because they exist, and important for people. WWF does not have the power and authority to impose its vision on people. Instead, we try to present evidence through research, and options for action. It is then up to the relevant authorities as to whether they will take action or not; the communities, the Inuit organizations, and the governments of the Last Ice Area will decide its future fate. We hope you will find the information in these reports useful, and that it will help you in making wise decisions about the future of the Last Ice Area.

Clive Tesar, Last Ice Area lead.

2. Executive Summary

This reader is a summary compilation of the main biophysical characteristics of the Canadian and Greenlandic regions of the LIA. It provides an up-to-date overview of the most important marine and terrestrial components of the LIA. “Biophysics” is the science that deals with the application of physics to biological processes. Hence, this document describes the main physical aspects of the marine and terrestrial LIA environment that are influencing the ecosystems and their biodiversity. Most of the species described have some level of ice dependence, underlying the importance of the LIA to their long-term survival. Predictions about the future state of the ecosystems and Arctic species within LIA are discussed, leading to potential scenarios about the future of the LIA. This is relevant, as it will inform the management decisions which need to be taken in the near future in order to safeguard biodiversity conservation and human use needs. The sources of this document are recent journal publications, scientific reports, websites and other relevant publications. It is intended to be a handbook for the WWF staff and it will be available publicly on the WWF website.

This reader recognizes the Arctic definition of the Conservation of Arctic Flora and Fauna working group, which comprises the Arctic Ocean and the adjacent terrestrial regions of the United States (Alaska), Canada, Denmark (Greenland), Iceland, Russia, Finland, Norway and Sweden. The LIA core area includes the Canadian High Arctic Islands north of the Parry Channel, and the northern part of Greenland (an imaginary line between the western settlement of Savissivik and the peninsula Kronprins Christian Land). The LIA exhibits many landscapes. The eastern part of the Canadian Arctic Archipelago is mountainous and ice caps, fiords and glaciers are present, while the central and western parts of the Canadian Arctic Archipelago are mainly flat. A very thick ice sheet covers Greenland, and its northern coastline harbours fiords and islands. Five marine ecoregions and three terrestrial ecoregions characterize the LIA region. Marine ecoregions are identified based on species groups of plants and animals, while terrestrial ecoregions are identified based on plant species groups.

Climate change due to human activities is now clear. The rate of climate warming in the Arctic has been twice faster than the global average in the last decades and this trend is projected to continue in the future. Major implications of a warmer climate for the Arctic environment are the melt of glaciers, a reduced sea ice cover, and a northward recession of the permafrost boundary. The Arctic climate is characterized by extremes in air temperature, light availability, and snow and ice covers. The climate of different locations in the Arctic varies greatly because of the topography and distance to the coast. Snow is a prominent feature of Arctic terrestrial landscapes and marine icescapes. It provides important habitats for several Arctic species, and snow cover on sea ice controls the light available for photosynthesis. Rising temperatures decrease the extent and duration of Arctic snow, which affect soils, plants, animals and marine productivity.

The Arctic Ocean occupies a huge portion of the Arctic marine environment. Broad continental shelves, large riverine inputs, and its predominant ice cover characterize this ocean. The LIA marine environment includes the continental shelves north of Greenland and of the Canadian Arctic Archipelago, water between islands of the Canadian Arctic Archipelago, Lancaster Sound and fiords located on the northern coast of Ellesmere Island and Greenland. Arctic marine productivity and biodiversity are influenced by connections to the Pacific and Atlantic oceans, and a strong stratification of the water layers with different densities. The wind-driven surface circulation of the Arctic Ocean controls the movement of sea ice. The Beaufort Gyre pushes ice along the northwestern coast of the Canadian Arctic Archipelago, and the Transpolar Drift moves ice from the Siberian coast across the Arctic Ocean towards Greenland. This results in the location of the thickest sea ice along the northern coast of Greenland and the northwestern coast of the Canadian Arctic Archipelago, and corresponds to the area covered by the LIA project. Major effects of climate warming on the Arctic Ocean water masses are the warming of the surface water and ocean acidification. Sea ice is found throughout the Arctic and its extent has dramatically declined in the last decades. The record low ice coverage reached in September 2012 was the lowest in the last 112 years. Also, the sea ice cover is now younger, thinner and the ice volume is reduced. Due to the surface circulation of the Arctic Ocean, the ice that remains at the minimum sea ice extent is mostly located within and north of the LIA. The loss of Arctic sea ice is projected to continue and the Arctic Ocean is projected to become completely ice free during summer by mid-century. Sea ice plays several roles such as influencing local and global climates, affecting the albedo and ocean circulation and, determining atmospheric-ocean exchanges. Some features of the sea ice environment (marginal ice zones, flaw leads and polynyas) are especially productive. Ice shelves, very thick ice attached to the coastline, were extensive along the northern coastline of Ellesmere Island a century ago but they have undergone a drastic decline in the last decades.

The Arctic Ocean and nearby marine environments provide diverse habitats for a multitude of unique life forms highly adapted in their life history, ecology and physiology to the extreme and seasonal conditions of this environment. Arctic marine food webs involve numerous pathways, are relatively simple and vulnerable to perturbations. Primary production in the Arctic Ocean depends on light and nutrients, and comprises ice algae and phytoplankton photosynthesis. Primary production is low in the Arctic Ocean compared to other oceanic environments of lower latitudes because of low light availability. The reduced sea ice cover may increase primary productivity in the next decades and modify the interplay between the water column and seafloor systems. The biodiversity in the sea ice is astonishing and consists of a complete food web. The water column biodiversity is composed of phytoplankton, zooplankton, bacteria, archaea and other tiny organisms. Phytoplankton and zooplankton communities reveal a high diversity. Arctic seafloor biodiversity ranges from unicellular life to large invertebrates and the Arctic seafloor presents varied habitats. A study on large organisms dwelling on the seafloor (larger than 0.5 mm) suggested an intermediate biodiversity. The Arctic Ocean inhabits few fish species compared to more temperate environments. Most fish live close to the seafloor but two species are closely associated with the sea ice. Subsistence fisheries are important for local communities in Canada and commercial fisheries are essential to the economy of Greenland. Seven marine

mammals (whales, pinnipeds and polar bears) live in the Arctic all year long and many other species occupy Arctic waters seasonally. Changes in the Arctic climate along with the loss in sea ice cover may challenge the survivorship of marine mammals reliant on sea ice in their life cycle. The Arctic is an important region for seabird diversity and large breeding colonies are found on cliffs and islands.

The Arctic terrestrial environment is characterized by numerous lakes that dot the landscape and by the predominance of snow and ice in the form of glaciers, ice caps, ice sheets and permafrost (permanently frozen ground). The Arctic contains numerous freshwater ecosystems of different types (lakes, rivers, ponds, streams, wetlands). They are important for hunting and fishing by local communities, as supplies of drinking water and are a key resource for industries such as transport and mining. Lake and river ice cover duration is declining because of a warmer climate. Arctic glacier ice comprises mountain glaciers, ice caps and ice sheets. Within LIA, glaciers and ice caps are present on Devon and Ellesmere islands, and at the periphery of Greenland. The Greenland Ice Sheet spreads up to the northern part of Greenland. Similar to the different ice type trends, glacier ice is rapidly declining. Permafrost (permanently frozen ground) underlies the vast majority of the surface of the terrestrial Arctic, and is linked with biodiversity and ecosystem processes. The permafrost is degrading rapidly in most Arctic regions.

Terrestrial biodiversity comprises soil microbes, vegetation, animal, and lakes and rivers biodiversity. The biodiversity of these groups of organism declines with latitude. Arctic soils hold large reserves of microorganisms, but the Arctic climate strongly limits their metabolic activity. Warmer temperatures will increase the metabolic activity of these organisms and will lead to higher decomposition rates. Arctic vegetation is strongly controlled by summer temperature. Higher summer temperature cause the size, horizontal cover, abundance, productivity and variety of plants to increase. Most plants of the Arctic are dwarf shrubs, herbs, lichens and mosses. Arctic vegetation is relatively poor. The main impacts of climate change on Arctic vegetation are greening, shrub expansion and floristic changes. The biodiversity Arctic terrestrial animals is low and Arctic terrestrial food chains are short and simple. Terrestrial Arctic animals possess adaptations that enable them to cope with low winter temperatures and conserve energy. Climate change is having observed impacts on terrestrial Arctic animals by altering freeze-thaw cycles and by changing animal behaviours. Arctic aquatic food webs are simple compared to temperate latitudes. The level of nutrients available in the system would strongly influence the food web structure and diversity. Shifts in lake and river ice cover regimes will have cascading effects on the biological communities.

There are several protected areas in LIA and its vicinity, which cover terrestrial and marine environments. The Arctic is experiencing pressure from numerous sources. Apart from climate change that is having drastic impacts on the Arctic environment and biodiversity, enhanced mining and oil and gas activities, increased shipping, and contaminants by local pollution or long-range transport are additional factors that threaten the integrity of Arctic ecosystems.

This document identifies significant data gaps regarding the LIA and nearby regions. The logistical challenges imposed by the harsh Arctic environment limit field expeditions, especially during winter and in the most remote environments such as the seafloor. It would be important to gain more knowledge on long-term climatic data for the Greenlandic part of the LIA. The existing records are incomplete and make statistical analyses difficult. Also, the circumpolar flaw lead is not well characterized in the LIA region. This flaw lead is projected to enlarge and to last longer in the next decades and may become a highly productive area within the LIA. The studies of marine and terrestrial biodiversity of the High Arctic regions generally suffer from lack of data and low sampling effort. This area is changing at one of the most rapid pace on the planet and there is a pressing need to learn more about its biodiversity before it vanishes.

There are many other resources both existing and in production that cover all or part of the LIA area and that will provide more detail on various aspects of the biological and physical environment of the area, for instance the Life linked to Ice report of the Arctic Council's Conservation of Arctic Flora and Fauna working group (published), The Canadian ArcticNet – IRIS 2 report (in production), and the Adaptation Actions for a Changing Arctic project of the Arctic council's Arctic Monitoring and Assessment Programme (in progress).

While this resource focuses on the Last Ice Area, it is important to view it also in the context of the future prospects of Arctic conservation as a whole. The ecology and the lives of Arctic peoples linked to that ecology are changing everywhere. In some places, resilient features (such as the continuing existence of summer sea ice) will likely allow for less change – in other places, those features will mean there is change in the ecology of the area, but it will likely remain biologically productive and important. WWF is working with local peoples and with governments to try to identify the sources of resilience for Arctic life, and to reduce the pressures on that resilience. The Last Ice Area is one pilot project in what must become a linked network of conservation if we are to preserve unique Arctic ecosystems and lifestyles.

3. Geography

WWF, like the Arctic Council, defines the Arctic as more than just the area within the Arctic Circle. It makes much more sense to include areas bound together by similar ecosystemic features, and also, for policy purposes there are political boundaries that help in defining what is Arctic. The result is a combination of factors that provide coherent and similar descriptions of the Arctic across the Arctic Council's working groups. As a conservation organization, WWF recognizes the boundary of the Conservation of Arctic Flora and Fauna working group of the Arctic Council as the most relevant to our work (Figure 1). Working with Arctic Council definitions, the Arctic is a vast region that covers more than 40 million square kilometres, and contains about four million people (AHDR (Arctic Human Development Report), 2004). It consists of the Arctic Ocean and

the adjacent terrestrial regions of the United States (Alaska), Canada, Denmark (Greenland), Iceland, Russia, Finland, Norway and Sweden.

The LIA boundaries are fuzzy as they are based on projections of sea ice persistence that are not accurate predictions of the exact location of that ice in the future. Nonetheless, the core of the area of interest includes the Canadian High Arctic Islands (also called the Queen Elizabeth Islands) that are located north of the Parry Channel, and the northern part of Greenland (an imaginary line between the western settlement of Savissivik and the peninsula Kronprins Christian Land) (Figure 2). The communities included in the LIA area are Grise Fiord and Resolute, in Canada, and Qaanaaq, in Greenland.

The LIA is composed of many landscapes. Towering mountains with peaks over 2,000 m are found in the eastern islands of the Canadian Arctic Archipelago (Ellesmere, Axel Heiburg and Devon). The higher land on these islands is commonly covered by ice caps. Spectacular fiords and glaciers are also part of the landscape. The central and western islands of the Canadian Arctic Archipelago are generally flat with low relief (less than 200 m). Greenland is the largest island and 85% is covered by an ice sheet nearly 3,000 m thick. Fiords and islands characterize the Greenlandic coastline.

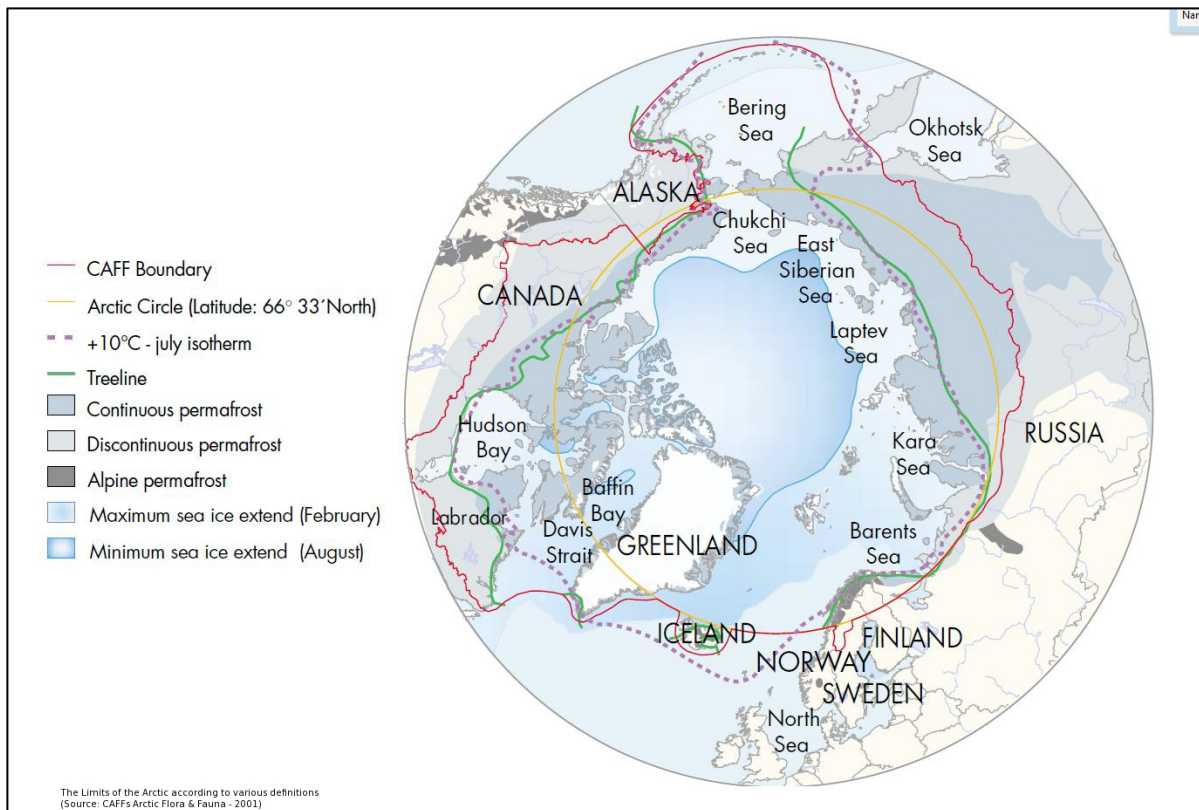
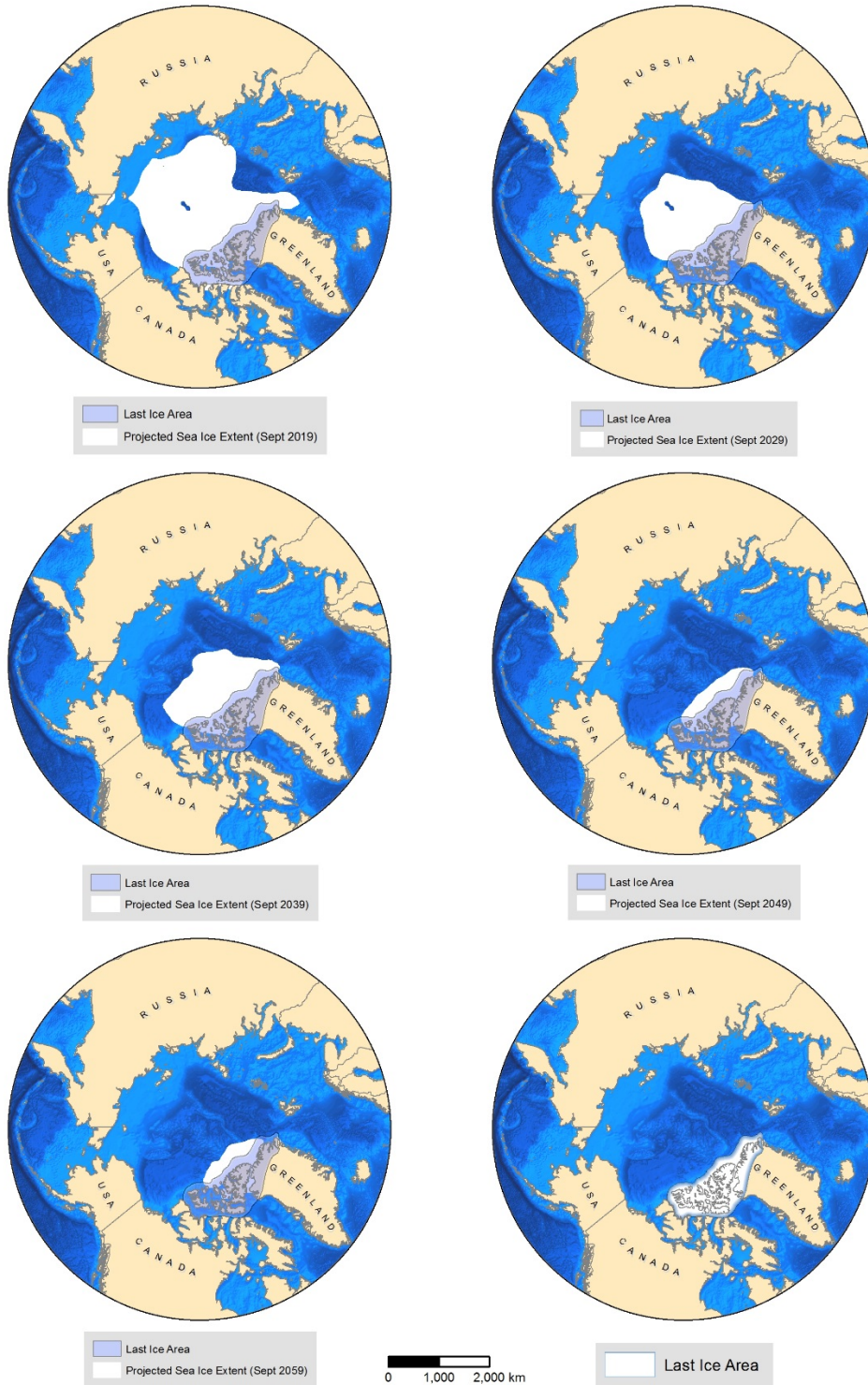


Figure 1. The limits of the Arctic according to different definitions (Arctic Council - CAFF Working Group, 2001b).



The WWF Last Ice Area boundary is based on projected September Sea Ice Extents, >15% Conc. from 2050 through to 2090 (Huard & Tremblay, 2013).

Figure 2. Map of the LIA core area and projected future ice extent (WWF, 2014).

4. Ecoregions

Fifty representative ecological regions, or ecoregions, have been defined within the circumpolar Arctic (WWF, 2012). The objective of designing ecoregions is to plan for conservation and set priorities (Skjoldal et al., 2012). Thirty-seven marine ecoregions were identified based on recognizable species groups of both plants and animals. Each marine ecoregion is an area of relatively homogeneous species composition that is clearly different from adjacent regions (Spalding et al., 2007). These species groupings are likely the consequences of oceanographic or topographic features such as temperature regimes, ice regimes or upwelling, that lead to biological differences (Spalding et al., 2007).

The LIA includes five marine ecoregions: Beaufort-Amundsen-Viscount Melville-Queen Maud, Lancaster Sound, High Arctic Archipelago, Baffin Bay (Canadian Shelf) and North Greenland (Figure 3). Within these ecoregions, Ecologically and Biologically Significant Areas (EBSAs) were identified (Skjoldal et al., 2012). These areas were selected based on their ecological importance to fish, birds and mammals, as these species are the most widely studied Arctic groups (Skjoldal et al., 2012). The Beaufort-Amundsen-Viscount Melville-Queen Maud includes one EBSA in Viscount Melville Sound. This area is important for the feeding of belugas and, as a feeding ground and rearing area for polar bears. The Lancaster Sound ecoregion comprises three EBSAs: Lancaster Sound, Wellington Channel and Cardigan Strait/Hell Gate. These three EBSAs are very productive as they each contain a recurrent polynya (area of open water within the sea ice) that is used by seabirds as a nesting, breeding and feeding area, and by walrus as haul-out and wintering grounds. Arctic cod, an important link in the Arctic food web, is abundant in these three EBSAs. Lancaster Sound is also used as a migration corridor for marine mammals such as bowhead, narwhal, beluga, killer whales, and seals, and has the highest known density of polar bears in the world. The High Arctic Archipelago ecoregion comprises six EBSAs. The Archipelago multiyear pack ice is critical as it the largest remaining island pack ice refugium in the world and it supports unique communities. This area is particularly important for under-ice communities, seabirds and polar bears. Norwegian Bay is important for marine mammals and has the most genetically differentiated polar bear population in the world. Ellesmere Island includes three EBSAs: the Ellesmere Island ice shelves (described at section 7.4), the Nansen-Eureka-Greely Fiord that supports unique fish communities and aggregations of polar bear and ringed seal and Princess Maria Bay that is used by several seal species, walrus and narwhal. The Arctic Basin pack ice is the EBSA that contains the thickest and oldest sea ice of the Arctic and is a unique habitat for under-ice and planktonic communities, and is a significant summer refuge for polar bear. The Baffin Bay (Canadian Shelf) ecoregion includes three EBSAs: the North Water Polynya (see section 7.3), the Eastern Jones Sound that is characterised by an earlier open water feature that joins the North Water Polynya a few months later, and the Northern Baffin Bay that is known as an important seafloor habitat. The North Greenland ecoregion contains Peary Land, an important area for marine mammals and seabirds.

Twenty-three Arctic terrestrial ecoregions were identified based on the variation in plant species groups and communities found in clearly recognizable regions (CAVM Team, 2003). Although many plants grow throughout the circumpolar Arctic, variation in some species groups are informative of glacial histories, topography and other factors that might have contributed to regional differences. Soil type, soil moisture and temperature correspond to the different terrestrial ecoregions. The LIA encompasses three terrestrial ecoregions: Ellesmere-Northern Greenland, Central Canada and, to a small extent, Western Greenland (Figure 4). Tundra, permafrost, ice caps and glaciers, the Greenland Ice Sheet and snow characterize the terrestrial portion of the LIA.

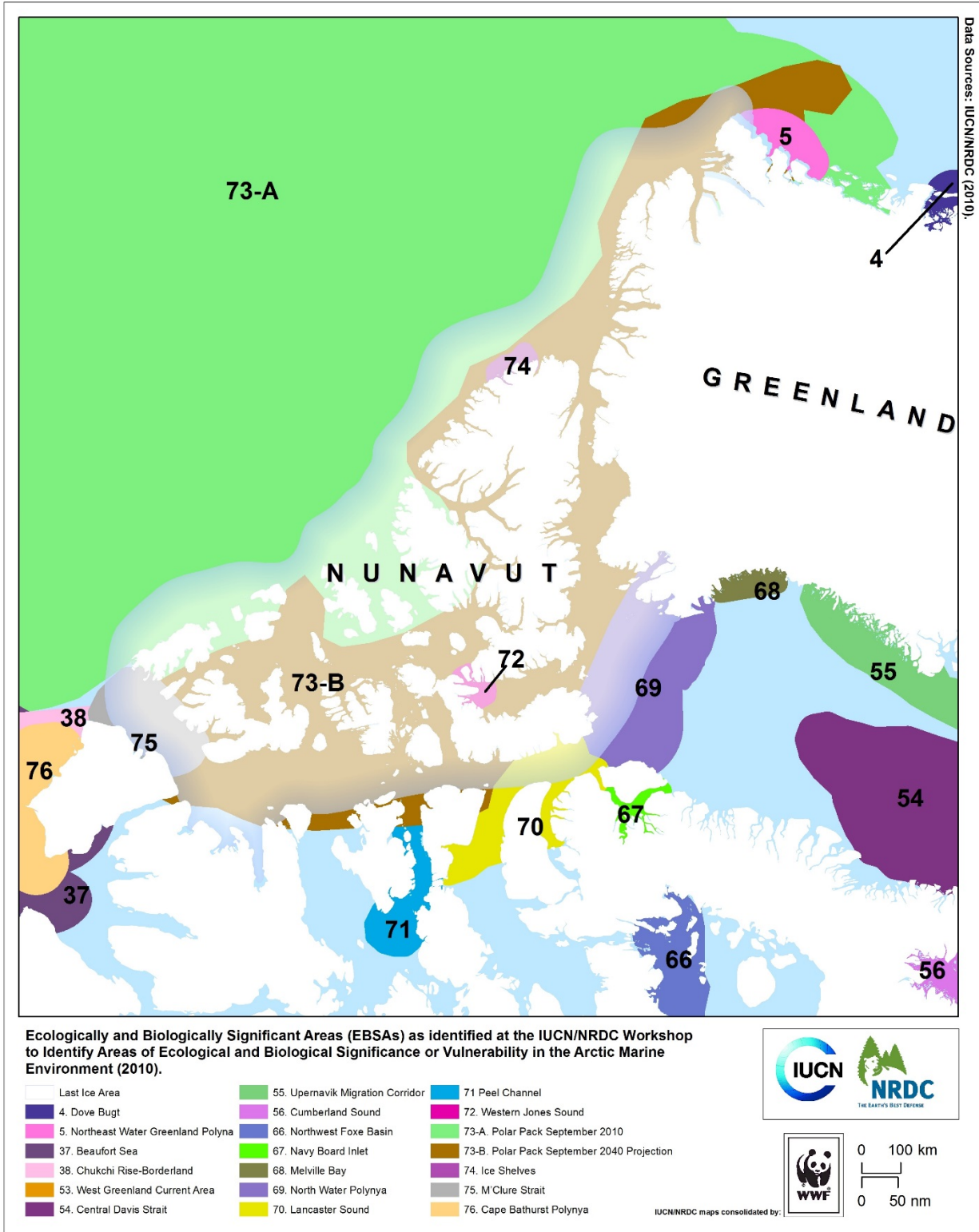


Figure 3. The LIA region with marine ecoregions and EBSAs.

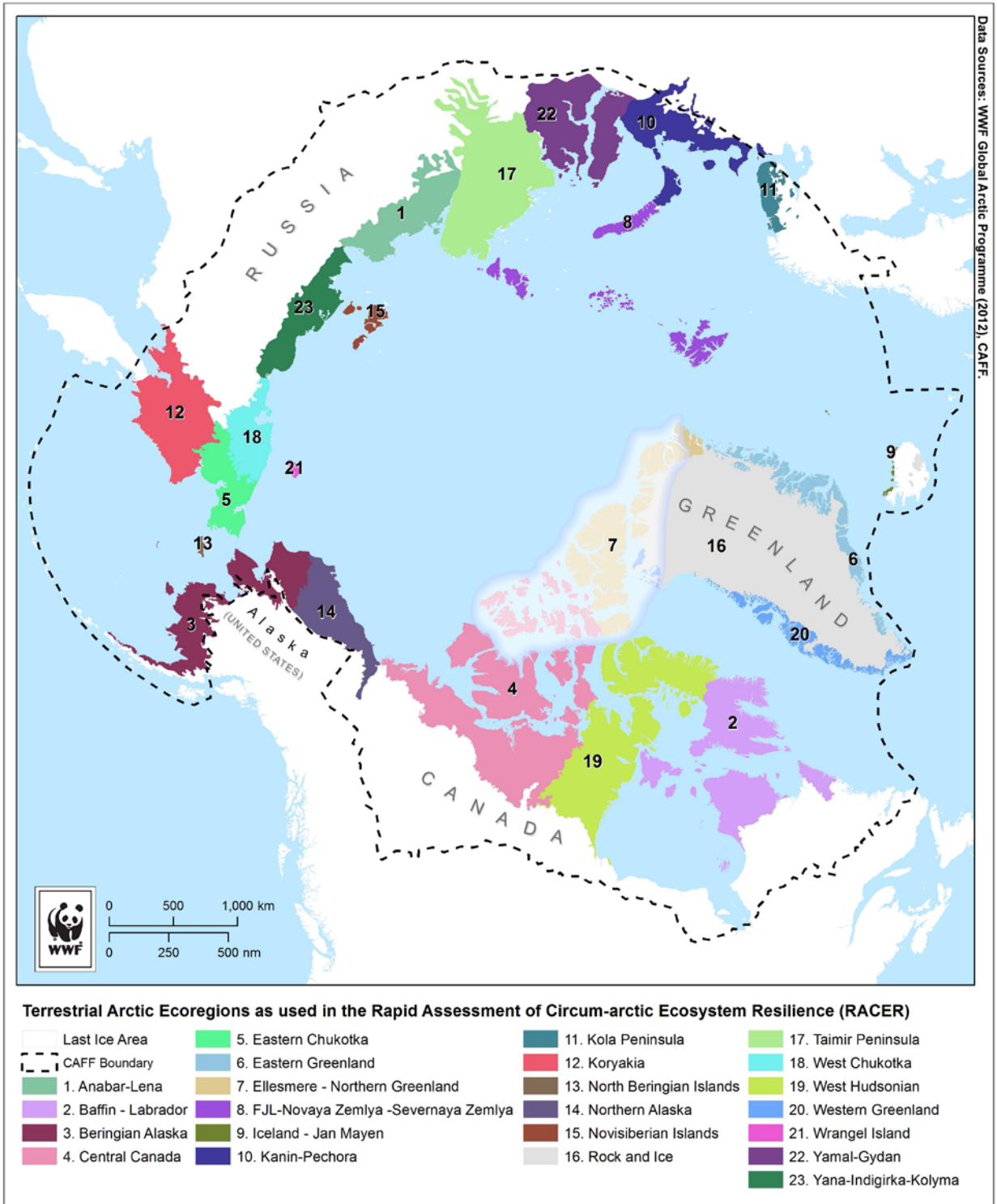


Figure 4. LIA region with terrestrial ecoregions

5. Climate

Climate change is now at the forefront of the agenda of politicians, scientists and the general public. Human influence on the climate system is now evident by the observed increase in greenhouse gases, such as carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O) and chlorofluorocarbon (CFC) (IPCC, 2013). Since 1750, the beginning of the industrial revolution, atmospheric concentrations of CO₂, CH₄, and N₂O have increased dramatically and reach values exceeding the interval of natural variation of the last 800,000 years (IPCC, 2013).

The planet has globally warmed by 0.89°C over the period 1901-2012 (IPCC, 2013). Air temperatures have increased in most regions although the most rapid changes are happening at high latitudes. Mean annual temperatures in the Arctic have increased from 2 to 3°C since 1950 (Anisimov et al., 2007; IPCC, 2013). The rate of climate warming in the Arctic has been almost twice the global average in recent decades (Screen and Simmonds, 2010) and this warming trend is projected to continue in the future (Meehl et al., 2007). The faster and greater warming trend in the Arctic, called the “Arctic amplification”, is explained by feedback processes that amplify climate warming in the Arctic (Sommerkorn and Hassol, 2009). There is a growing concern that these feedback processes are starting to accelerate significantly beyond the projections currently considered by policy-makers. Among others, the release of CH₄ from thawing permafrost beneath the East Siberian Sea, as the sea ice cover declines, is projected to have dramatic effects on the global mean temperature increase. Increased temperatures in the Arctic have major implications such as the melt of glaciers (Sharp et al., 2011), a reduced sea ice cover (Parkinson and Comiso, 2013) and a northward recession of the permafrost boundary (Callaghan et al., 2011a). Moreover, another approach to evaluate the effects of climate change is to identify critical thresholds in ecosystems, where further change results in abrupt, discontinuous shifts in ecosystem properties. Recent observations suggest that some systems are at the edge of these tipping points and this will have global implications. Finally, although they were ignored until recently, the economic impacts of a warming Arctic are now attracting the media interests (Whiteman et al., 2013). As an example, the economic consequences of the release of methane from thawing permafrost due to global climate change would cost trillions of dollars in the absence of mitigating action, since this extra methane in the atmosphere would increase flooding of low-lying areas, and cause extreme heat stress, droughts and storms.

The Arctic climate is challenging for life. It is characterized by extreme seasonality; air temperature vary from glacial to temperate, the winter polar night is followed by the summer midnight sun, and snow and ice covers fluctuate significantly between seasons. Precipitations are generally low and some particularly arid regions are classified as “polar deserts”. The climates of specific locations within the Arctic are likely to vary since this is a vast region and specific features such as the topography or the distance to the coast, can influence local conditions (Figure 5). For instance, Alert (located on the northern coastline of Ellesmere Island) is influenced by cold air advection from the Arctic Ocean and the blocking of solar radiation by frequent low clouds and fog, while

Eureka (located on the coastline of a fiord on Ellesmere Island but not exposed to the Arctic Ocean) is subject to the rain shadow effect of surrounding mountains (Maxwell, 1981).

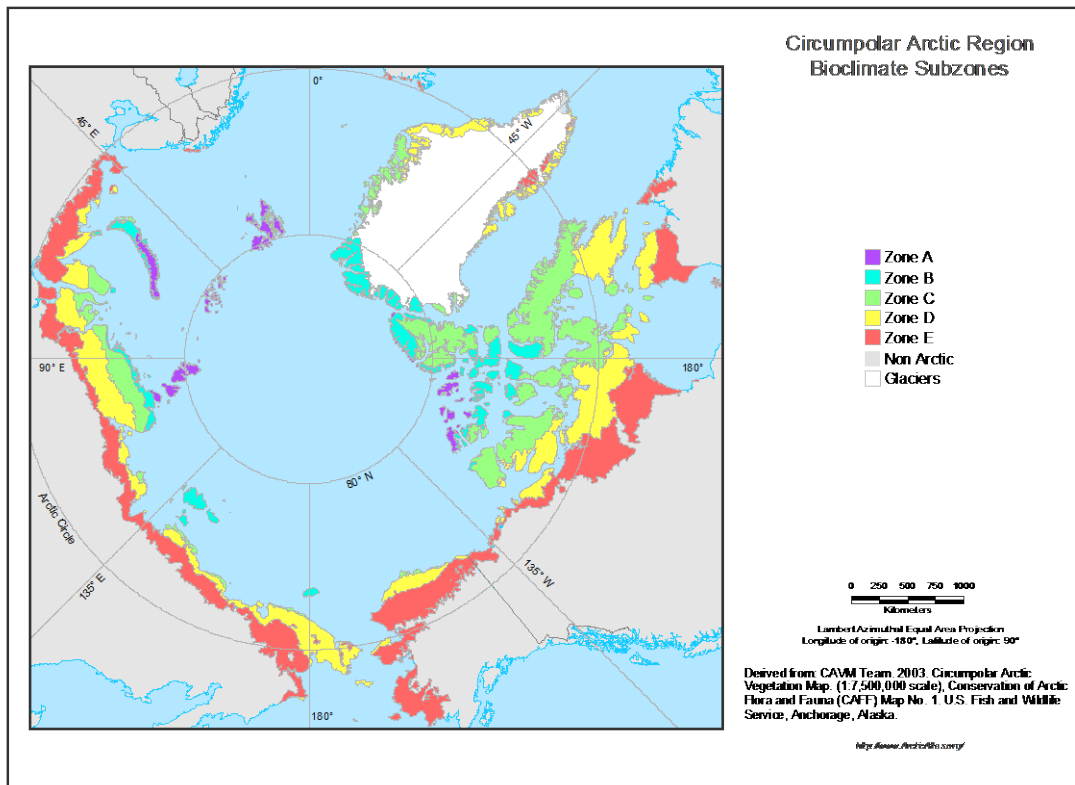


Figure 5. Bioclimate subzones of the circumpolar Arctic based on the Circumpolar Arctic Vegetation Map. Mean July temperature of zone A is 0-3°C, for zone B, 3-5°C, for zone C, 5-7°C, for zone D, 7-9°C, and for zone E, 9-12°C (CAVM Team, 2003).

The availability of Canadian and Greenlandic Arctic climate data is skewed towards coastal stations. In addition, the records are often interrupted and long-term trends are difficult to calculate. In the Canadian portion of the LIA region, 6 weather stations owned by the Government of Canada exist (Alert, Eureka, Resolute, Grise Fiord, Pond Inlet, Clyde River). Normals for the period 1981-2010 are available for five of these stations (Table 1). Also, the Centre for Northern Studies (www.cen.ulaval.ca) has created a network of climate observatories along a south-north transect, from the boreal forest to the High Arctic, which is named the SILA Network. This network has stations within or close to the LIA on Bylot Island and on the northern coastline of Ellesmere Island, in the vicinity of Ward Hunt Island, and data are publicly available.

	Lat. (°N)	Long. (°W)	Temp. (°C)	Days 0°C	> Precipita- tion (mm)	Rainfall (mm)	Snowfall (cm)
Alert	82.52	62.28	-17.69	80.62	158.29	17.43	184.64
Eureka	79.98	85.93	-18.75	98.95	79.07	32.53	60.30
Resolute	74.72	94.97	-15.67	92.90	161.20	59.47	111.21
Pond Inlet	72.69	77.97	-14.56	119.62	189.01	91.02	131.90
Clyde River	70.49	68.52	-12.58	122.67	NA	63.29	194.74

Table 1. Location and climate data for Canadian weather stations located in the LIA region or in its vicinity from 1981 to 2010. Data were obtained from the Government of Canada (Government of Canada, 2013a). Lat.: latitude, Long.: longitude, Temp.: me

The Danish Meteorological Institute owns several meteorological stations located in the LIA region: Pituffik, Kitsissut, Qaanaaq, Hall Land, Kas Morris Jesup, Kap Harald Moltke and Station Nord (Cappelen, 2012). However, the data records of these stations are discontinuous (raw data are publically available at www.dmi.dk). A long-term station south of the LIA region, Upernavik (72.78°N, 56.13°W), has a mean daily temperature of -7.1 °C for 1981-2010 (Cappelen, 2011). Also, the north drainage basin of Greenland, which include the LIA region, has a mean daily temperature of -21.3°C and a total of precipitation of 182.5 mm (Lucas-Picher et al., 2012). In Greenland, there are sharp differences in temperatures from the coasts to the fiords (Cappelen, 2013). In summer, drift ice and cold water along the coast make the fiords warmer places. In winter, the situation is reversed and coastal areas are warmer. Ellesmere Island and the north of Greenland are therefore very cold. Nevertheless, unusual very warm temperatures have been recently recorded, such as a maximum of 20.5°C at Ward Hunt Island (83°N, 74°W) in summer 2008 (Vincent et al., 2009).

6. Snow

Snow is an important and dominant feature of Arctic terrestrial landscapes and marine icescapes, with cover present for eight to ten months of the year. Its extent, dynamics, and properties (e.g. depth, density, water equivalent, grain size, and changes in structure throughout its vertical profile) affect climate (e.g. ground thermal regime), human activities (e.g. transportation, resource extraction, water supply, use of land, and ecosystem services), as well as infrastructure, hydrological processes, permafrost, extreme events (including hazards such as avalanches and floods), biodiversity, and ecosystem processes (Callaghan et al., 2011b). Air temperature and precipitation are the main drivers of regional-scale snow cover variability over the Arctic region, with local-scale variability in snow cover related to interactions with vegetation cover and topography through processes such as blowing snow and sublimation (when water changes directly from solid to vapor form without thawing) (Callaghan et al., 2011b). Impurities in the snow (e.g. leaf litter and organic and black carbon) contribute to local (landscape) and regional (circum-Arctic) differences in how much of the sun's energy is absorbed which influences spring season

melt rates (Callaghan et al., 2011b). In contrast to temperate regions, most of the Arctic snowmelt during spring occurs over a very short period of time.

Snow provides important denning habitat for several Arctic species such as polar bears and ringed seals (Callaghan et al., 2011b). For instance, female ringed seals give birth to their young in snow dens on the sea ice. The snow cover provides protection from cold temperatures and predators. These snow dens are especially critical when pups are nursed from late March to June. To successfully rear young, ringed seals in the central Arctic need on-ice snow depths in April of at least 50 cm. Such snow depths are usually found as snow drifts next to sea ice ridges but can be present on flat landfast ice (Hezel et al., 2012). Thus, the period over which snow accumulates on ice is considered to be the primary factor influencing the quality of ringed seal breeding habitat (Smith and Lydersen, 1991). Inadequate snow depths increase pup mortality through exposure and predation (Ferguson et al., 2005).

Snow cover on sea ice controls the underwater light availability by strongly attenuating light penetration. Snow cover influences the timing of the early spring under ice productivity in the Arctic Ocean, since primary production is initiated by the growth of ice algae as soon as a critical amount of light reaches the ice-water interface in spring. If the snow cover persists during the summer, it will also reduce the light available for photosynthesis by the phytoplankton. The huge importance of snow cover in attenuating light penetration of ice-covered aquatic ecosystems was demonstrated by a field experiment that removed the snow cover from an area of a perennially ice-covered lake. Removing the snow greatly increased light that was available at the ice-water interface (Belzile et al., 2001). This study also showed the much greater role of the snow cover compared to the ice cover in attenuating light penetration (Belzile et al., 2001).

Rising temperatures have implications for Arctic snow. The extent and duration of snow cover have decreased throughout the Arctic over the last decades. The Arctic land area covered by snow in early summer has reduced by 18% since 1966, and the average snow cover duration is expected to decline by up to 20% by 2050, due to earlier melting in spring (Callaghan et al., 2011b). The rate of loss of June snow cover extent between 1979 and 2011 (-17.8% per decade) is even greater than the loss of September sea ice extent over the same period (-10.6% per decade) (Derksen and Brown, 2012). Arctic landscapes are predicted to dry out more during summer because of higher air temperatures. Despite these observed and predicted trends, snowfall is projected to increase in all seasons, but mostly during winter (Callaghan et al., 2011b). The reduction in sea ice cover during late fall increases the atmospheric water vapor content in the Arctic region and support increased snowfall (Liu et al., 2012). All projections suggest that maximum snow depth will increase during winter over many areas (Callaghan et al., 2011b).

Changes in the amount of snow and the structure of the snowpack affect soils, plants, animals and marine productivity. Some species, such as pink-footed goose, benefit from less snow cover in spring. But animals grazing through snow, such as caribou, suffer if winter rainfall creates an ice-crust over the snow. This is already happening more often in northern Canada, Greenland and Scandinavia. In addition, the Arctic snowpack is a habitat for microbial communities (Harding et

al., 2011). Less snow and faster melting are also causing summer drought in forests, wetlands, and lakes supplied by snow melt, which are related to increased frequency and extent of fires (Mack et al., 2011).

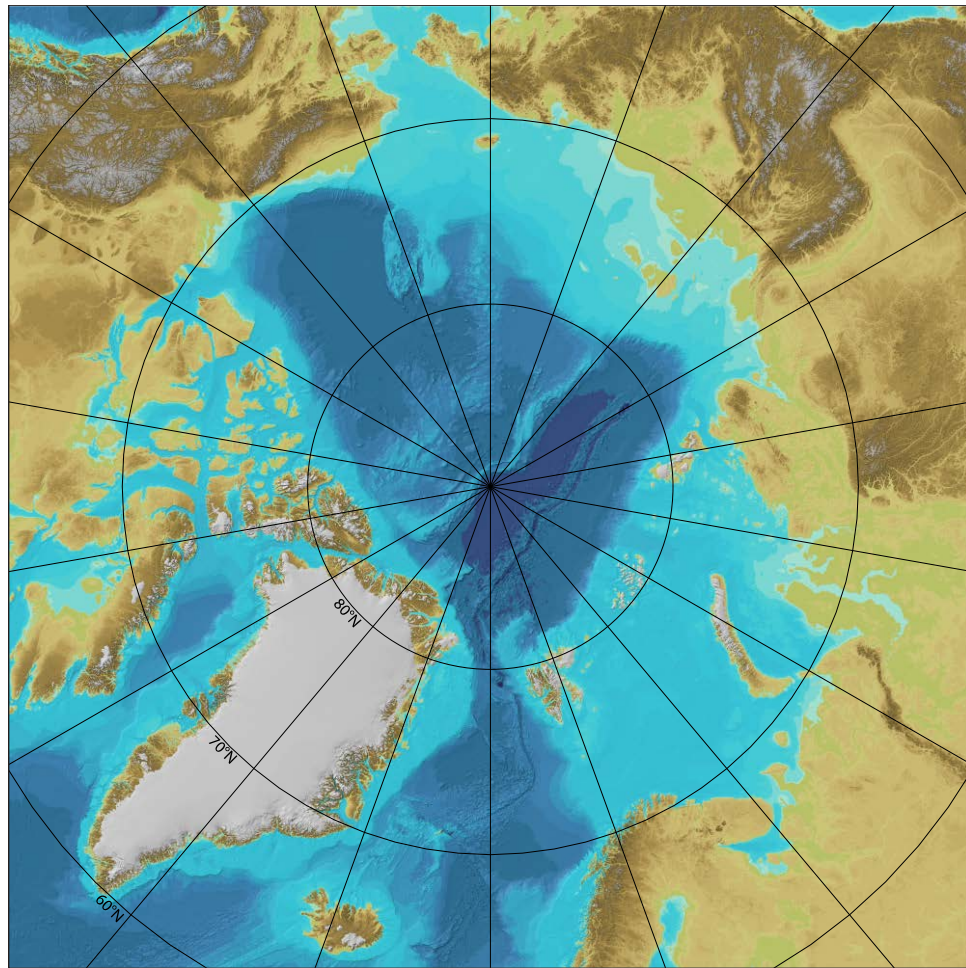
7. The marine environment

The Arctic Ocean is unique. It has the most extensive continental shelves of all oceans: they cover 50% of its total area. It is the most extreme ocean in regard to the seasonality of light, large riverine inputs and its predominant ice cover. In addition, Arctic marine productivity and biodiversity are shaped by connections to the Pacific and Atlantic oceans, and a strong stratification (layering of water with different temperatures and salt levels).

7.1 Physical oceanography

Bathymetry

The Arctic Ocean is a nearly landlocked ocean and receives large amounts of freshwater from large rivers such as the Ob, Lena, Yenisey and MacKenzie. The Arctic Ocean consists of a deep central basin (maximum depth of 4,400 m) divided by ridges (i.e. a chain of mountains that form a continuous elevated crest) and surrounded by broad and narrow continental shelves (Figure 6; an interactive map can be seen at www.arkgis.org). It is the smallest of the world's oceans, but has the highest proportion of continental shelves, with shelf regions covering around 50% of the Arctic marine area (Jakobsson et al., 2004). The continental shelves north of Greenland and of the Canadian Arctic Archipelago, part of the LIA, extend for a maximum of 300 km off the coast, up to a depth of around 400 m, until they reach the shelf break (i.e. where the slope is very steep). Water depths in the central Canadian Arctic Archipelago are generally shallow (< 100 m) although Lancaster Sound reaches depths of up to 800 m (Niemi et al., 2010). Fjords on the northern coast of Greenland can be very deep (Petermann Fjord is 1,100 m deep (Johnson et al., 2011)) while fjords located on the northern coast of Ellesmere Island is not well known, except that Disraeli Fjord is about 450 m deep (D. Antonaides, pers. comm.).



Bathymetric and topographic tints (Meters above and below Mean Sea Level)

0 700 800 1000

Figure 6. Bathymetry of the Arctic Ocean (Jakobsson et al., 2012).

Currents and water masses

The circulation of surface waters in the Arctic Ocean flows predominantly from the Pacific to the Atlantic Ocean (Figure 7). The flow to the Atlantic Ocean is through several routes in the Canadian Arctic Archipelago, mainly in Lancaster Sound/Barrow Strait and in Nares Strait, and through Fram Strait, down the east coast of Greenland. The Pacific Ocean water is characterized by a low salinity (less than 33 ‰) and is nutrient-rich compared to the Atlantic Ocean water. The Pacific waters are therefore less dense and form a layer on top of the Atlantic water mass. Freshwater from sea ice melt and river discharges add to this surface layer and contribute to the stability of the water column. A consequence of these high freshwater inputs is the permanent stratification of the central Arctic Ocean with a surface salinity of 32 ‰ and a deep water salinity of 34 ‰ (Gradinger

et al., 2010). Surface waters become rapidly depleted in nutrients due to the blooms in primary productivity but the underneath layers remain nutrient-rich. The interplay between the winds and the stability of the stratification determine the vertical supply in nutrients by mixing deep waters into the surface layers (upwelling).

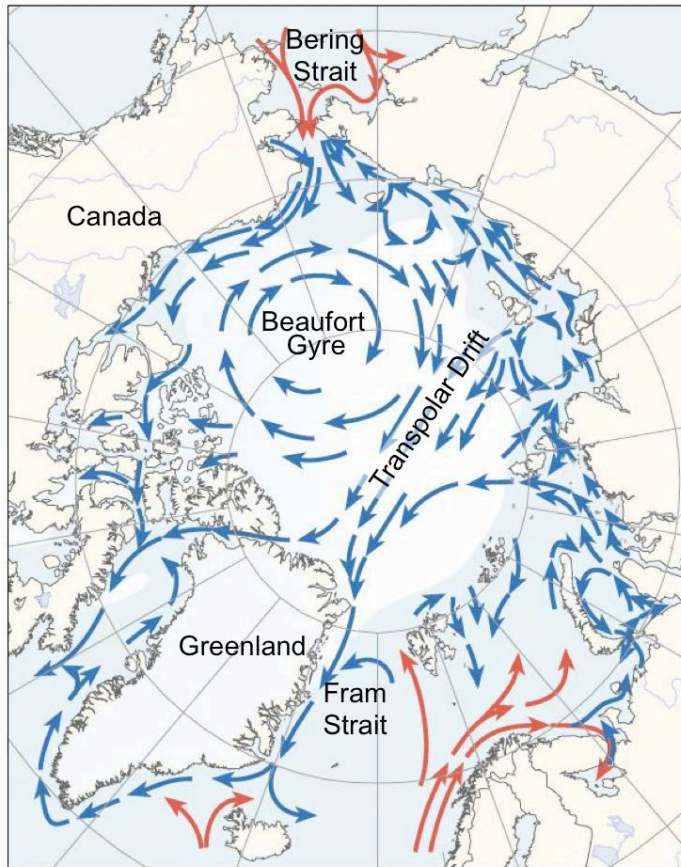
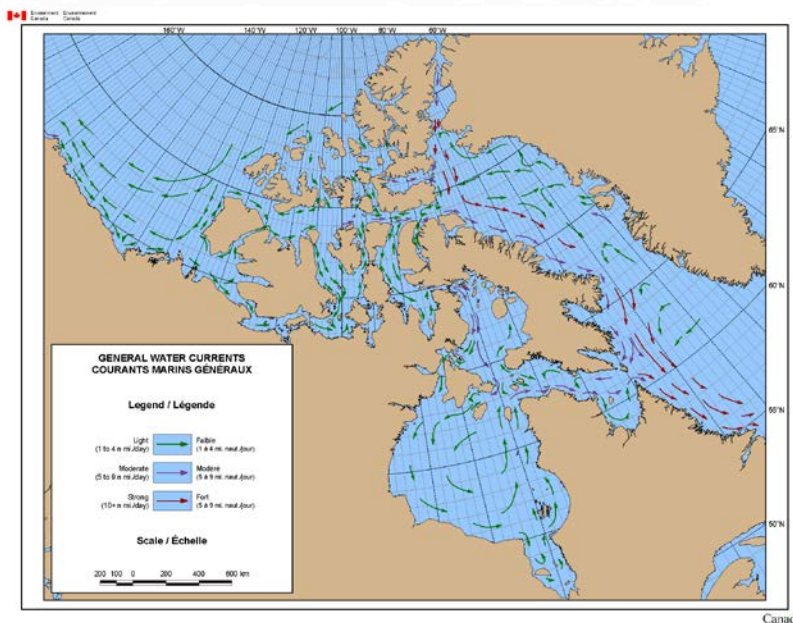


Figure 7. Surface ocean currents in A) the Arctic Ocean and B), the Canadian Arctic Archipelago. In A), blue arrows indicate cold currents and red arrows, warm currents (modified from (Arctic Council - CAFF Working Group, 2001a)). In B), green arrows indicate light currents, purple arrows, moderate currents and red arrows, strong currents (Environment Canada - Canadian Ice Service, 2013).



Water masses of the Arctic Ocean are found to vary in temperature, salinity and position from year to year. These changes, apart from modifying water stratification and mixing regimes, may affect nutrient concentrations, and the distribution of plankton, fish larvae and larger invertebrates. Arctic marine biodiversity is therefore linked to the dynamic pattern of oceanic conditions (CAFF, 2013b).

The wind-driven surface circulation in the Arctic Ocean also determines the movement of sea ice. The clockwise Beaufort Gyre controls the movement of the Arctic pack ice off the northern coast of Greenland and along the northwestern margin of the Canadian Arctic Archipelago (Figure 7). By recirculating ice, the Beaufort Gyre produces the thickest and oldest ice in the Arctic Ocean (Lee et al., 2012). Moreover, the Transpolar Drift moves ice from the Siberian coast region across the Arctic Ocean towards and eventually through Fram Strait (National Snow and Ice Data Centre, 2013a). As a result, on a basin-scale, the thickest sea ice (mean thicknesses of 4 to 6 m) is located off the northern coast of Greenland and along the northwestern margin of the Canadian Arctic Archipelago, and is the region covered by the LIA project.

Climate warming impacts on water masses

Climate warming has implications for the water masses of the global ocean, and changes have been observed for the Arctic Ocean. First, the surface waters of the Arctic Ocean have warmed in recent years (Xue et al., 2013). The Arctic Ocean has also warmed as a result of the influx of warmer water from the Pacific and Atlantic oceans. The global ocean will continue to warm during the 21st century. Heat will penetrate from the surface to the deep ocean and affect ocean circulation (IPCC, 2013). The thermal expansion of water and glacier mass loss is causing the sea level to rise. Over the period 1901-2010, global mean sea level rose by 19 cm (IPCC, 2013).

Rising carbon dioxide gas (CO₂) concentration in the atmosphere since the industrial revolution is causing ocean acidification. The primary driver of ocean acidification is the water absorbing CO₂ emitted to the atmosphere by human activities. Around one third of the CO₂ produced by human activities has been taken up by the oceans (Sabine et al., 2004). Although this has slowed the rate of climate warming, it has made the ocean more acidic and may affect marine life significantly (Fabry et al., 2008). The increase in CO₂ concentration in the ocean surface waters decrease the pH and lead to undersaturation in calcium carbonate (CaCO₃). Under these conditions, marine organisms such as plankton, invertebrates and fish that use calcium to form shells and external skeletons are negatively affected (Fabry et al., 2008). Ocean acidification is therefore likely to affect the abundance, productivity, and distribution of marine species. The Arctic marine environment is especially prone to ocean acidification. This is due to the better dissolution of CO₂ into colder water than warmer water and to specific characteristics of Arctic Ocean water. In particular, increasing amounts of sea ice meltwater may deplete surface waters of the calcium carbonate ions necessary to build shells and skeletons (Yamamoto et al., 2012). The CO₂ can be absorbed during open water conditions and rejected along with brine from growing sea ice (Rysgaard et al., 2009). A study involving sea ice coring and water sampling north of Greenland (some sampling sites located within the LIA) concluded that the Arctic seas are among the few regions in the world that take up substantial amounts of atmospheric CO₂ throughout the year

(Rysgaard et al., 2009). It is still unclear exactly what changes increased acidification will bring, but it is very likely that the water column food web of the Arctic Ocean will be affected (Riebesell et al., 2013).

7.2 Sea ice

What is sea ice?

Sea ice is frozen ocean water and it is found throughout the Arctic and around the Antarctic. Different types of sea ice are found and they have distinct properties (Figure 8). First-year ice is floating ice of no more than one year's growth. Its thickness ranges from 0.3 to 2 m. This ice type is generally level but ridges that occur are rough and sharply angular (National Snow and Ice Data Centre, 2013a). As sea ice forms, it expels salt into the ocean water by the formation of brine (droplets of highly saline water) that is trapped in pockets between the ice crystals. Another way that salts are expelled on new seasonal ice is by the forming of frost flowers on top of it (Barber et al., 2012a). When sea ice becomes multiyear ice (ice that has survived at least two summer melt seasons (Parkinson and Comiso, 2013), it becomes fresh as the salts have been expelled and all that remains is frozen water. Multiyear ice is therefore stiffer and it is harder for icebreakers to navigate through it (National Snow and Ice Data Centre, 2013a). Extensive multiyear ice forms in the Arctic Ocean as it is land-locked (Figure 9) (National Snow and Ice Data Centre, 2013a). Perennial ice is defined as ice that has survived at least one summer melt season (Parkinson and Comiso, 2013). Landfast ice is defined as ice that grows out from the shore (Vincent et al., 2011).



Figure 8. Photos showing examples of the different sea ice types: on the left, first-year is shown (<http://ice-glaces.ec.gc.ca/App/WsvPageDsp.cfm?ID=10975&Lang=eng>) and, on the right, multiyear sea ice is illustrated (worldcomplex.blogspot.ca/2010/08/blowing-up-arctic_12.html).

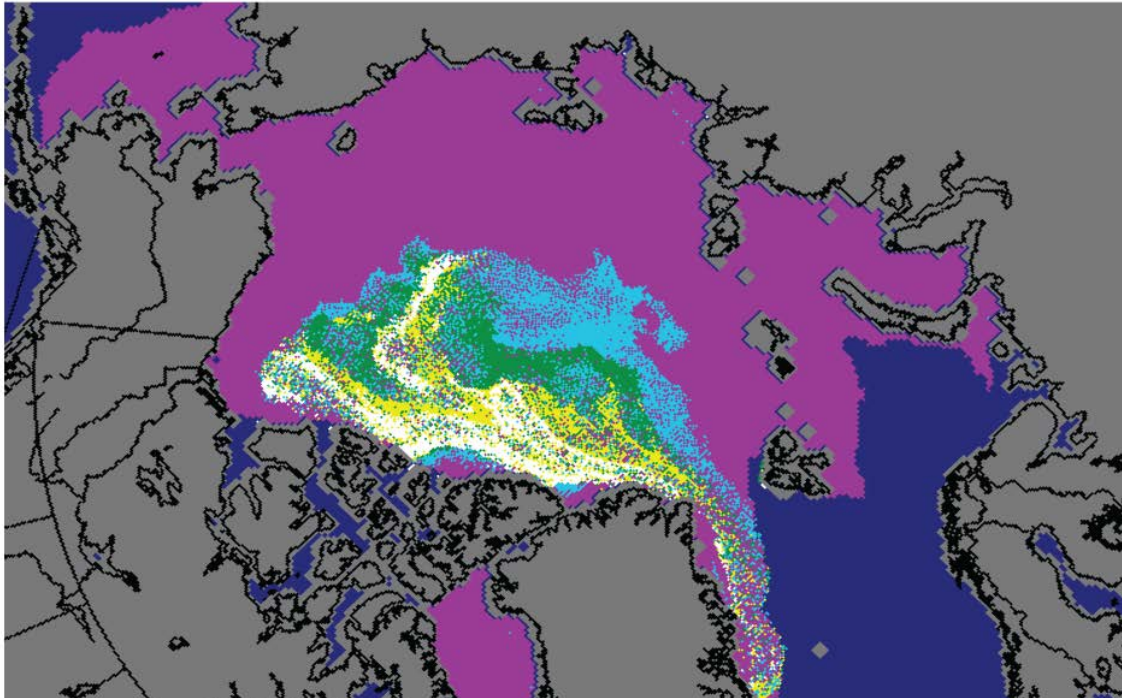


Figure 9. Arctic sea ice ages at the end of March 2013 (NSIDC courtesy J. Maslanik and M. Tschudi, University of Colorado). Areas cover by first-year ice (< 1 year old) are represented in magenta, ice of 1-2 years old in blue, ice of 2-3 years old in green, ice of 4 years old in yellow, and ice older than 4 years in white.

Recent decline in sea ice

Several variables describe the Arctic sea ice cover: extent, concentration, volume, thickness, and age. Sea ice extent (ocean area with ice concentration of at least 15%) is the main variable used to describe the state of the Arctic ice cover and is accurately monitored by satellites since 1979 (Perovich et al., 2012). Sea ice extent has dramatically declined in the last decades and the minima of the last seven summers (2007-2013) were the seven lowest since 1979 (National Snow and Ice Data Centre, 2013b). The record low of 3.4 million km² was reached on 13 September 2012 (Parkinson and Comiso, 2013; Figures 10 and 11). This is the lowest ice coverage in at least the last 112 years (Parkinson and Comiso, 2013). It is also interesting to note that although the summer minimum sea ice extent is declining rapidly, the winter maximum is relatively stable, although it is increasingly composed of first year ice. An animation of the change in ice extent is available online at http://nsidc.org/data/virtual_globes/images/seaice_2008_climatology_lr.mov.

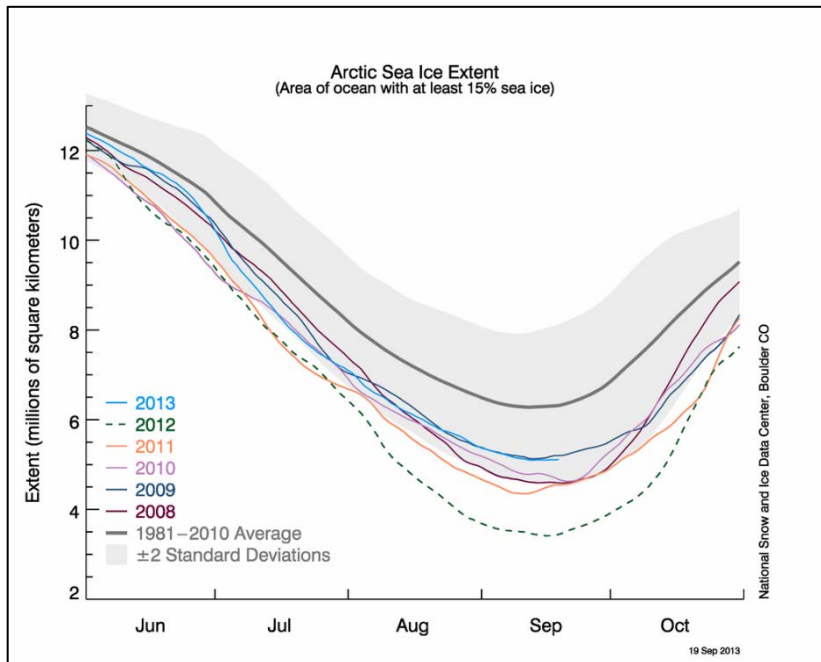


Figure 10. Comparison of the Arctic sea ice extent from 2008 to 2013 with the 1981-2010 mean (image provided by National Snow and Ice Data Center, University of Colorado, Boulder).

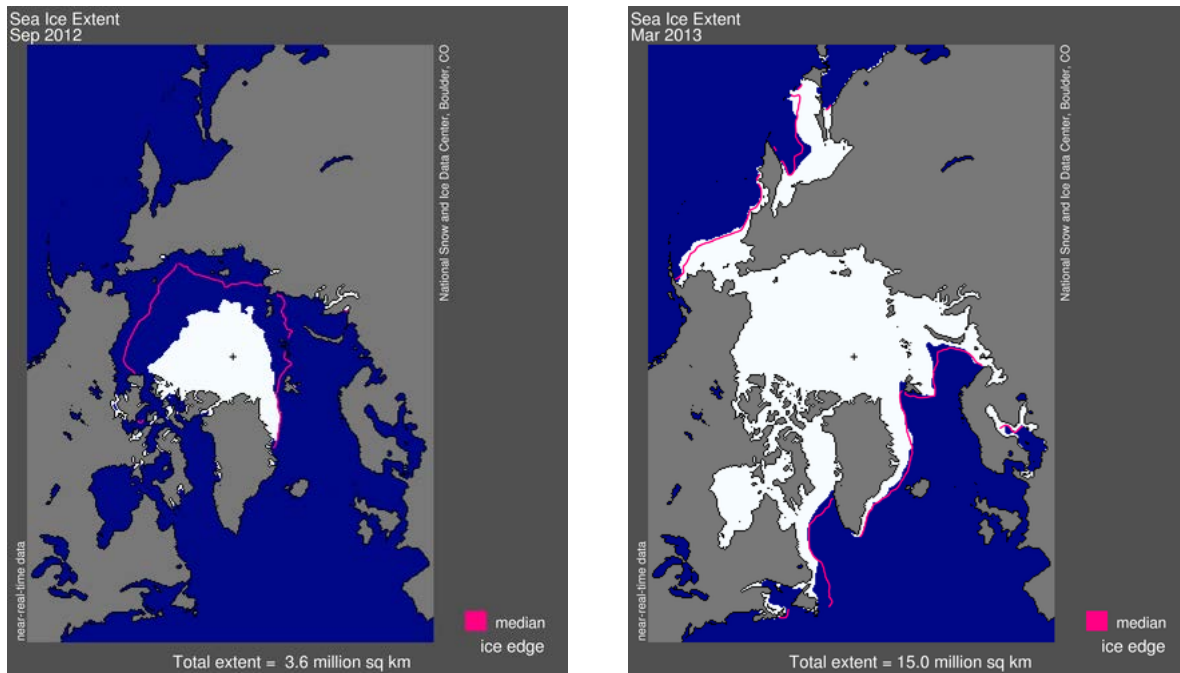


Figure 11. Arctic sea ice extent in September 2012 (left) and March 2013 (right) showing the summer minimum and the winter maximum in sea ice extent, respectively. The magenta line indicates the median ice extent for 1981-2010. Maps are from the National Snow and Ice Data Center Sea Ice Index, http://nsidc.org/data/seaice_index.

In addition to a decline in Arctic sea ice extent, the ice cover is now younger, thinner and the ice volume is reduced. A 32-year record (1980-2011) of estimated sea ice age showed a decrease in multiyear ice extent. Multiyear ice extent has decreased at -15.5% per decade (Comiso, 2012) and the extent of particularly old age sea ice that has survived at least four summers, declined from 50% to 10 % (Maslanik et al., 2011). This implies a reduction in the average ice thickness. A study found that the mean Arctic sea ice thickness declined from 3.64 m in 1980 to 1.89 m in 2008 (Kwok and Rothrock, 2009). Younger and thinner sea ice cover leads to a significant reduction in the sea ice volume (Schweiger et al., 2011). First year ice is also the most likely to melt during the summer (Parkinson and Comiso, 2013), is more vulnerable to wind forcing and is more mobile (Rampal et al., 2009). Where sea ice melts during summer, annual sea ice is formed in the next winter.

Figure 11 also illustrates that the ice that remain at the minimum summer sea ice extent is mostly located within and north of the LIA. Regional western and eastern Arctic weekly ice cover (Figure 12) similarly illustrate that the Canadian Arctic Archipelago and the western coast of Greenland are never completely ice-free. Nonetheless, the graphing tool is not indicating data on specific areas and does not include the northern coast of Ellesmere Island and Greenland. The coast of Ellesmere Island was reported to be fringed with multiyear land fast sea ice that is typically several decades of age (Jeffries, 1992). However, loss of this type of ice has also been reported in recent years and open water of several km off the coast along the shores and in bays and fiords is now occurring (Copland et al., 2007; Vincent et al., 2009). Similarly, models also project that the summer sea ice cover of the LIA region will remain the longest and will be the thickest of the entire Arctic (Huard and Tremblay, 2013). Shifts in ecosystems in LIA can be expected to be less rapid and of a smaller amplitude compared to elsewhere in the Arctic. However, specific changes are already documented and changes observed elsewhere in the Arctic may be relevant for the LIA.

Models projected that the loss in Arctic sea ice will continue over the next decades under an ongoing air temperature warming trend. It is projected that the September sea ice will disappear completely over the period 2045-2055 (Huard and Tremblay, 2013).

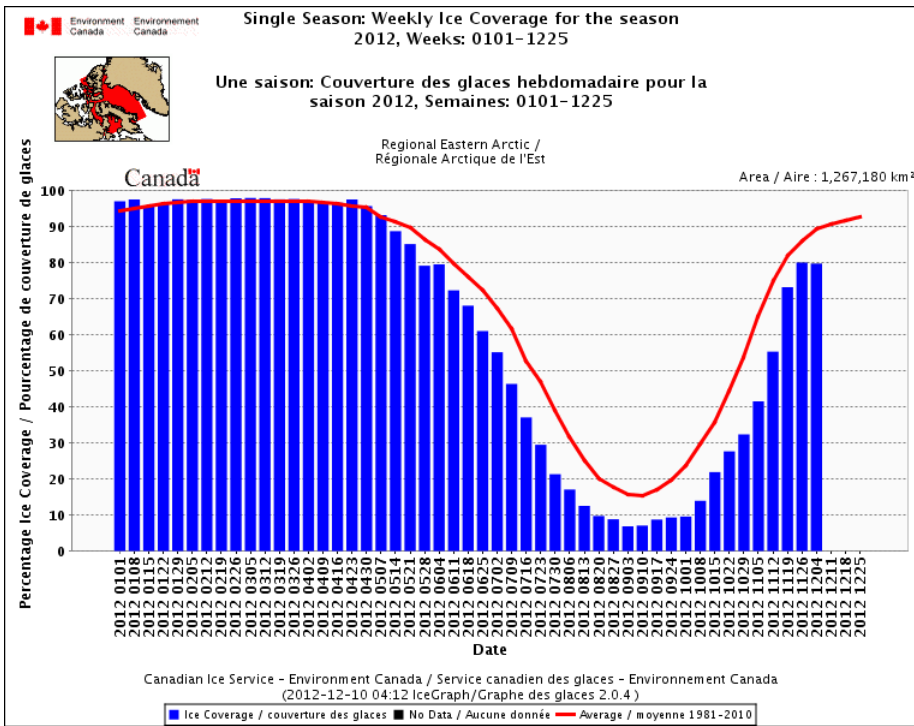
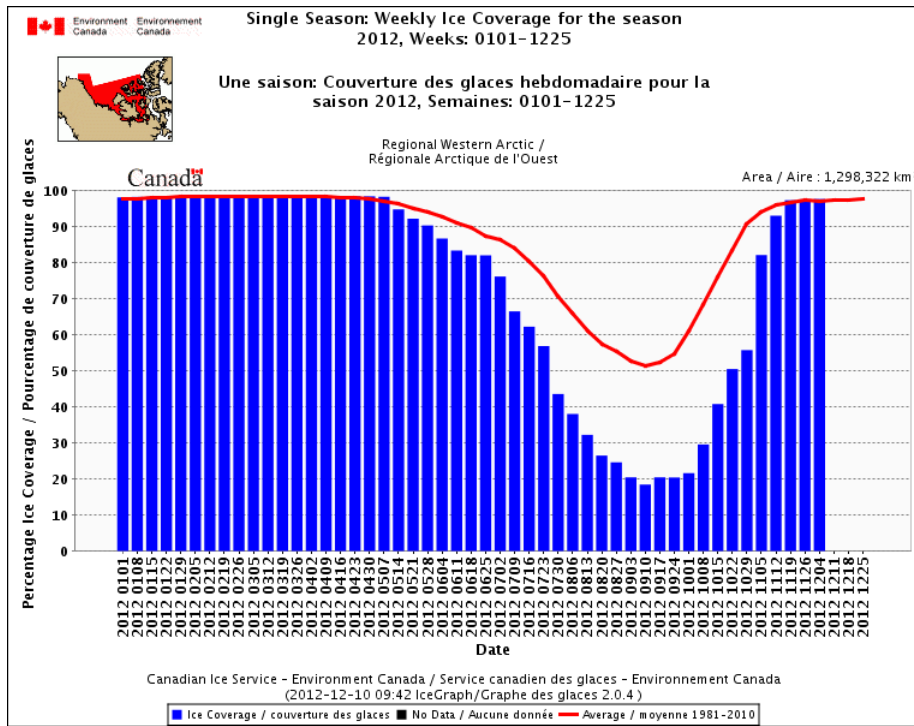


Figure 12. Regional western (upper panel) and eastern (lower panel) Canadian Arctic weekly ice cover in 2012 (Environment Canada, IceGraph Tool, 2012).

The roles of sea ice

Sea ice is the most dominant feature of the Arctic marine environment. It influences the climate locally and globally. Sea ice has an impact on albedo, ocean circulation via brine expulsion, and ice melting influences the transport of cold and low salinity waters with ice drift. In addition, ice cover controls atmospheric-ocean exchanges.

Sea ice albedo is an important positive feedback process for the global climate. Albedo is a unitless measure of how well a surface reflects solar energy. A white surface has a high albedo (i.e. 1) while a black or transparent surface has a low albedo (i.e. 0) since most of the light it receives is absorbed and converted into heat. Arctic sea ice has an albedo of around 0.7 while ocean open water albedo is around 0.06 (Huard and Tremblay, 2013). Climate warming causes the sea ice cover to melt and increase the open water area. This results in the reduction of the surface albedo and decreases the amount of solar energy (light and heat) that is reflected back to space. Areas of open water absorb more solar energy and contribute to further warming and more sea ice melt. This process contributes substantially to the Arctic amplification of climate change.

Sea ice also affects the movement of ocean waters. When sea ice forms, brine is pushed into the ocean water just underneath the ice. This water has a high concentration of salt and is denser than surrounding ocean water, thus sinks. By this process, sea ice contributes to the ocean's global thermohaline circulation (Figure 13). Changes in the amount of sea ice formed can disrupt normal ocean circulation, thereby leading to changes in the global climate. In contrast, when the sea ice cover melts in the Arctic Ocean or in Fram Strait, it creates a layer of freshwater on top of the ocean water. Since freshwater is less dense than seawater, it tends to stay at the top of the ocean. This lower density discourages the normal process of sinking at high latitudes that supports the thermohaline circulation.

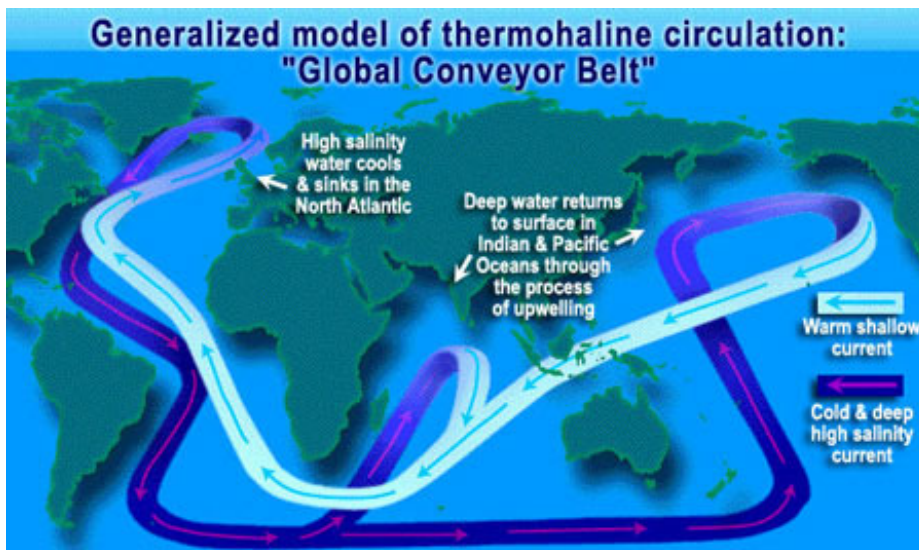


Figure 13. The thermohaline circulation (image courtesy of NASA GSFC; National Snow and Ice Data Centre, 2013a).

Ice cover also controls atmosphere-ocean exchanges. It isolates the upper ocean from direct wind forcing which physically protect the surface water from mixing and damps surface wave motion. Ice cover also protects the coasts from erosion by bigger wave heights leading to greater coastal erosion and recessions. It also served as an efficient thermal insulator. The Arctic's atmosphere is very cold during the winter while the ocean is relatively warmer. The sea ice cover prevents the heat in the ocean from warming the overlying atmosphere. Nonetheless, heat can escape from leads and polynyas. As the ice melts, energy and moisture move out of the ocean to the atmosphere resulting in more storms such as cyclones (cells of air that rotate in a counter-clockwise direction), characterized by high winds and precipitation.

The sea ice cover also plays important roles for Arctic marine ecosystem. Similar to the snow cover, the ice cover influences how much light will penetrate to the under ice ecosystems and affects the timing and extent of ice algal and phytoplankton production. The recent thinning of the sea ice cover contributes to an increase in light transmission, which is mirrored in greater primary production by phytoplankton (see section 8.1 (Arrigo et al., 2012)). The different components of the Arctic marine biodiversity use and depend on sea ice in different ways. Sea ice cover is the substrate for organisms that thrive within it (see section 8.2). Two fish species use the sea ice cover as habitat, protection from predators and a place to spawn (see section 8.5). Marine mammals that live in the Arctic all year long rely on sea ice as a platform for resting, hunting or breeding (see section 8.6). Loss of Arctic sea ice will push these organisms to adapt their life cycle in order to survive, and the sea ice diversity will change as multiyear ice is replaced by first-year ice. The impacts of a reduced sea ice cover for species that use sea ice occasionally (e.g. seabirds, whales present in the Arctic only during summer) is less clear. The decline in the sea ice cover implies that islands will be separated by open water longer during summer and will prevent terrestrial animals to migrate easily between habitats.

Other impacts of a reduced sea ice cover will be more indirect. Navigation through the Northwest Passage will be easier. This could result in shipping impacts, including spills of bunker fuel oil, or hazardous cargoes (Arctic Council, 2009). Subsistence harvesting practices will have to change in some communities, as traditional over-ice routes become unstable during shoulder seasons, and prey change their patterns.

7.3 Marginal ice zones, flaw leads and polynyas

Some features of the sea ice environment are of particular ecological significance since they are highly productive: marginal ice zones, flaw leads and polynyas (Figure 14).

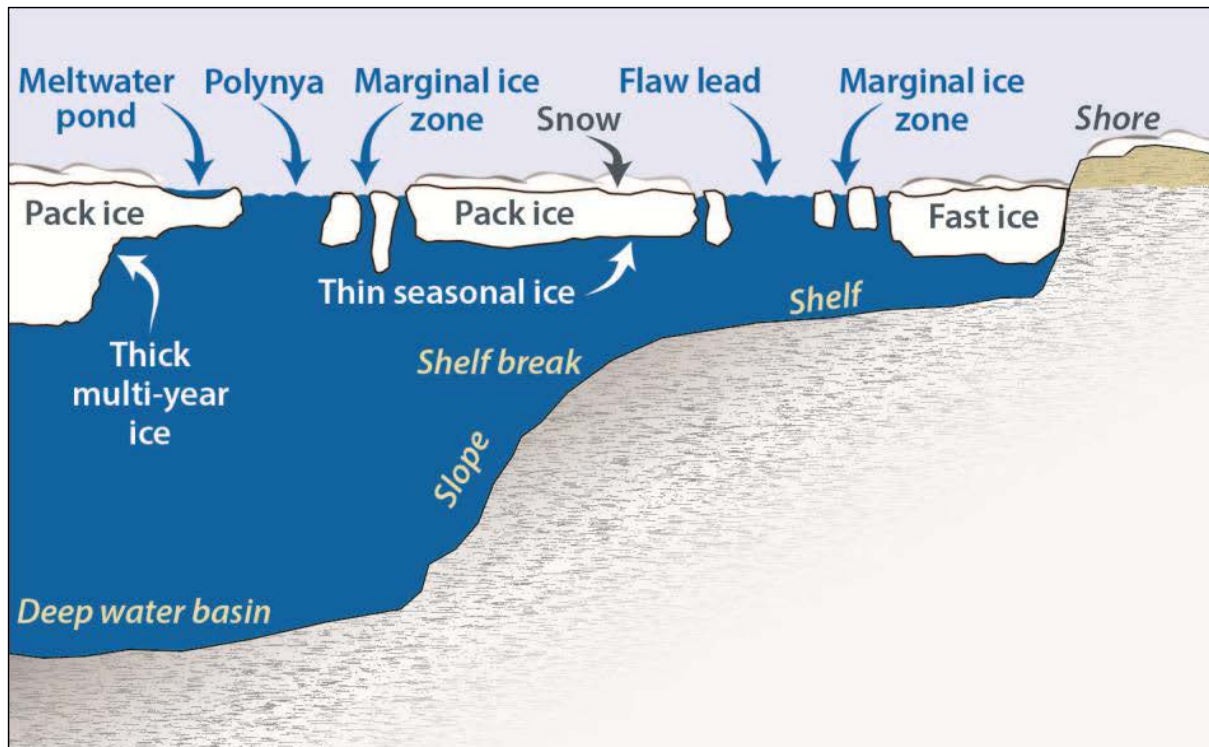


Figure 14. Some features of the sea ice environment (CAFF, 2013b).

Marginal ice zones

The marginal ice zone is the transition area from ice-covered seas to open water, where sea ice is significantly influenced by the action of waves. Waves are responsible for the break-up of ice floes (drifting pieces of sea ice) and determine the extent of the marginal ice zone. They represent narrow zones that are 25-100 km wide (Dumont et al., 2011). These areas are complex and variable sea ice environments. Swells and waves are lower as they enter the marginal ice zone. Typical marginal ice zone conditions are found along the southern edges of the ice pack in the Bering, Greenland, Chukchi, and Barents Seas, and in Baffin Bay (Roed and O'Brien, 1983).

Marginal ice zones are recognized as biologically productive regions, where large numbers of phytoplankton, zooplankton, seabirds and marine mammals converge. In the Arctic, this is due to upwelling occurring at the sea-ice edge (Smith et al., 1987). Upwelling is the process by which deep, nutrient-rich waters rise to the surface due to the action of the winds or currents. Arctic surface waters are typically reduced in nutrient concentrations and the water column is highly stratified, which limit the growth of phytoplankton. Upwelling, created by the action of the wind on the open water, inject nutrients into the surface waters.

A significant implication of the recent decrease in sea ice extent has been the retreat of the ice edge away from the coast and continental shelves (Lee et al., 2012). At the end of the summer, when sea ice extent reaches its minimum, the marginal ice zone is located above the deep ocean

which was until recently perennially ice covered (Lee et al., 2012). As an example, the recent decrease in sea ice extent has resulted in the production of a substantial marginal ice zone in the deep Beaufort Sea (Lee et al., 2012). Extending open water conditions in the marginal ice zone permit more direct connection with the atmosphere and can have implications for the upper ocean structure and sea ice evolution.

The LIA as described in Figure 2 does not include marginal ice areas but these areas will be increasingly present in its surrounding as sea ice extent decreases.

Flaw leads

Flaw leads are areas of unconsolidated ice or ice-free waters between the mobile multiyear pack ice and the fixed coastal fast ice (Deming and Fortier, 2011). The circumpolar flaw lead is a perennial feature of the Arctic observed throughout the winter (Figure 15). It consists in a large crack in the ice at the periphery of the Arctic Ocean, along the coastlines of the shallow seas that surround the deep Arctic Ocean basins (Deming and Fortier, 2011). The circumpolar flaw lead in the LIA area is relatively narrow since multiyear landfast sea ice is still substantial in this area even during the summer. In some areas, the circumpolar flaw lead widens significantly in spring and summer and forms recurrent polynyas where biological productivity is increased (Deming and Fortier, 2011). Flaw leads are also areas of high ice production (Dethleff et al., 1998).

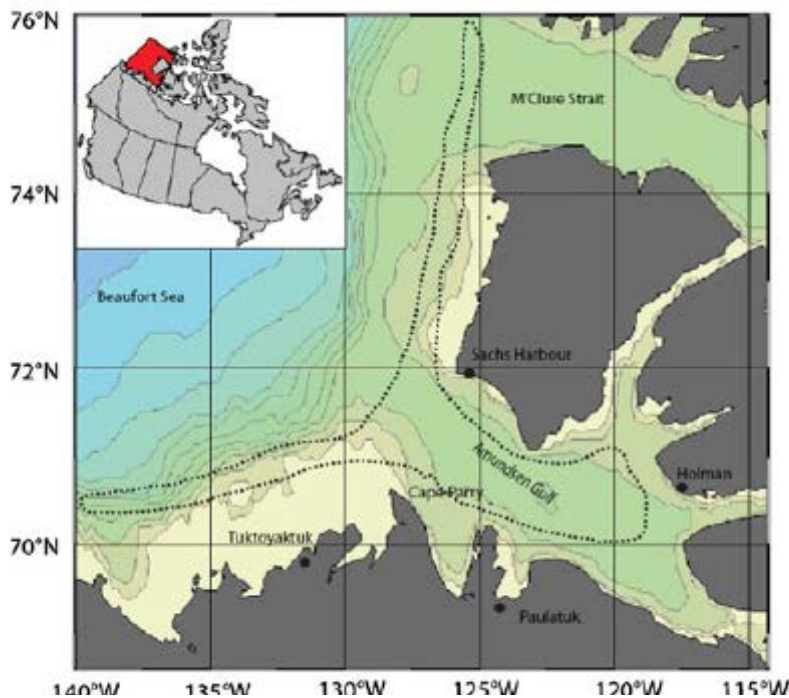


Figure 15. Map of the circumpolar flaw lead (indicated by the grey dashed line) in the Beaufort Sea and local communities (Barber et al., 2012b).

The ice edges of a flaw lead are areas of high biological productivity (Barber et al., 2012a). Upwelling is caused by strong winds which mixes water layers and introduces deeper water replete with nutrients close to the surface, making them available for biological growth (Barber et al., 2012a). As the sea ice cover and volume are decreasing with a warming climate, the open-water season at the periphery of the Arctic Ocean is lengthening and the circumpolar flaw lead is projected to enlarge and to last longer (Deming and Fortier, 2011). Ecosystem-wide enhancements in productivity are expected in these areas (Barber et al., 2012a).

Polynyas

Polynyas are large areas (10 - 90,000 km²) of permanently or frequently open water surrounded by thick sea ice (Barber et al., 2001b). Polynyas are generated by warm water input from below or by the action of strong winds that move away sea ice as soon as it is formed (Barber et al., 2001a; Tremblay and Smith Jr, 2007). Similar to the flaw leads, polynyas produce a lot of sea ice.

Polynyas are highly productive areas and hotspots of diversity compared to other ice-covered areas of the Arctic Ocean (Barber et al., 2001a). In most Arctic waters, low winter sun and a thick ice cover limit primary production. However, the open waters associated with polynyas permit phytoplankton blooms in early spring and, this increased algal production is reflected in high densities of zooplankton (Arrigo and van Dijken, 2004). They are a very important habitat for high densities of birds and mammals that use these areas for feeding, mating, spawning and overwintering grounds (Heide-Jorgensen et al., 2013). This high productivity at all trophic levels is mirrored by a great export of carbon and nutrients to the seafloor at the end of the bloom season (Grant et al., 2002). Polynyas are also of special significance for air-breathing Arctic organisms (Heide-Jorgensen and Laidre, 2004). They form breathing holes for narwhal, beluga, walrus and seals species. Areas adjacent to polynyas can form suitable hunting ground for polar bears because of the aggregation of seals. Also numerous seabirds use polynyas for hunting and major winter bird colonies in the Canadian islands are located adjacent to polynyas (e.g. the North Water Polynya). Upwelling and vertical mixing of water masses entrain nutrients from below into the surface waters that can become rapidly exhausted in nitrate during blooms (Tremblay and Smith Jr, 2007). Polynyas are often described as polar oases. Archaeological records also show that Inuit used the shores of polynyas as a predictable food source since prehistoric times as Inuit settlements are often found in the vicinity of persistent polynyas (Henshaw, 2003; Pedersen et al., 2010).

The largest polynya in the LIA region is the North Water Polynya (NOW) in northern Baffin Bay between Canada and Greenland (Figure 16). This polynya forms each spring and is the largest and most productive recurring polynya in the Arctic (Deming et al., 2002; Dumont, 2012). Its formation is due to a combination of factors: strong northerly winds blow the ice downstream of an ice bridge that forms at the constriction point between Greenland and Ellesmere Island, leaving behind an area of open water (Dumont et al., 2010). The former Northeast Water polynya (NEW), off the northeast coast of Greenland, is no longer considered a polynya due to changed ice conditions (Kovacs and Michel, 2011). The NEW polynya was only moderately productive due to

little replenishment of nutrients (Schneider and Budeus, 1995). Several polynyas smaller than the NOW can be found within the LIA region (Niemi et al., 2010).

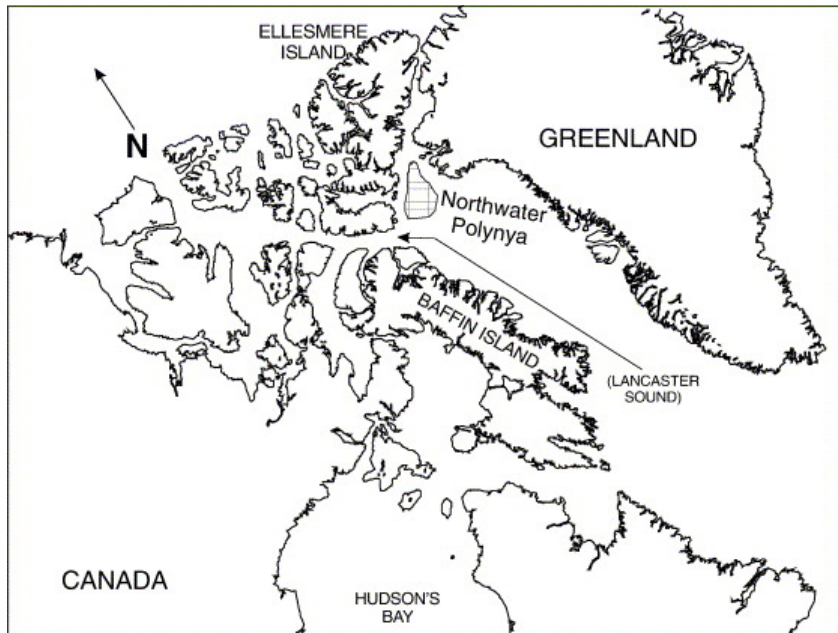


Figure 16. Location of the Northwater Polynya between Greenland and Ellesmere Island in Baffin Bay in May/June (map from Campbell et al., 2005).

Polynyas are dynamic features that vary in timing, extent and duration from year to year (Dumont, 2012). Moreover, a warmer climate associated with a reduction in thick sea ice cover may affect polynyas in different ways, although it is expected that they will more commonly decrease in duration (Smith Jr and Barber, 2007). For instance, trends over the last 4 decades show that the NOW polynya is occurring less frequently and break-up earlier. Also, its formation is due to the presence of thick sea ice and a slightly warmer

Arctic winter could lead to its demise (Dumont, 2012). In contrast, the Wrangel Island polynya, located in the Chukchi Sea, has more than doubled in extent over the last 30 years (Moore and Pickart, 2012). New polynyas could be generated at other sites (Ingram and Carmack, 2006). Species reliant on polynyas will need to adapt where they go and when if they are to remain connected to these areas. Alternatively, they will have to adapt to less productive habitats (Ingram and Carmack, 2006).

7.4 Ice shelves

Ice in bays and fiords can become very thick since less dynamic conditions in wind and current, compared to offshore, have permitted ice growth over periods lasting from tens to thousands of years. Ice shelves are defined as thick (> 10 m) ancient ice attached to the coastline (multiyear landfast sea ice) and floating on the sea (Veillette et al., 2008). Ice shelves are in hydrostatic equilibrium with the ocean and hence, only ~ 10% of their total thickness is emerging above sea level (freeboard) (Mortimer, 2011). Ice shelves are a predominant feature of the Antarctic, where they border ~ 55% of the coastline (Dowdeswell and Jeffries, 2011), but they are also present in the Arctic (Eurasian High Arctic, Greenland and the Canadian High Arctic) (Dowdeswell, 2011). In the Canadian High Arctic, ice shelves are found on the northern coastline of Ellesmere Island. These are formed, on the underside, by the accretion of basal ice and, on the upper side, by the accumulation of ice from snow and rain precipitations. Ice shelves loss processes include melting and calving events that create ice islands (Jeffries, 2011; Figure 17). In Greenland and Antarctic,

however, ice shelves are composed of the floating extensions of glaciers floating off the continents (Williams and Dowdeswell, 2001).

Ice shelves along the northern coastline of Ellesmere Island have undergone rapid attrition of more than 90% in extent over the last decades. At the beginning of the 20th century, a single ice shelf covering around 8,900 km² was reported to fringe this coastline (Vincent et al., 2001). This ice shelf subsequently deteriorated into several smaller ice shelves and accelerated major changes occurred since 2000 (Mueller et al., 2008; Vincent et al., 2011). At the end of the summer of 2008, there were four remaining main ice shelves in Canada, totalling an area less than 675 km² (Figure 18; Mueller et al., 2008; Vincent et al., 2011). In addition, the Ward Hunt Ice Shelf, the largest of the four, has undergone substantial fractures during the summers of 2010 and 2011 (W. Vincent, pers. comm.). Milne Ice Shelf is now the thickest in Canada with a maximum thickness over 90 m and a mean thickness of 55 m (Mortimer, 2011). Warmer air temperature, by controlling ice melt, is playing a role with the numerous calving events and the disintegration of the remnant ice shelves. Offshore winds also move fractured ice away from the coast and no longer provide a barrier to the waves that batter the ice shelves (Copland et al., 2007; Mueller et al., 2008; Veillette et al., 2008). The decline in the number, thickness and area of Canadian ice shelves may be irreversible given the current and projected climate warming and that multiyear landfast sea ice is also decreasing along the northern coastline of Ellesmere Island (Copland et al., 2007).

Ice shelves provide the physical structure for unique ecosystems. Cold-tolerant microbial communities occur in association with sediments on the ice shelves' surface (Mueller et al., 2006). The surface morphology of ice shelves is characterized by undulations parallel to the coast that would be caused by the alongshore winds (Figure 19; Hattersley-Smith, 1957). During the summer, meltwater flows in the troughs of these undulations and creates long (up to 15 km), thin (10-20 m), and shallow lakes (maximum of 3 m) that are also characterized by their microbial mat communities (Mueller et al., 2006). DNA profiling demonstrated that the mat microbial communities were composed of all three domains of life (Bacteria, Archaea and Eukarya) and viruses (Varin et al., 2010, 2012). Moreover, when an ice shelf completely dams a fiord or an embayment, a lake called "epishelf" may be formed on the landward side (Veillette et al., 2008). These ice-dammed lakes are highly stratified since a layer of freshwater from snow and ice melt floats on top of sea water. These waters do not mix because of their different densities, and because the perennial ice cover stops wind from mixing them (Veillette et al., 2008). There is currently only one known remaining Arctic epishelf lake, in Milne Fiord (Veillette et al., 2011). Ice shelves and their associated epishelf lakes are vulnerable Arctic ecosystems that have become extremely rare and will likely become extinct in the coming decades (Veillette et al., 2011).

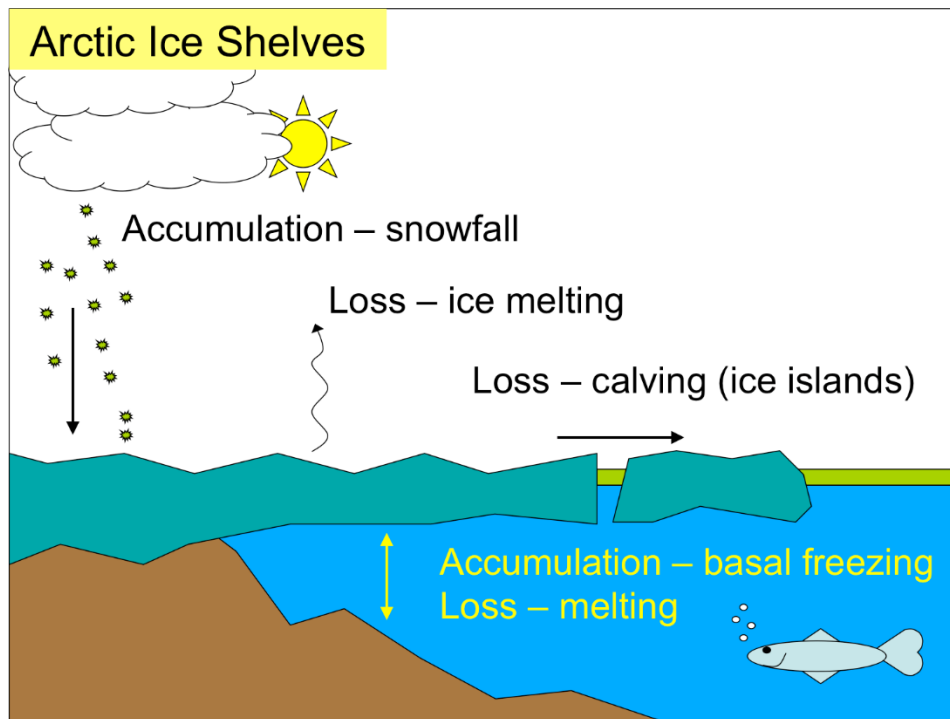


Figure 17. The formation and loss processes of most Canadian Arctic ice shelves (figure courtesy of Derek Mueller).

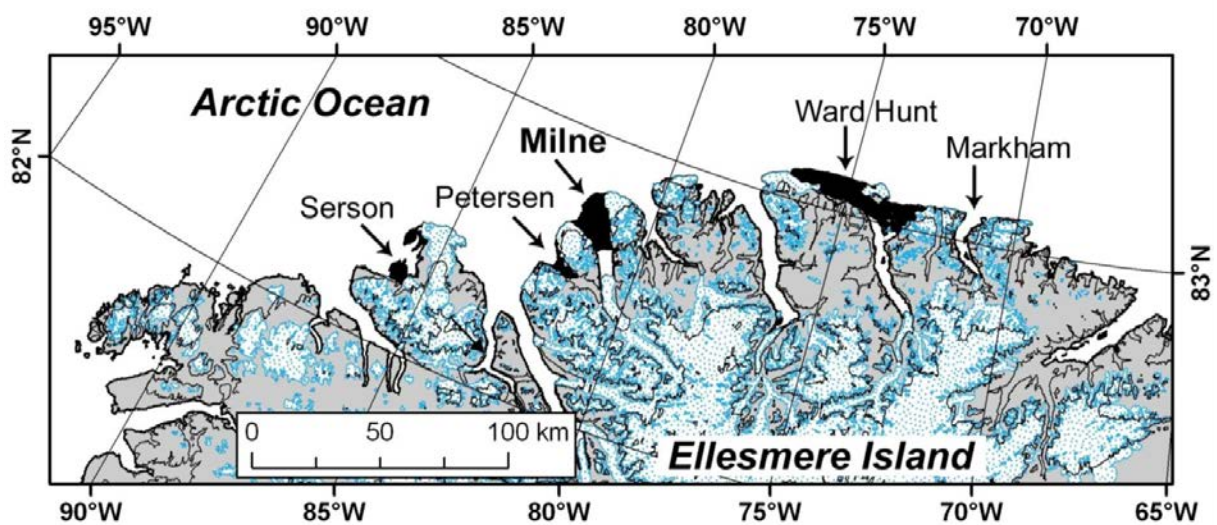


Figure 18. Map of the northern coastline of Ellesmere Island showing the location of the 4 remnant ice shelves at the end of summer 2008 (note that Markham Ice Shelf is completely lost)(figure courtesy of Warwick Vincent).



Figure 19. The Ward Hunt Ice Shelf in August 2008 when the characteristic undulations were clearly visible (Photo: J. Veillette).

8. Marine biodiversity

The Arctic Ocean provides diverse habitats for a multitude of unique life forms highly adapted in their life history, ecology and physiology to the extreme and seasonal conditions of this environment. The logistical challenges imposed by the harsh Arctic environment limit our knowledge of the marine biodiversity. This is especially true for the High Arctic where biological data are sparse and almost non-existent for some habitats (e.g. the benthos) (Piepenburg et al., 2011).

This section first presents information on Arctic marine food webs and productivity. Then, the biodiversity of the different Arctic Ocean habitats (in the ice, in the water column and on the seafloor) is overviewed. After, the biodiversity of fish, marine mammals and seabirds, and the description of key species are presented. Finally, the impacts of climate change for marine biodiversity are tackled since they are likely to affect all Arctic life on top of, within and beneath the ice, and also in the open water and on the ocean floor. A special emphasis is placed on the LIA region.

Overall, it is predicted that there will be more life but that it will be less diverse (Fortier et al., 2012). Only organisms that are adapted to low temperatures, strong seasonality, a perennial or seasonal ice cover, limiting nutrients in the stratified surface layer of the water column and a pulsed annual cycle of primary production have survived in the extreme climate of the Arctic over the last 3.5 million years. These Arctic specialists are now being challenged by more productive southern species that will migrate north. This is because individuals can inhabit areas within their preferred metabolic temperature tolerances. The southern generalists grow faster, are more fertile and achieve higher survival rates since they never had to adapt to the hostile Arctic conditions. It is predicted that these generalists will outcompete the native, specialist species (Fortier et al., 2012). Relationships among species are changing too, with new predation pressures and shifts in diets recorded for some animals.

8.1 Arctic marine food webs and productivity

Structure of Arctic marine food webs

Arctic marine food webs comprise the interconnections between microbes, algae and animals (Figure 20). Primary producers (ice algae and phytoplankton) support the base of the Arctic marine food web. They convert the energy from the sun into food energy. Then, zooplankton, such as copepods, and bacteria graze on these primary producers. In turn, carnivorous zooplankton, fish (Arctic cod) and whales feed on zooplankton. Arctic cod are the main food source of seals. Top predators such as humans, polar bears, seals and whales are then generally feeding on a combination of different species. Detritus, which typically includes the bodies or fragments of dead organisms as well as fecal material and nutrients, sink to the sediments where they support invertebrates and microbial communities. The relatively short growing season implies that consumers have a narrow window of opportunity to grow and accumulate energy reserves for winter survival and/or reproduction. Arctic marine food webs involve numerous pathways but are not considered complex compared to the food webs of more temperate systems. These food webs are considered vulnerable to perturbations (de Santana et al., 2013).

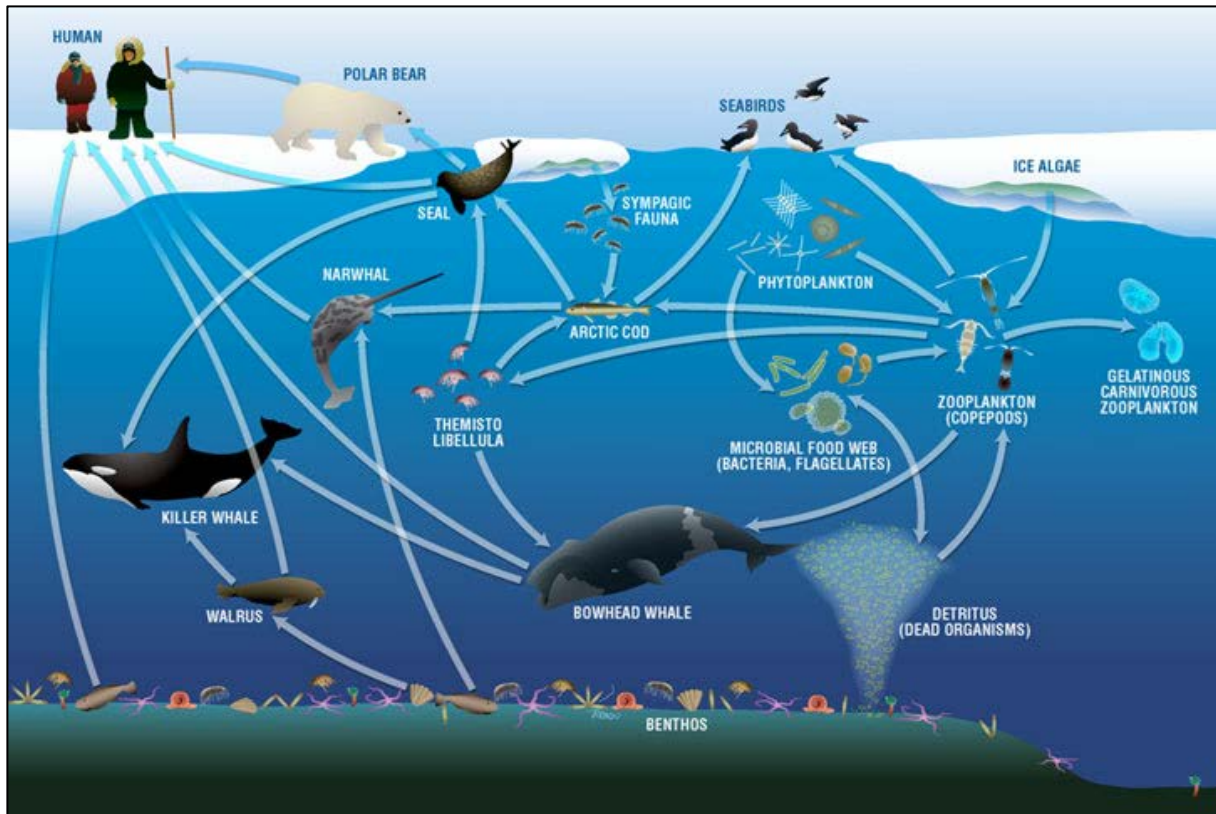


Figure 20. Representation of an Arctic marine food web (Darnis et al., 2012)

Primary production

Primary production determines the amount of food that is available to consumers. Also, primary producers, by fixing the greenhouse gas CO₂, help to reduce its burden in the atmosphere since sinking algae and detritus remove carbon from the surface waters (a process known as the biological pump). Primary production in the Arctic Ocean depends on light and nutrients (i.e. nitrate is usually limiting). It starts with the growth of ice algae as soon as a critical amount of light reaches the ice-water interface in spring. Since snow cover strongly attenuates light penetration, it influences the timing of ice algal growth. Ice algal production then blooms and ice algae synthesize fats. At the onset of ice melt, fat-rich ice algae are released in the water column and provide high energy food for the zooplankton, and eventually to the seafloor, at a time when little food is available (Tremblay et al., 2012). Phytoplankton then take over as the dominant primary producers. The intensity of the late spring or early summer phytoplankton bloom is controlled by the availability of nutrients, which are readily depleted from the surface layer. The surface layer derived from ice melt is relatively less dense and restricts the mixing with nutrient-rich water from deeper waters. The primary production declines during summer and until the ice forms in the fall. A second bloom can occur in polynyas where ice growth is delayed (Tremblay and Smith Jr, 2007).

This classical view of the annual cycle of primary productivity in the Arctic Ocean, presented in the above paragraph, is challenged by some works that report phytoplankton blooms under the ice cover over continental shelves in Barrow Strait in the Canadian Arctic Archipelago (Fortier et al., 2002) and in other seas (Arrigo et al., 2012; Mundy et al., 2009; Strass and Nöthig, 1996). The recent thinning of the ice cover and the proliferation of melt ponds increase light transmission and make it possible for the required amount of light to reach underneath the ice (Arrigo et al., 2012). This suggests that under-ice phytoplankton blooms may be more widespread over nutrient-rich Arctic continental shelves and that satellite-based estimates of annual primary production in these waters may be underestimated by up to 10-fold (Arrigo et al., 2012).

Primary productivity is low in the Arctic Ocean and in the Canadian Arctic Archipelago compared to other oceanic environments located at lower latitudes (Niemi et al., 2010). This is explained by the reduced availability of light since the sun is up only during the summer and, the sea ice cover controls the amount of light that reaches the water column. Snow on the ice cover also contributes to reduce light penetration. Primary productivity is also extremely variable among different areas of the Arctic Ocean. Figure 21 illustrates the depth integrated primary production from 1998 to 2007. Depth integrated primary production is used since vertical profiles of primary production at many sites in the Arctic Ocean revealed persistent subsurface peaks during most of the summer period (Hill et al., 2013). The annual integrated primary production was estimated to be a minimum of $466 \pm 94 \text{ Tg C yr}^{-1}$ and a maximum of $993 \pm 94 \text{ Tg C yr}^{-1}$, when corrected for subsurface production (Hill et al., 2013). Coastal seas account for 75% of annual integrated primary production while the central basin and Beaufort northern sea were the regions with the lowest annual integrated productivity, due to persistently stratified, nutrient-depleted and ice-covered conditions. The highest primary production is located in the northern Bering Sea and southern Chukchi Sea, and this is explained by the more nutrient-rich waters of the Pacific Ocean compared to the Atlantic Ocean. The overall LIA region is moderately productive with the NOW polynya being a hotspot of primary productivity (Figure 21). This variation in primary productivity in the Arctic Ocean is influenced by latitude, seasonal and multiyear sea ice and snow cover, depth and stability of the surface mixed layer, discharge of inorganic sediments (causing light attenuation) and nutrients from rivers and water circulation patterns (Gosselin et al., 1997; Pabi et al., 2008). Ice algae contribute around 60% of the entire primary production (sea ice and water column) in the central Arctic Ocean but only 3% in the coastal seas (Gosselin et al., 1997). However, primary productivity within and under the sea ice may increase with higher light transmission through thinning sea ice (Boetius et al., 2013). Primary productivity in the coastal seas and in the deep central basin are also very different in terms of timing and composition (Tremblay et al., 2012).

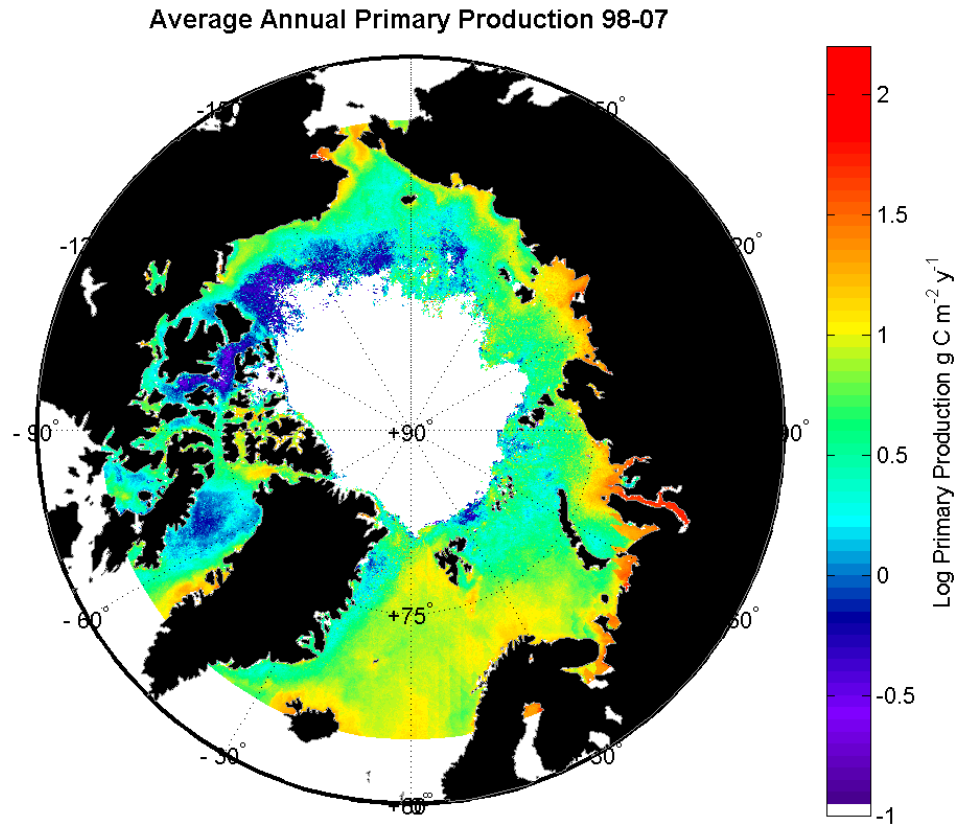


Figure 21. Annual pan-Arctic primary production taking into account the subsurface peaks in primary production (i.e. depth integrated primary production) using SeaWiFs based model for 1998-2007 (based on Hill et al., 2013) .

Implications of a reduced Arctic ice cover for primary productivity

In the next decades, removal of the ice cover during summers in the Arctic Ocean may increase primary productivity, especially in areas where multiyear ice was present (Arrigo et al., 2008). Similarly, Michel Gosselin, a biological oceanographer specialist of the Arctic Ocean, predicts that phytoplankton production in the Arctic could increase up to 10 times in nutrient-rich regions and three times in nutrient-poor regions as climate warming continues (Gosselin et al., 2012). This increase in primary productivity is associated to a better penetration of light in the water column due to more areas of open water and to a longer phytoplankton growing season. However, this increase might slow as the surface nutrients become exhausted (Arrigo et al., 2008), unless upwelling of deep nutrient-rich waters in coastal areas become initiated as multiyear ice cover retreats offshore and favourable winds blow (Tremblay et al., 2012). Therefore, flaw leads and polynyas will continue to play a crucial role in primary production. Nonetheless, the strong stratification of the central Arctic Ocean will likely persist (Tremblay et al., 2012). Although the Arctic sea ice can be productive (Gosselin et al., 1997), the ice-free pelagic (i.e. the water column) environment is typically much more productive. Enhanced primary productivity can strongly

increase the efficiency of the biological pump and counteract the effects of global warming (Fortier et al., 2012). These changes in primary production will have consequences for the entire Arctic Ocean marine food web and the yield of harvestable resources in the Arctic Ocean. It is predicted that there will be increased fish and marine mammals for Northerners, and exploratory small-scale commercial fisheries by local communities is underway (CBC News, 2013). However, it will most likely not be sufficient to support industrial fisheries (Tremblay et al., 2012).

Implications of a reduced Arctic ice cover for ecosystem structure

Changes in the extent and duration of the Arctic sea ice cover may influence ecosystem structure by modifying the coupling between the pelagic and the benthic (i.e. the seafloor) systems (Figure 22; Arrigo et al., 2008). Under abundant sea ice conditions, as it was observed until recently, Arctic marine ecosystems are strongly influenced by ice algal production that starts as soon as enough light reaches underneath the ice. Ice algal production then blooms and when the ice cover melts, ice algae are released in the water column and are grazed by zooplankton. However, the pulse in ice algae is large and the zooplankton do not graze all of it and the remainder falls to the seafloor and can be consumed by benthic communities. On the other hand, an earlier ice break-up in Arctic spring could potentially shift the ecosystem from the current benthic dominated system towards one where more energy is directed towards pelagic food webs (Figure 22; Carroll and Carroll, 2003). Under this scenario, the release of ice algae during ice melt would be earlier and smaller. The zooplankton could graze almost everything and little would be left to sink to the sediments. Phytoplankton could subsequently be available in a less pulsed manner and the zooplankton would graze a large proportion of it and less particulate matter would be exported to benthic communities (Wassmann and Reigstad, 2011). However, this scenario assumes that zooplankton grazers would still be synchronized with the availability of ice algae.

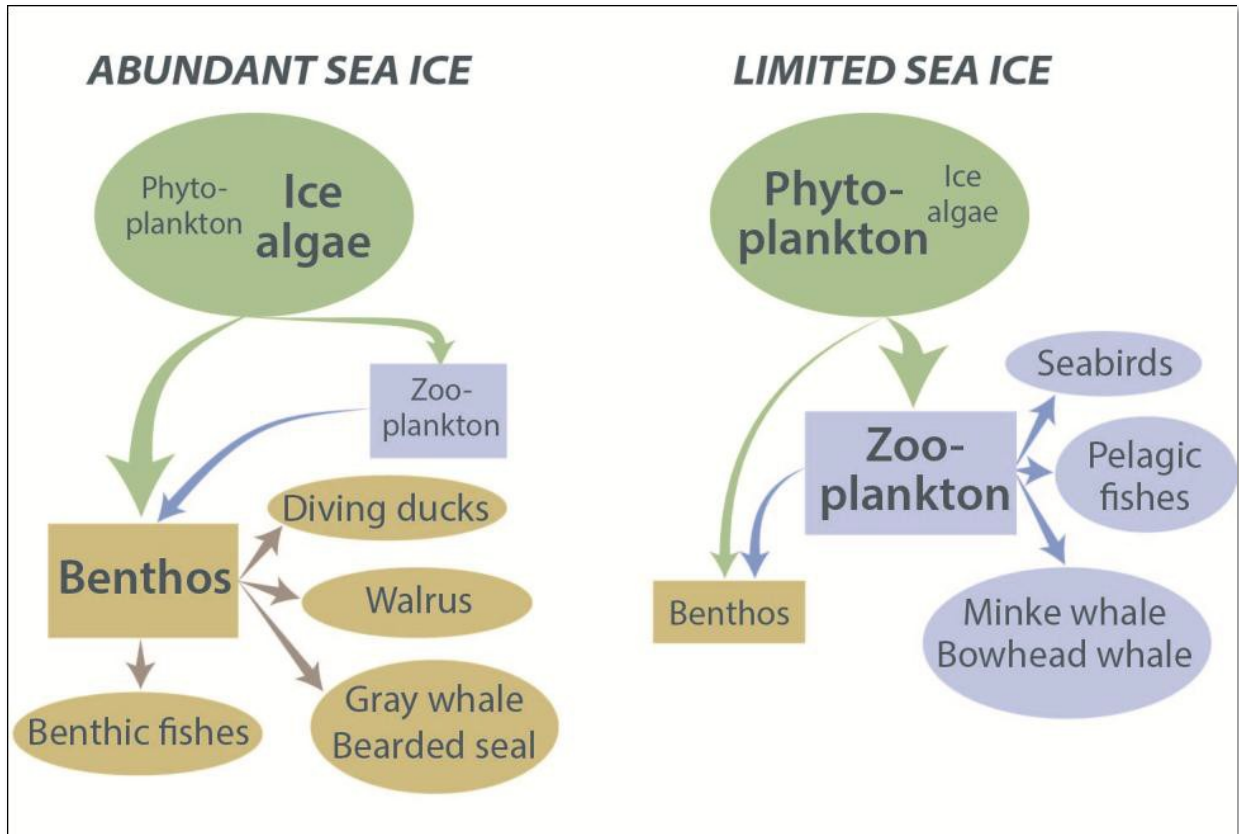


Figure 22. The diagram on the left illustrates an ecosystem strongly influenced by ice algal production under abundant sea ice conditions, while the diagram on the right shows an ecosystem dominated by phytoplankton production that may result from reduction of sea ice (figure from CAFF, 2013).

It is also possible that ice algal communities would be released in the water column at a time when zooplankton abundance is relatively low. This potential mismatch between primary production and zooplankton grazing would have negative consequences for the reproductive cycles of key zooplankton communities, and, eventually, for the entire Arctic marine ecosystem. This is explained by the reliance of zooplankton for the high-quality food that is produced during the two primary production blooms (1. ice algae bloom under the ice cover in late spring; 2. phytoplankton bloom just after the ice break-up) (SØReide et al., 2010). Nonetheless, a recent study indicated that zooplankton showed a high level of activity during winter, well before the spring release of ice algae (Darnis et al., 2012). The authors suggested that zooplankton are well adapted to variability in the timing of the primary production season and that extreme mismatch between primary production and secondary production is unlikely. Nevertheless, a mismatch between primary production and zooplankton grazing would reduce the grazing losses by the zooplankton and increase the sinking flux of particulate matter from the sea ice to the sediments, enhancing benthic production (Michel et al., 2006). Hence, the relative importance of ice algae and phytoplankton for zooplankton and benthic communities would depend on the rate at which the algae are released from the sea ice or the phytoplankton produced in the water column and on the abundance of zooplankton at specific times. At higher trophic levels, seabirds and mammals have evolved to

use the seasonal pulse in productivity by migrating to the Arctic at the most productive time of the year to breed, raise their young and feed. They will have to adapt to the changing conditions (Arrigo et al., 2008).

8.2 Biodiversity in the sea ice

The sea ice cover is a dynamic living system. It is a substrate for diverse and abundant organisms that thrive in sea ice (Figure 23; Krembs and Deming, 2011). The sea ice biota consists of a complete food web and observed taxa include viruses, archaea, bacteria, protists, and multicellular organisms (worms and crustaceans small enough to navigate the brine channels) (Bluhm et al., 2011b). Microorganisms, nutrients and other constituents are incorporated into sea ice as the ice is formed. Larger organisms are selectively scavenged from the water column into the sea ice at the time of its formation (Kovacs and Michel, 2011). Sea ice organisms are assumed to be the founding members for the development of the ice-algal bloom that occurs in spring with the seasonal increase in solar radiation.

Multiyear and first-year sea ice communities differ substantially (Bowman et al., 2012). First-year ice supports more organisms than multiyear ice. This is due to the greater presence of pores and brine channels that offer more habitats than does multiyear ice (Kovacs and Michel, 2011). Dramatic decreases in the extent of Arctic multiyear ice suggest that this environment may disappear in the next decades and be replaced by ecologically different first-year ice (Bowman et al., 2012). This may result in higher biomass of sea-ice associated organisms available for upper trophic levels before light reaches the surface waters in spring (Poulin et al., 2011).

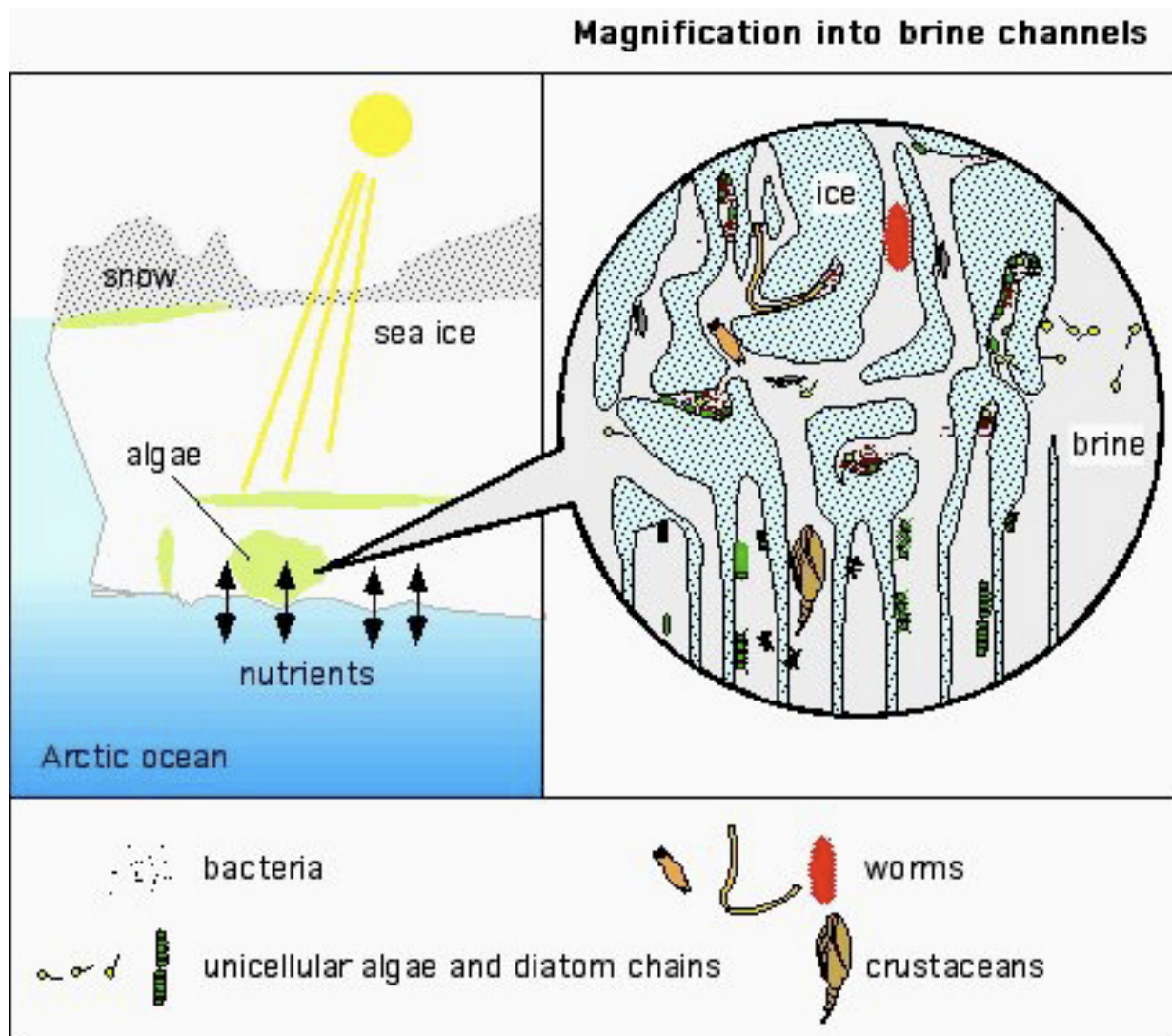


Figure 23. The flourishing life within the briny habitat of sea ice. The ice specific ecosystem includes bacteria, viruses, unicellular algae, diatom chains, worms and crustaceans (from www.arctic.noaa.gov).

Sea ice is important as a habitat for photosynthetic algae. They can be present on the upper and lower surfaces of the ice as well as within it. However, in the Arctic, sea ice algae flourish mainly at the ice-water interface (Kovacs and Michel, 2011). Ice algal communities in the Canadian Arctic Archipelago are diverse (Michel et al., 2006). Marine single celled eukaryote (algae and other non-autotrophic organisms) associated with sea ice were recently surveyed and the authors reported 1,027 taxa (Poulin et al., 2011). Many of the invertebrates within the ice feed on ice algae. Invertebrates and fish feed on ice algae on the underside of the ice when the water column does not support phytoplankton growth. Ice algae are grazed by zooplankton when they are release from the ice cover and by benthic communities if they sink to the sediments. Some algal species, such as the diatom *Melosina arctica*, grow meter-long filaments that are not used as food by zooplankton and sink rapidly to the seafloor. A recent cruise reported widespread deposition of

this ice algae to the deep seafloor of the central Arctic basins and feeding by opportunistic megafauna (Boetius et al., 2013).

8.3 Water column biodiversity

The open water of the Arctic Ocean harbours a multitude of habitats that include coastal and oceanic regions, downwelling or upwelling areas and polynyas. The water column food web is composed of phytoplankton, zooplankton, bacteria and archaea, and other tiny organisms such as various animal larvae and other floating animals like jellyfish. “Plankton” describes the organisms that are drifting with the currents in contrast to other pelagic organisms that are able to propel themselves (e.g. fish and whales). “Phytoplankton” comprises single-celled algae that mostly photosynthesize and other protists between 0.2 and 200 μm (Poulin et al., 2011). “Zooplankton” are small animals that feed on other zooplankton, phytoplankton or particles of organic matter. Many common phytoplankton and zooplankton species are not Arctic specialists and are also found in other oceans (Bluhm et al., 2011b).

Phytoplankton

A recent pan-Arctic assessment of marine phytoplankton reported 1,874 single-celled types (Poulin et al., 2011). This number is indicative of a well-diversified group of organisms (Poulin et al., 2011). Pennate and centric diatoms, dinoflagellates and prymnesiophytes are the most frequently reported marine phytoplankton groups in the Arctic (Poulin et al., 2011). The vast majority of the identified microorganisms consist of large cells ($>20 \mu\text{m}$) because of the magnification capability of light microscopy. Recent major technological advances in molecular biology permitted identification of most major groups of marine microbes in the three domains of life (Bacteria, Archaea and Eucarya) in Arctic marine waters (Lovejoy et al., 2011). Communities of phytoplankton are dynamic and change with the seasons (Terrado et al., 2009).

Climate change has already had impacts on phytoplankton communities. The warming and freshening of the surface layer lead to increased stratification and nutrient depletion. Small picoplankton, being very small ($<2 \mu\text{m}$ diameter), have a large surface-area-to-volume ratio that provides effective acquisition of nutrients as well as hydrodynamic resistance to sinking. Hence, these small cells are thriving and displace the larger cells (Li et al., 2009). Increased ice-free conditions may also favour and extend northwardly the intrusion of Atlantic phytoplankton species (Hegseth and Sundfjord, 2008).

Zooplankton

Zooplankton communities are much better characterized than phytoplankton communities. Despite a relatively low sampling effort, they reveal a surprisingly high diversity (Darnis et al., 2012). The inventory of Arctic metazoan (multicellular) zooplankton is around 350 species with nearly 200 species largely restricted to the shelves and 174 listed from the central basins (Bluhm et al., 2011b; Kosobokova et al., 2011). Arctic crustaceans dominate in terms of species number

with copepods being the most diverse group, followed by the Cnidaria. However, zooplankton diversity of the Arctic has not been exhaustively characterized (Archambault et al., 2010). As climate change modifies oceanographic conditions, the number of zooplanktonic species will likely increase in this region (Archambault et al., 2010).



Arctic krill (*Thysanoessa raschii*). Photo: Dr. Russell R. Hopcroft, Institute of Marine Science, University of Alaska Fairbanks

Large suspension feeders, such as the copepods *Calanus glacialis* and *Calanus hyperboreus*, dominate the biomass of zooplankton in the Arctic (Darnis et al., 2012). These species feed on large phytoplankton and build huge lipid reserves that are essential for all animals, making them key drivers of the transfer of energy through Arctic marine ecosystems. These species perform long-range seasonal vertical migrations to depths of several hundred meters where the late developmental stages overwinter (Darnis et al., 2012). Small, numerically dominant copepods (*Oithona similis*, *Triconia borealis*, *Pseudocalanus* spp., and *Microcalanus* spp.) are active year-round and feed opportunistically throughout the winter on variable food sources (Darnis et al., 2012).

8.4 Seafloor biodiversity

The benthos is the community of organisms dwelling on the seafloor. Arctic benthos ranges from unicellular life in the spaces among sediment particles to large invertebrates (Figure 24). The Arctic seafloor presents a multitude of habitats that include intertidal areas, fiords, estuaries, an expanded shelf zone, and the deep sea with several basins separated by deep sea ridges (Josefson and Mokievsky, 2013). At smaller scales, benthic areas contain different sediment habitats such as sand and mud as well as harder substrates like boulders and bedrocks. Nearshore locations are affected by ice scouring and present impoverished benthic diversity. Macroalgae (seaweed) are found in shallow waters.

Much remains unknown about what species are found in the Arctic benthos, particularly in deep waters, where new species are still being described and where half of the species were observed at only one or two locations (Bluhm et al., 2011a). An inventory of benthic species colonizing the central Arctic deeper than 500 m resulted in 1,125 species (Bluhm et al., 2011a). Crustaceans, foraminifers, annelids and nematodes dominated this inventory. A recent study on macrofauna (large enough to be retained on sieves with a mesh size of 0.5 mm, mostly fauna that live in the mud) and megafauna (larger than 1 cm, mostly live on the surface of the substrate and are visible on seafloor images) colonizing the seafloor of Arctic shelves suggest an intermediate biodiversity (Piepenburg et al., 2011). A total of 2,636 species were listed and the highest species numbers were for crustaceans, annelids, molluscs and echinoderms (Piepenburg et al., 2011). The authors

of this work also estimated that the entire benthic macro- and megafauna (excepting fishes) of the Arctic shelves could numbered up to 4,700 species (Piepenburg et al., 2011). It is worth noting that the number of reported benthic species is influenced by the sampling methods and the sampling frequency. Bacteria and algae (in shallow waters) are also present on the seafloor (Bluhm et al., 2011b).

Most benthic communities are supported by the food supplied from the water column. Plankton, ice algae, and organic matter sink through the water column and fuels benthic food webs. Amounts of phytoplankton and zooplankton production and the timing of algal blooms and peak zooplankton production are important to determine the coupling of the benthic and pelagic communities (see section 8.1). The location, timing and duration over which food from the water column drifts to the seafloor affects the distribution and biomass of benthic communities. For instance, the NOW polynya has high primary production and tends to be associated with enriched benthic biomass due to a longer period over which the benthos receive food (Darnis et al., 2012; Grant et al., 2002). The macrofauna and megafauna of the Arctic shelves provides major feeding grounds for fishes, mammals and seabirds.

It is expected that the benthic fauna may show increased diversity, due to a combination of anticipated increased food availability and immigration of faster-growing species adapted to warmer waters in the southern areas of the Arctic (Josefson and Mokievsky, 2013). Moreover, fisheries of commercially relevant species might become more important in the LIA. Commercial shrimp fisheries for Northern (*Pandalus borealis*) and striped (*Pandalus montagui*) shrimp began in the late 1970s off Baffin Island and expanded southward to the area of Resolution Island (Hudson Strait) in the mid-1990s, where the main fishery remains to date (DFO, 2008). The Northern shrimp is the most important marine resource in Greenland, and represents 70% of the total fisheries revenues (Dahl-Jensen et al., 2011). The snow crab fishery is also important in Greenland (Boertmann et al., 2009).

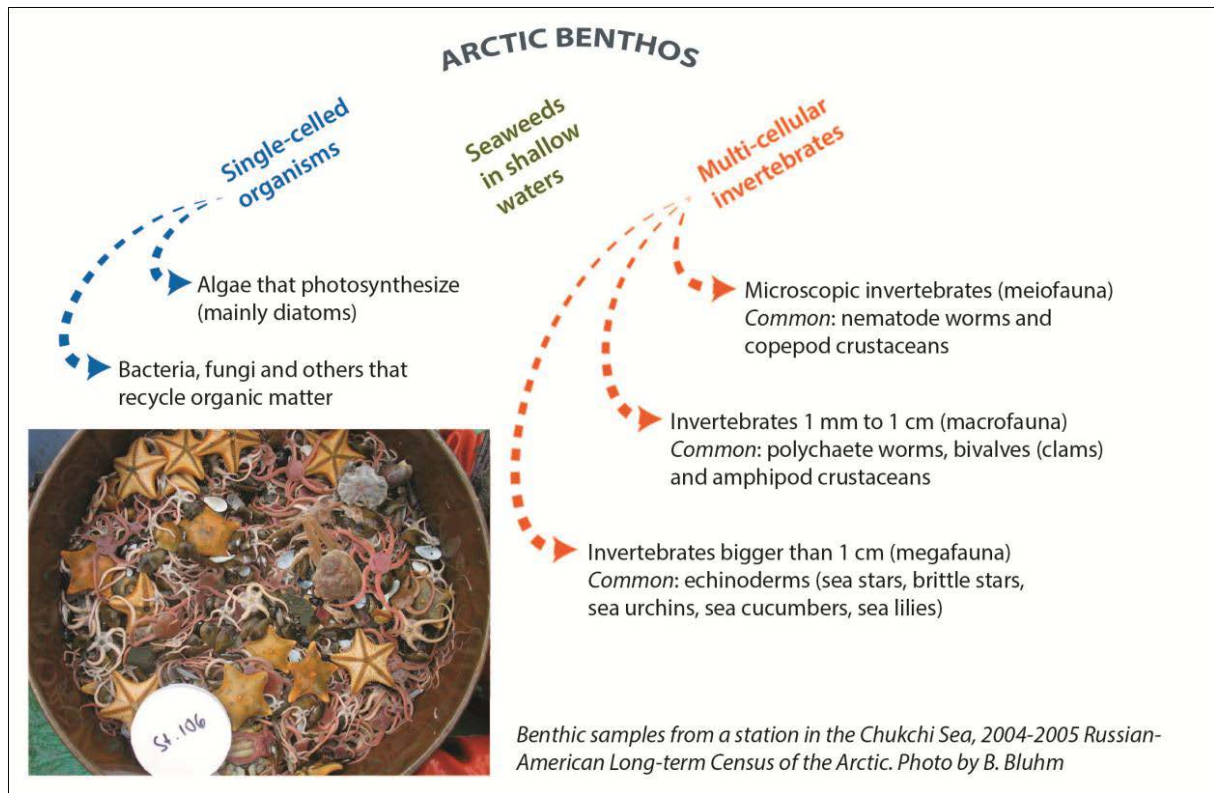


Figure 24. Arctic seafloor diversity (CAFF, 2013b).

8.5 Fish

Nearly 250 marine fish species are known from the Arctic Ocean, but this number rises to 633 fish species if the adjacent Arctic seas are included (Christiansen and Reist, 2013). These 633 species represent 2.2% of the fish species on the planet (Christiansen and Reist, 2013). Of these, 63 species are restricted to Arctic waters (Christiansen and Reist, 2013). Hence, polar seas are considered species-poor compared with more temperate latitudes. Most Arctic marine fishes are living on or closely associated with the seafloor (benthic and demersal fish respectively).

Two species can at times be closely associated with sea ice, using it as habitat, protection from predators and a place to spawn: Arctic cod (*Boreogadus saida*, also called polar cod) and ice cod (*Arctogadus glacialis*) (Christiansen and Reist, 2013). Arctic cod is considered as a keystone species and is particularly abundant and widespread in marine waters throughout the Arctic (Christiansen and Reist, 2013). They are the dominant fish on the extent Arctic shelves and the central element of the pelagic food web of the Arctic Ocean (Welch et al., 1992). They feed mainly on copepods, amphipods and mysids (small shrimp-like animals), and they play a key role in the diet of many Arctic marine mammals, seabirds and fish. The distribution of Arctic cod varies seasonally in habitats ranging from coastal brackish waters to regions deeper than 200 m, and from just above the seafloor to under sea-ice habitat. They can occur in a dispersed state all year

round but schools often appear in nearshore waters during summer (Welch et al., 1992). Large schools of Arctic cods are present at the productive ice edge during late spring-early summer where they would hide from predators (Gradinger and Bluhm, 2004) and to feed on zooplankton and other ice-associated taxa (Bradstreet and Cross, 1982). Northward shifts in marine boreal fish distribution have already been documented as a consequence of climate warming (Renaud et al., 2012). The native Arctic cod is therefore starting to be challenged by more productive southern species on its territory. Arctic cod is also dependent on zooplankton for food. The changes in sea ice will likely impact the developmental life cycles of zooplankton and thereby, influence the diet composition of Arctic cod. The ice cod is much less abundant and it primarily found in fiords and Arctic shelves (Christiansen and Reist, 2013).



An 11-foot Greenland shark, *Somniosus microcephalus*, and an ice ledge, Arctic Bay, Baffin Island, Northwest Territories, Canada © National Geographic Stock / Nick Caloyianis / WWF

Other common marine fish species include the Greenland halibut (*Reinhardtius hippoglossoides*), sculpins (Cottidae) and the Greenland shark (*Somniosus microcephalus*). The Greenland halibut is a Subarctic and Arctic species and occur in deep water along continental slopes. It is a flatfish but it lives and feeds mainly in the water column. Sculpins are benthic fishes that occur in many types of habitats and they are found mostly in shallow waters. Their pectoral fins (i.e. fins located on each side of the body) are smooth on the upper edge and webbed with sharp rays along the lower edge, which make them well adapted for gripping the seafloor substrate. Sculpins are

a important food source for other fishes but are not consumed by humans. The Greenland shark is the northernmost species of shark and is native to the North Atlantic Ocean and waters around Greenland and Iceland. This shark species is large (up to 7 m in length). It feeds mostly on other fishes but also sometimes on seals. Greenland sharks occupy deep environments where the temperature is cold and they swim very slowly. The flesh of this shark is poisonous unless it is boiled in several changes of water, dried or fermented.

Herring and Greenland halibut are important for subsistence fishing in the Canadian Archipelago (Niemi et al., 2010) and essential to the economy of Greenland (Tejsner and Frost, 2012). There is commercial fishery adjacent to the LIA. Greenland halibut is fished commercially since 1986 in Cumberland Sound (in southwest Baffin Island) (see references in Niemi et al., 2011) and around Greenland (Kovacs and Michel, 2011). This Arctic species is expected to decline in response to warming temperatures (Albert and Høines, 2003). Atlantic cod (*Gadus morhua*) is also fished around Greenland (Kovacs and Michel, 2011). This species is a former boreal species and has been observed in increasing densities recently (Berge et al., 2008). As the sea ice retreat and ocean waters warm, this species will likely spread northwards and may lead to greater populations

and enhanced fisheries values (Christiansen and Reist, 2013; Drinkwater, 2005). Newly opened waters will become accessible for commercial fishing. The LIA region may become more important for several marine fish species. However, while enhanced primary productivity could result in increased fish harvests for Northerners, it will probably be insufficient to sustain large-scale commercial fisheries in the Canadian Arctic (Tremblay et al., 2012).

The impacts of climate change and of Arctic fisheries on Arctic marine fish will act in concert. New commercial fisheries in the Arctic are imminent and they will affect species of boreal origin that are already commercially harvested, and fishes native to Arctic waters (Christiansen and Reist, 2013). A warmer ocean will cause shifts in fish distribution as they are very sensitive to changes in water temperature, although different species and life stages will respond in different ways (Christiansen and Reist, 2013). Nevertheless, the invasion of boreal fish species into Arctic waters has already started (Renaud et al., 2012). There are currently 59 species that are fished in the Arctic and sub-Arctic waters (Christiansen and Reist, 2013). Demersal fish are collected by bottom trawls, affecting significantly the sea bed and producing considerable bycatch of non-targeted fish (species and sizes not desirable by the industry) (Christiansen and Reist, 2013).

8.6 Marine mammals

Seven marine mammals species (three whales, three pinnipeds (fin-footed marine mammals) and polar bears) live in the Arctic all year long and many other species occupy Arctic waters seasonally (see Appendix I). Arctic marine mammals use several specific types of ice habitats and feed on diverse food sources (Table 2). Changes in the Arctic climate may challenge the adaptive capacity of these species. Sea ice plays a crucial role for these animals either as platform, marine ecosystem foundation and barrier to non-ice-adapted marine mammals and human commercial activities (Moore and Huntington, 2008). A clear example is that reduction in sea ice cover removes the hunting platform of polar bear and likely reduces the survivorship of their primary prey, the ringed seal. The fitness of Arctic marine mammals is therefore influenced by changes to the dynamic balance among sea ice effects on ecosystem structure and prey availability.

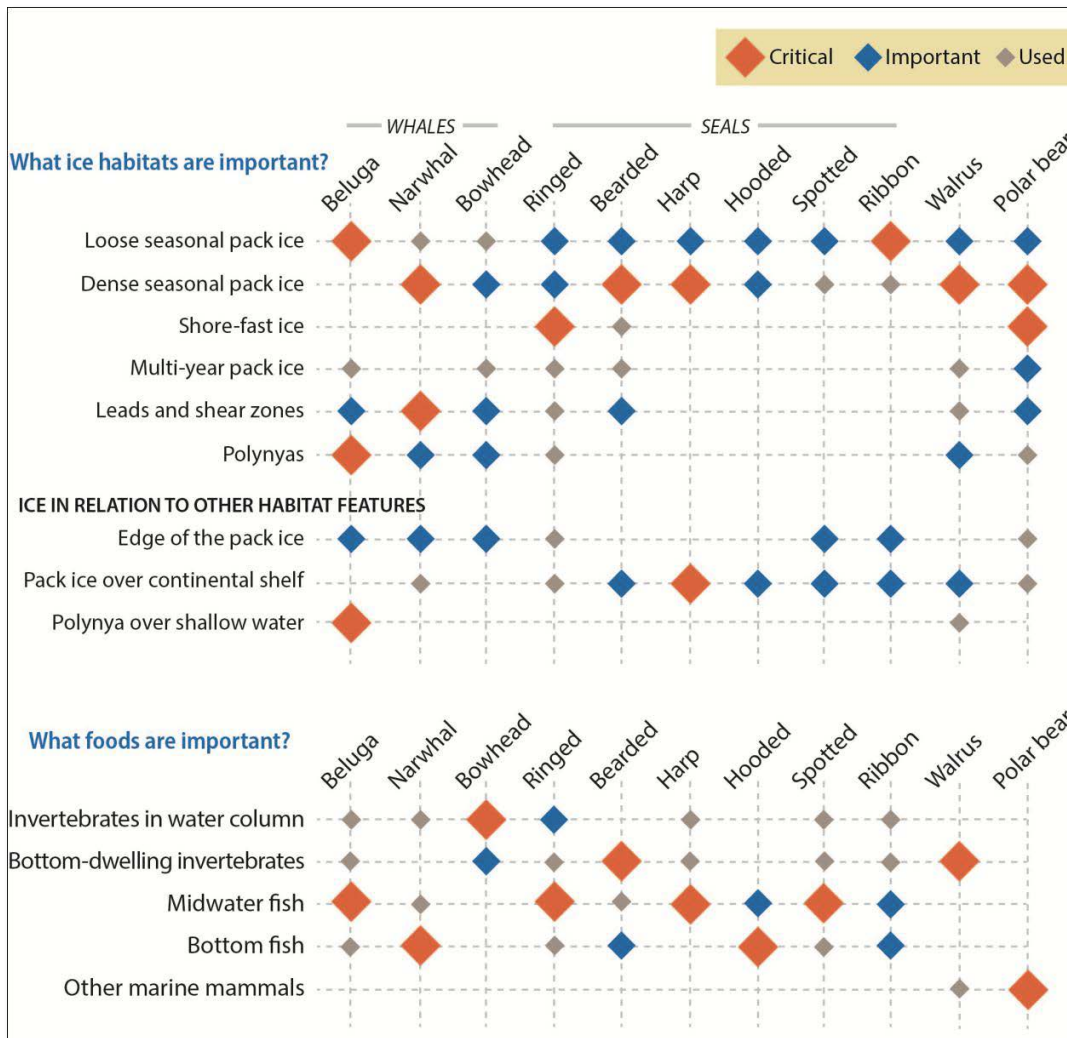
One approach to quantify marine mammal resilience to climate change is to classify them in regard to the species relationship to the ice (Moore and Huntington, 2008). Polar bear, walrus, bearded seal and ringed seal are classified as ice-obligate species since they are reliant on sea ice as a platform for resting, breeding or hunting. Harp seal, hooded seal, ribbon seal, spotted seal, beluga, narwhal and bowhead whale are ice-associated species since they are adapted to marine ecosystems of which ice is predominant. Fin, minke, humpback, gray and killer whales are seasonally migrant species that encounter sea ice in parts of their migration. Ice-obligate species are especially vulnerable to changes in the sea ice cover. The scenario for ice-associated species is harder to predict but decreases in the sea ice cover will have negative impacts on these species, except perhaps reduced risk of sea ice entrapment. The five migrant whale species are likely to benefit from loss in sea ice since the pelagic system will be more accessible.

Another approach to assess the sensitivity of marine mammals to climate change is to use an index that include the species narrowness of distribution and specialization of feeding in addition to the seasonal dependence on sea ice and reliance on sea ice as a platform to access prey and predator avoidance (Laidre et al., 2008). This index suggests that the hooded seal, the polar bear, and the narwhal are the three most sensitive Arctic marine mammal species, primarily due to reliance on sea ice and specialized feeding. The least sensitive species were the ringed seal and bearded seal, primarily due to large circumpolar distributions, large population sizes, and flexible habitat requirements.

Overall, climate change is forecast to have serious negative impacts on Arctic marine mammals by altering the seasonal patterns, the extent and the quality of sea ice habitat. Species seasonally occupying the Arctic might stay north longer, and compete for food resources with existing Arctic species. Also, temperate marine mammals are expanding their distribution northward, which are likely to cause competitive pressure on Arctic endemic species and to put them at greater risk of predation, disease and parasite infections (Kovacs et al., 2011).

Since the LIA is predicted to hold the last remaining ice during summer, the area may become increasingly important for ice-obligate and ice-associated marine mammal species. This is why WWF scientists are in discussion with Inuit and governments located in the LIA region in order to plan the future management of this area to ensure the resilience of all life forms dependant on sea ice. A recommendation of the Arctic Biodiversity Assessment (CAFF, 2013a) goes in that sense and states the importance of developing and implementing mechanisms to conserve Arctic biodiversity under the deteriorating trend of sea ice, glaciers and permafrost.

Table 2. The diversity of ice habitats and prey items for Arctic marine mammals species (from CAFF, 2013).



Whales

Only three whale species live year round in the Arctic. These are the bowhead whale, a large baleen whale, and the narwhal and the beluga, which are middle-sized toothed whales. The bowhead whale and the beluga have a circumpolar distribution while the narwhal only occupy the Atlantic sector of the Arctic (Figure 25; Reeves et al., 2013). Thirteen other whales species (baleen whales: blue, fin, sei, humpback, minke, North Atlantic right and gray whales; toothed whales: sperm, Sowerby's beaked and killer whales, Atlantic white-sided and white-beaked dolphins, and harbour porpoise) seasonally occupy Arctic and Subarctic waters. The loss of summer sea ice cover is allowing an increasing number of killer whales to use the Canadian High Arctic as a hunting ground (Darnis et al., 2012). The stronger presence of this apex predator species will likely affect the populations of the bowhead whale, the narwhal and the beluga. The three Arctic whale species are described in the following paragraphs.



Bowhead whale © naturepl.com M. Holmes WWF-Canon

Bowhead whales (*Balaena mysticetus*) measure between 15 and 18 m and weight up to 100,000 kg. They live in Arctic waters during summer but migrate to Subarctic seas during winter (Laidre et al., 2008). This whale species occurs within the LIA region in Baffin Bay and in the eastern side of the Canadian Arctic Archipelago (Figure 25). The global population size of bowhead whale would be over 20,000 individuals. The pre-whaling population of bowhead whales has been estimated at about 50,000 individuals (COSEWIC, 2009). Commercial whaling ended around 1910 and

reduced the population to less than 3,000 animals. The bowhead whale is listed as “least concern” on the IUCN Red List, since the population appears to be increasing (Reilly et al., 2012). This whale species is well adapted to ice-covered waters and can move through areas of nearly solid ice cover. They prefer areas of low ice coverage in winter, presumably to reduce risk of ice entrapment while remaining within the ice (Ferguson et al., 2010). In contrast, during summer, these whales select high ice coverage regions to reduce risk of killer whale predation while providing enriched feeding opportunities (Ferguson et al., 2010). Bowhead whales also inhabit polynyas and the marginal ice zone during winter and early spring (Laidre et al., 2008). The bowhead whale is feeding on zooplankton throughout the water column including near the bottom (Laidre et al., 2008).



Beluga © K. Schafer WWF-Canon

Belugas (*Delphinapterus leucas*) or white whales occur in estuaries, at the continental shelves and in deep ocean basins. They measure between 4 and 6 m and weigh between 900 and 1,300 kg. Belugas are divided in discrete populations around the Arctic, depending on their summering (fiords or estuaries, to which they show high fidelity) and wintering (shallow or coastal areas) grounds (see references in Laidre et al., 2008; Figure 25). DNA studies have indicated genetic differences between some of the populations (de March and Postma, 2003).

The world wide population estimate is well over 150,000 animals and has been divided into 29 different populations (or stocks) by the International Whaling Commission (Jefferson et al., 2012a). This species is listed as “near threatened” on the IUCN Red List because there is large uncertainty about population numbers and trends over parts of the species range, and because its survival relies on national and international conservation programs that monitor and manage hunting (Jefferson et al., 2012a).

The different populations of belugas are subject to different levels of threat which call for individual assessments (Jefferson et al., 2012a). Two populations are present within the LIA for at least parts

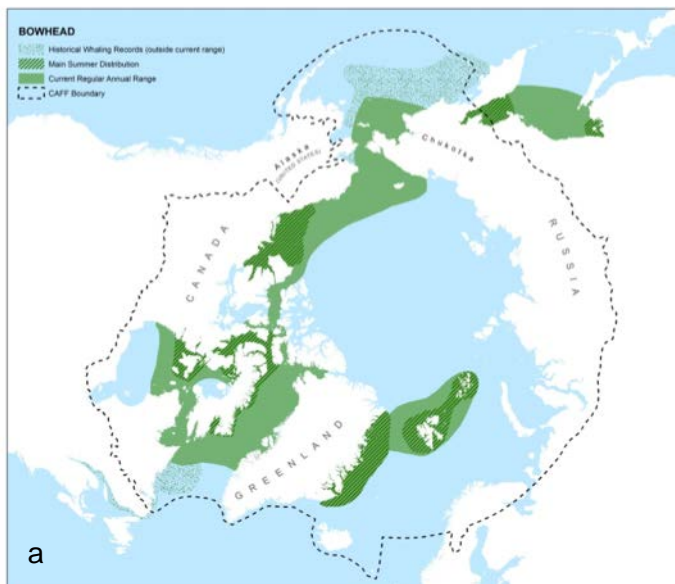
of the year: the North Water winter (North Baffin Bay) stock, with an estimated population size of 21,213 belugas based on 1996 surveys (Innes et al., 2002) and the West Greenland winter stock, with an estimated population size of 7,941, based on 1998 and 1999 surveys (Heide-Jørgensen and Aquarone, 2002). Ice edges serve as important feeding grounds for belugas as their predominant prey is Arctic cod.



Narwhals. © P. Nicklen National Geographic Stock / WWF-Canada

Narwhals (*Monodon monoceros*) are medium sized (4 to 6 m, 1,600 kg) toothed whales that occupy waters of the eastern Canadian Arctic Archipelago, West and East Greenland, Svalbard and Franz Joseph Land (Figure 25). They are widely present in the LIA region. It is the Arctic whale with the most restricted distribution. Narwhals perform annual migrations over long distances. During summer, narwhals spend approximately two months in High Arctic ice-free shallow bays and fiords. They overwinter in offshore, deep, ice-covered habitats along the continental slope in more southern

locations (Heide-Jørgensen and Dietz, 1995). Narwhals feed mainly during winter on benthic organisms and Greenland halibut in offshore deep ocean basins (Laidre et al., 2008). The narwhal is listed as “near threatened” on the IUCN Red List, although there is uncertainty about numbers and trends in large parts of the species range and evidence of decline for specific subpopulations (Jefferson et al., 2012b). The total population is greater than 80,000 individuals (Jefferson et al., 2012b). Narwhals are the most ice-associated whales: they are found in dense pack ice and are highly dependent on leads and cracks in the ice during migrations (Laidre et al., 2008).



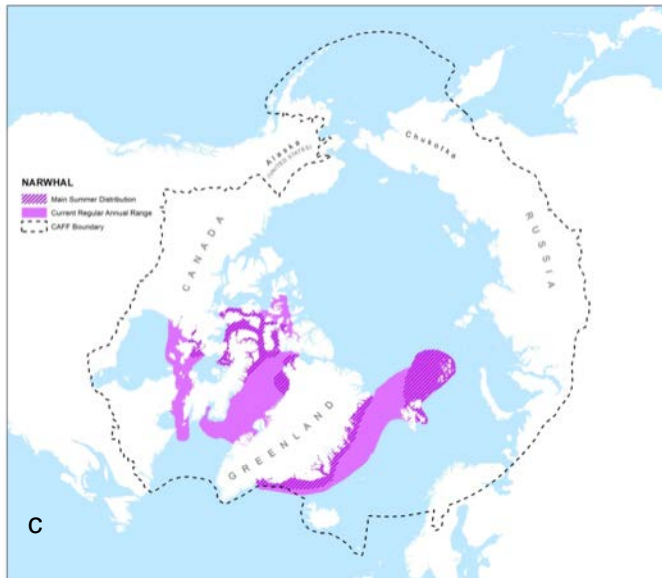


Figure 25. Distribution of a) bowhead whales, b) belugas and c) narwhals (Reeves et al., 2013).

Pinnipeds

Arctic ice-associated pinnipeds with a circumpolar distribution are the ringed seal, the bearded seal and the walrus (Laidre et al., 2008). Other seal species that can be found in Arctic waters are the spotted seal, the common seal, the harp seal, the ribbon seal and the hooded seal (Greenland Institute of Natural Resources, 2012; Laidre et al., 2008). These latter species depend on sea ice only for some parts of their life cycle, especially for birthing, molting, mating and resting during spring. In contrast to Arctic ice-associated species, they are not year round in the Arctic and they rely on sea ice only seasonally. The ribbon seal and the spotted seal only occur in the Bering, Chukchi and Okhotsk seas while the common seal, the harp seal and the hooded seal occur only in the North Atlantic (Greenland Institute of Natural Resources, 2012; Laidre et al., 2008). The three Arctic ice-associated seal species found year round in the Arctic occur within the LIA region, but only ringed seals are reported to occur along the northern coastline of the Canadian Archipelago and Greenland (Figure 26). These are briefly described in the next paragraphs.



Ringed seal. © WWF-Canon S. Kinnerød

The ringed seal (*Pusa hispida*) is the most common and widely dispersed marine mammal of the Arctic. It is the smallest of the seal species (up to 1.65 m and up to 70 kg) and they get their name from the light-coloured circular patterns that appear on their darker grey back. The species has a circumpolar distribution (Figure 26) and is the only seal species that is able to occupy large areas of consolidated sea ice, since they are able to maintain breathing holes (Norwegian Polar Institute, 2013). They are dependent on sea ice for all aspects of their lives: for giving birth, as a staging area

for breeding, for moulting, resting and aquatic predator avoidance (Norwegian Polar Institute, 2013). Landfast ice over the continental shelves would be their favoured habitat for breeding and giving birth (Laidre et al., 2008). The ringed seal is listed as “least concern” on the IUCN Red List (Kovacs et al., 2008). Five subspecies are recognized: Arctic Ringed Seal (*P. h. hispida*), Baltic Sea Ringed Seal (*P. h. botnica*), Lake Ladoga Ringed Seal (*P. h. ladogensis*), Lake Saimaa Ringed Seal (*P. h. saimensis*), and Sea of Okhotsk Ringed Seal (*P. h. ochotensis*). The global population estimate would be between 3 and 8 millions but the population size of the different subspecies varies greatly (Kovacs et al., 2008). Climate change, contaminants and bycatch in fishing gear are the current threats to this species (see references in Kovacs et al., 2008). Ringed seals feed on Arctic cod and a variety of large zooplankton (crustaceans) under the ice or in the first 50 m of the water column (Laidre et al., 2008). Ringed seal are a keystone species in the Arctic since they compose the majority of the polar bear diet, especially in spring, and they are a major food source for Arctic communities (Norwegian Polar Institute, 2013).



Bearded Seal. © Wild Wonders of Europe O. J. Liodden WWF

The bearded seal (*Erignathus barbatus*), named so because of their long whiskers, measure between 2.0 and 2.5 meters and weigh between 260 and 360 kg. They have a circumpolar distribution and two subspecies of bearded seals are widely recognized: *E.b. barbatus* in the Atlantic sector, and *E.b. nauticus* in the Pacific sector (Figure 26). Only the subspecies *E. b. barbatus* can be found with the LIA. A minimum estimate for Canadian waters of 190,000 animals was suggested (Cleator, 1996) and no clear population numbers are available for the Greenlandic waters.

The species is listed under the category of “least concern” on the IUCN Red List (Kovacs and Lowry, 2008). Bearded seals are found mainly over the shallower waters of the continental shelves and usually in association with moving ice or leads and polynyas (Laidre et al., 2008). The seasonal movements and distribution of bearded seals are linked to seasonal changes in ice conditions. The seals generally move north in late spring and summer, as the ice melts and retreats, and move south in the fall, as sea ice reforms to remain associated with their preferred ice habitat. Bearded seals are closely associated with sea ice, particularly during the critical life history periods related to reproduction and moulting, and they can be found in a broad range of different ice types (see references in (Cameron et al., 2010)). Ice provides a platform on which the seals haul out, bear and nurse pups, and rest and moult. Bearded seals feed primarily on benthic organisms that include epifaunal (are attached to substrates) and infaunal (live in the substrate/ soft sea bottom) invertebrates and demersal fishes (fish that live near the seafloor). Polar bears and walrus are the main predators of bearded seals (Laidre et al., 2008).

Walrus (*Odobenus rosmarus*) is the largest species of pinniped in the Arctic, measuring between 3.0 and 3.6 meters and weighing between 600 and 2,000 kg. Walrus have a discontinuous

circumpolar Arctic and Subarctic distribution (Figure 26). Three subspecies are distinguished: the Atlantic walrus (*Odobenus rosmarus rosmarus*), the Pacific walrus (*Odobenus rosmarus divergens*) and the Laptev walrus (*Odobenus rosmarus laptev*), although the taxonomic status of the latter is uncertain. Only the Atlantic subspecies is found within the LIA. The population estimates that are available have a low precision (Lowry et al., 2008). Nevertheless, the Atlantic population would be around 18,000 individuals, the Pacific, around 200,000 individuals and the Laptev, around 5,000 individuals (WWF, 2013b). The walrus was once threatened by commercial hunting but today the biggest danger it faces is climate change. The walrus is listed under the category of “data deficient” in the IUCN Red List (Lowry et al., 2008).

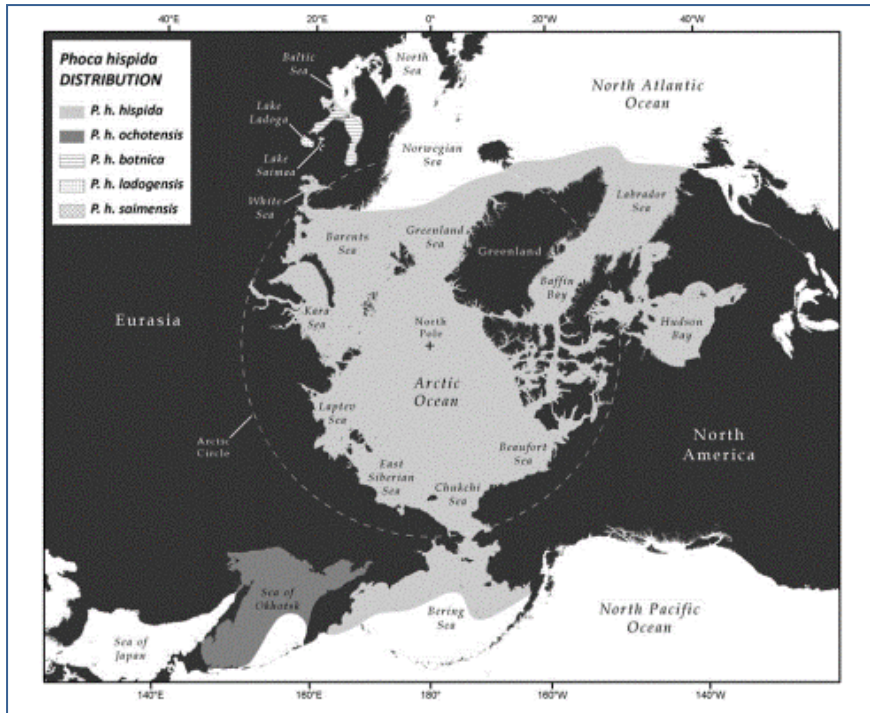


Walrus. Photo: Tom Arnbom / WWF

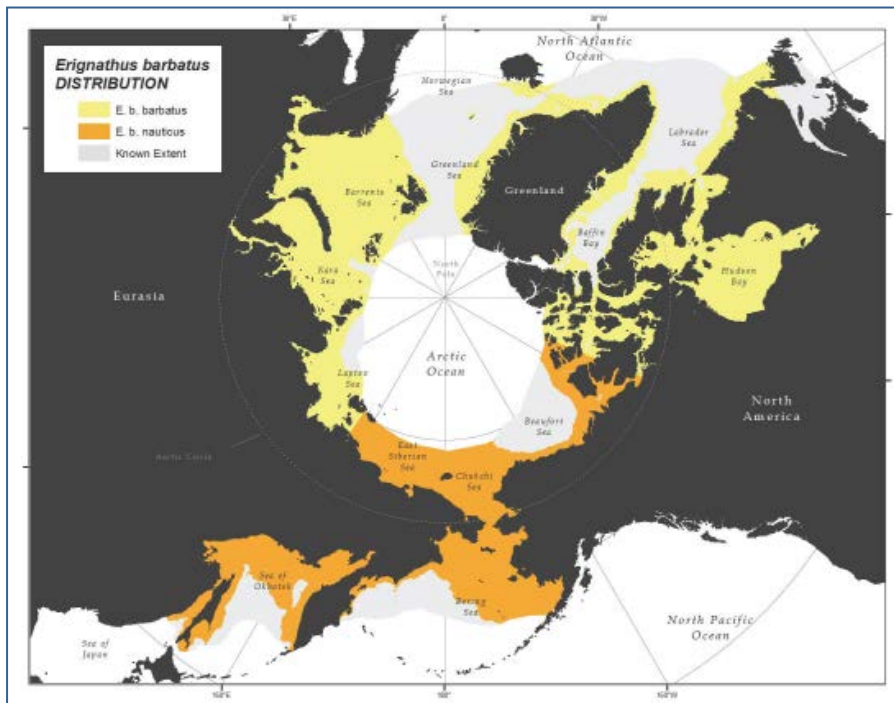
Walrus in the Atlantic display sex-specific distribution and movement patterns. Females with young and males move to separate areas during summer but they occupy the same areas during winter (see references in Laidre et al., 2008). Walrus show high fidelity to their terrestrial haul-out sites (beaches on islands or remote stretches of mainland coastlines) and wintering areas from year to year (Laidre et al., 2008). They can overwinter close to polynyas that provide access to seafloor food resources. All subspecies of walrus are found in relatively shallow continental shelf areas and seldom occur in deep waters (maximum of 200 m).

Walrus are benthic feeders and shallow divers; they generally feed on molluscs and other invertebrates in depths around 20-30 m.

A



B



C

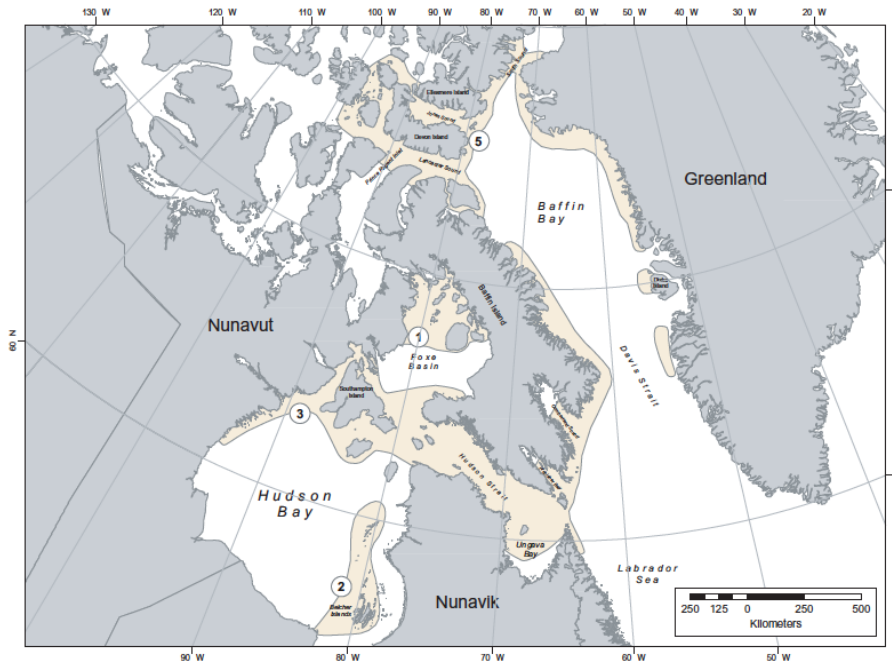


Figure 26. Distribution of a) ringed seals (Kelly, 2001), b) bearded seals (Cameron et al., 2010) and c) walrus (Stewart, 2008).

Polar bear



Polar Bear © Geoff York

Polar bears (*Ursus maritimus*) are an iconic Arctic species. They are considered marine mammals because they live predominantly on the sea ice throughout the Arctic. They are an ice-obligate species, using the sea ice as a platform for hunting seals. Polar bears are 2-3 m in length and can weight up to 680 kg. They have a circumpolar distribution (Figure 27) and are found mainly in areas of annual ice cover over the continental shelf and the inter-island channels of various archipelagos. Polar bears prefer to forage on seasonal sea ice but will also use multiyear sea ice.

In more southern locations, such as Hudson Bay and Davis Strait, where annual ice melts completely, bears spend up to several months on land waiting for the ice to freeze again. Polar bears have annual movement patterns within their home ranges and they show high fidelity to denning and spring feeding areas (Laidre et al., 2008; Lone et al., 2013). Sea ice also facilitates, but is not essential, for seasonal movements, mating, and in some cases, maternal denning (Laidre et al., 2008). They feed mainly on ringed and bearded seals but they also eat belugas,

narwhals and walrus (Laidre et al., 2008). They also feed on land, eating eggs, berries, and whatever they can scavenge.

The worldwide polar bear population is divided into 19 subpopulations (Figure 27) and four ecological regions have been described (Figure 28; Amstrup, 2011). This species is listed as “vulnerable” on the IUCN Red List with an estimated global number of 20,000 to 25,000 individuals and the population trend is declining (Schliebe et al., 2008). In 2008, the polar bear was listed as Special Concern under the Federal Species at Risk Act of Canada (Government of Canada, 2013c). Out of the 19 subpopulations, seven are considered to be declining in numbers (Vongraven and Richardson, 2011). The main threat to the polar bears long-term survival is the loss of sea ice habitat (Stirling and Derocher, 2012). The critical feeding time occurs in late spring and early summer, when they feed on ringed seal pups that are born in early April and weaned about six weeks later. At that time, pups are up to 50% fat, naïve about predators and accessible from the surface of the ice. After the ice break-up, seals are mostly inaccessible to the bears. A reduced extent in sea ice and an earlier sea ice break-up in spring results in less time to access prey, longer periods of fasting, less healthy body condition and lower survival of cubs (Rode et al., 2010; Stirling and Derocher, 2012). While all bear species have adapted to changes in their environment in the past, the adaptive capacity of polar bears is limited since they are highly specialized for life in the Arctic, and they exhibit low reproductive rates with long generational spans. Moreover, the pace of Arctic sea ice habitat loss may be too fast for polar bears to adapt. Projections of polar bear habitat losses for this century are the greatest in the southern seas of the polar basin (e.g. Chukchi and Barents seas) and least along the Arctic Ocean shore included in the LIA region, from Banks Island to Greenland (Durner et al., 2009). On the basis of these projected losses in essential habitats and if climate warming continues, a research team argued that two thirds of the global polar bear population could disappear by 2050 (Amstrup et al., 2008). For the other third, the LIA is likely to be prime habitat. A global coordinated monitoring framework of polar bear subpopulations is proposed as this would provide a better circumpolar understanding of ongoing patterns and future trends in polar bear subpopulations, and would improve the monitoring of the effects of stressors on polar bears (Vongraven et al., 2012).

Trends in Polar Bear Subpopulations

Subpopulation size

No. of Bears

- <200
- 200-500
- 500-1000
- 1000-1500
- 1500-2000
- 2000-2500
- 2500-3000
- ⊙ Unknown

Population Trend (2013)

- Stable
- Increasing
- Declining
- Data deficient

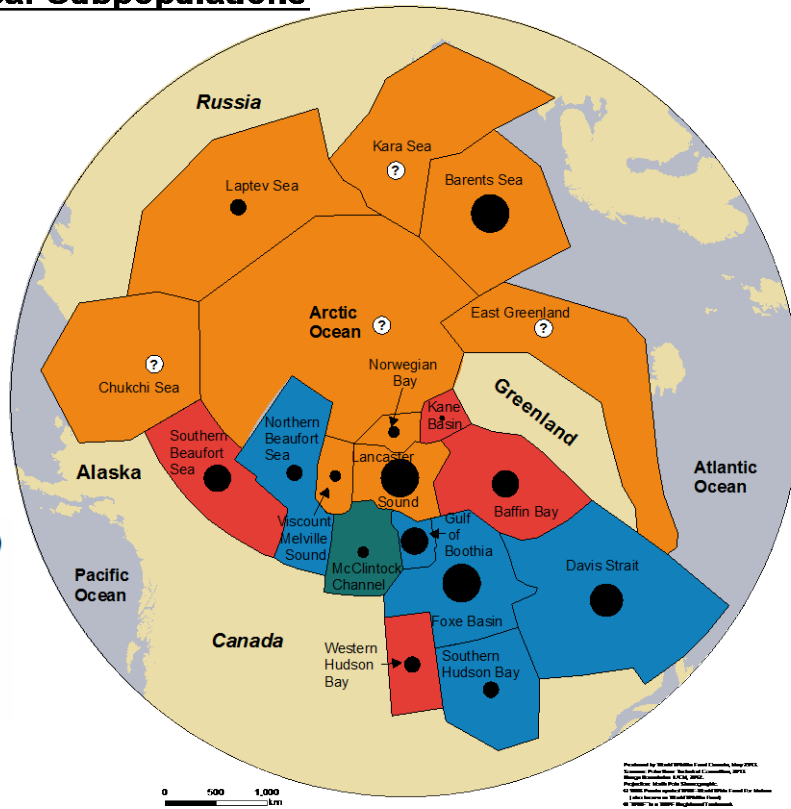


Figure 27. Map of location, size and trends of polar bear subpopulations.

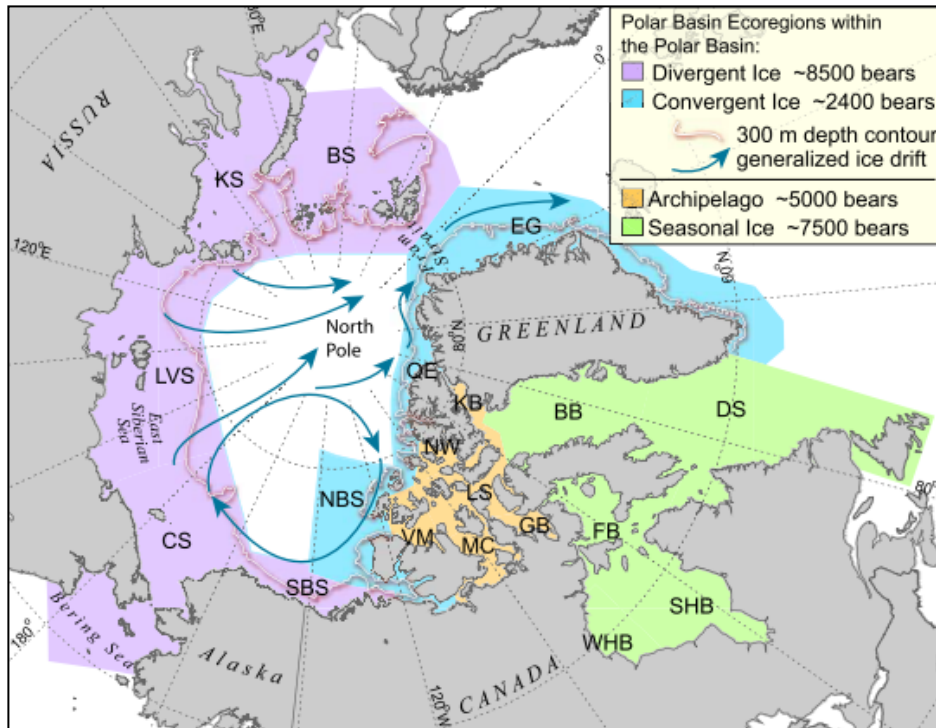


Figure 28. Ecoregions used in analysis of the future global status of polar bears. Ecoregions include the 19 Polar Bear management units (black initials) as defined by the IUCN Polar Bear Specialists' Group, and blue lines represent general ice flow patterns (Amstrup, 2011).

LIA is home to six polar bear subpopulations (Table 3). The populations of the Archipelago and Baffin Bay are in decline, even if sea ice is still extensive in these regions. Harvest pressures from both Canada and Greenland in Baffin Bay and Kane Basin are responsible for this decline and an agreement between both parties signed in 2009 should help in making harvest sustainable (CBC News, 2009). Within LIA, thick multiyear ice will be replaced by annual ice, which is associated with greater productivity, and may create more favourable habitats for polar bears over the short term (in the next three to four decades), acting as potential refugia. However, this region is also predicted to become ice-free during summer in the foreseeable future. Nevertheless, LIA will remain the best habitat available for polar bears as this region will retain ice the longest. The long-term viability of polar bears is uncertain (Stirling and Derocher, 2012).

Table 3. Numbers and trends of the polar bear subpopulations found in the LIA region (data are from Vongraven and Richardson, 2011).

Ecoregions	Subpopulation	Number (year of estimate)	Trend
Seasonal ice	Baffin Bay (BB)	1546 (2004)	Decline
Archipelago	Kane Basin (KB)	164 (1998)	Decline
	Norwegian Bay (NW)	190 (1998)	Decline
	Lancaster Sound (LS)	2541 (1998)	Decline
Convergent Ice	Arctic Basin	Unknown	Data deficient
	East Greenland (EG)	Unknown	Data deficient

8.7 Seabirds



Thick-billed murre. © Kevin Schafer / WWF-Canon

Seabirds are birds that frequent coastal waters and the open ocean. Loons, petrels, cormorants, jaegers/skuas, gulls, terns and auks are all seabirds. Seabirds are important components of Arctic ecosystems, and are culturally and economically important for local communities. They are also frequently used as indicators of environmental changes. The Arctic is an important region for seabird diversity. Forty-four species of seabirds breed in the Arctic (Gaston, 2011). Twenty-three occur in the High Arctic and forty-one in the Low Arctic. Fifteen species have a circumpolar distribution. West Greenland (24 species) and eastern Canadian Arctic (Nunavut, northern Quebec and Labrador, 22 species), are recognized as biodiversity hotspots (Gaston, 2011). Many seabirds are very conservative in their breeding sites. The 42 species that can be found within LIA are listed in Appendix II.

Large breeding colonies of seabirds can be found on cliffs and islands (see Appendix II) and some are associated with highly productive areas such as the North Water Polynya. Major breeding seabird colonies of the Canadian portion of LIA include Prince Leopold Island (murres, kittiwakes, fulmars and guillemots), Coburg Island (Thick-billed Murres and Black-legged Kittiwakes), Cape Hay and Cape Graham on Bylot Island (thousands of seabirds and geese), Hell Gate and Cardigan Strait (Black Guillemot, Northern Fulmar, Common Eider), eastern Devon Island (Ivory Gull, Iceland Gull and Glaucous Gull colonies), Hobhouse Inlet on Devon Island (Northern fulmar), Cape Liddon and Radstock Bay on Devon Island (Northern fulmar), Baillie-Hamilton Island (Black-legged Kittiwakes), and Browne Island (Black-legged Kittiwakes) (Figure 29). Breeding seabird colonies are present in northwest Greenland (Figure 29). Melville Bay (just south of the core area of LIA), has been explored in detail for breeding seabird colonies and this area revealed low density of breeding colonies and low numbers of breeding seabirds (Boertmann and Hufferdt, 2012).

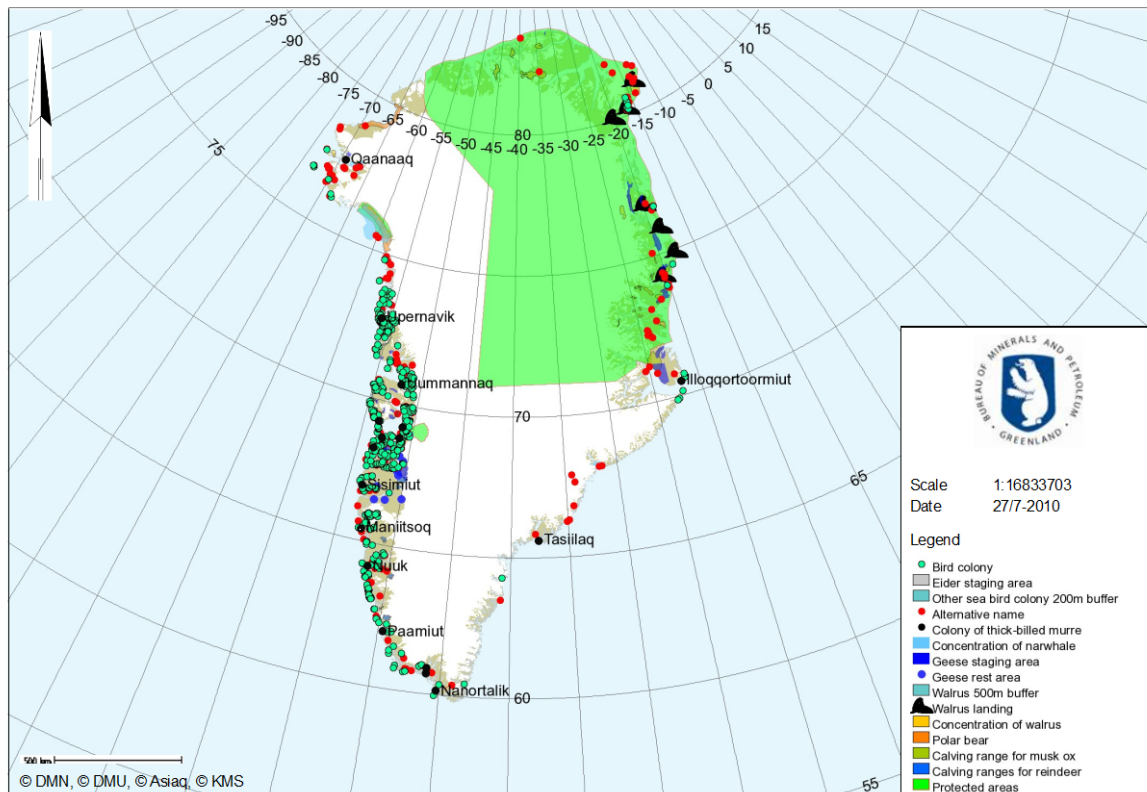


Figure 29. Seabird colonies and other important wildlife areas in Greenland

Most Arctic seabirds have large population sizes and many species are represented by millions of individuals (Gaston, 2011). One exception is the ivory gull (*Pagophila eburnea*), an iconic seabird that inhabits the Arctic Ocean throughout the year, with less than 12,000 breeding pairs globally (Gilchrist et al., 2008). However, most Arctic seabird populations have shown declining trends in recent years (Gaston, 2011). Stressors to Arctic seabirds include overharvesting, fisheries activities, pollution and climate change (Gaston, 2011). The contribution of climate change to the decline in population trends is generally linked to the food chain as seabirds rely on ice edges and polynyas as key foraging locations (see references in Gantner and Gaston, 2013). The timing of breeding initiation with seasonal peak food (mainly fish and invertebrates) is influencing the reproductive success. Changes in sea ice cover conditions also allow northward spread of predominantly temperate or Low Arctic species (see references in (Ganter and Gaston, 2013)) at the expense of High Arctic species. As an example, the range of the High Arctic ivory gull is contracting in North Nunavut while most colonies located at the southern edge of its distribution are deserted (Environment Canada, 2013d). Sea ice is also used as a platform for social activities and to escape from marine predators and for resting.

9. The terrestrial environment

The Arctic terrestrial environment is characterized by numerous lakes that dot the landscape and by the predominance of snow and ice in the form of glaciers, ice caps, ice sheets and permafrost (permanently frozen ground).

9.1 Lakes and rivers

The Arctic contains an abundant and wide range of freshwater ecosystems, including lakes, rivers, ponds, streams and a complex array of wetlands and deltas. These aquatic environments are habitats for diverse biological communities (see section 10.4) and are important for hunting and fishing by indigenous communities. They also provide drinking water supplies to communities and are a key resource for industries such as transport and mining. Moreover, Arctic aquatic environments have global significance as sentinels of climate change, as sources of greenhouse gases, and large rivers bring major inputs of freshwater and organic materials to the Arctic Ocean (Vincent et al., 2008). Four sites within LIA are important for lake ecological studies: Cornwallis Island (Char Lake, Meretta Lake, Amituk Lake), Ellesmere Island (Lake Romulus, Cape Hershel ponds), Ward Hunt lake and northern Ellesmere Island meromictic lakes, and Peary land in northern Greenland (Vincent et al., 2008).

Arctic lakes are very diverse. Their salinity ranges from freshwater to hypersaline, and their ice cover can be perennial or seasonal. This diversity leads to different mixing regimes; some lakes mix fully during open water conditions in summer, others mix at spring and fall and stratify strongly during summer (as most temperate lakes), and others never mix (Vincent et al., 2008). These physical differences bring large variations between lake chemical characteristics, such as oxygen concentration, and even within the same lake at different depths or times. Some lake types with unusual features are found exclusively in the polar regions, such as solar-heated perennially ice-capped lakes of northern Ellesmere Island (Veillette et al., 2010), and epishelf lakes (see section 7.4). The Arctic also harbours a diversity of streams and river ecosystems, from spring-fed streams to large rivers.

Most Arctic lakes are ultra-oligotrophic (have very low levels of nutrients) and are therefore very unproductive, but some are greatly enriched by human activities (e.g. Meretta Lake (Schindler et al., 1974)). Several variables would control biological production in Arctic aquatic ecosystems (Vincent et al., 2008). First, the availability of liquid water is essential for aquatic life. For some ecosystems (e.g. meltwater lakes on ice shelves), this limits biological activity to only a few weeks each year. However, liquid water persists all year round under snow and ice cover for most aquatic ecosystems. Streams and rivers are fed by melting snowpack and glaciers, and their flow is the most important during the peak snowmelt in spring. Second, the reduced irradiance, since the sun is up only during the summer, compounded to the attenuating effects of snow and ice cover on the underwater irradiance strongly limits the annual production in Arctic aquatic ecosystems.

However, the primary variable controlling daily primary production by phytoplankton during summer would be nutrient availability (Vincent et al., 2008). Nutrient delivery for biological production to plankton communities in lakes and rivers is low in the Arctic. The release of nutrients from the catchments by soil microbes is limited due to low temperature, low moisture, and freezing. Nutrient recycling rates are also slowed with the low temperature of waters. Also, low temperature would likely slow the metabolic rate and growth of many of the organisms colonizing Arctic aquatic ecosystems. Hence, it is suggested that nutrient supply exerts a strong control on phytoplankton production with the interplay of light and temperature (Vincent et al., 2008).

Lake floor communities of many Arctic aquatic ecosystems flourish and dominate the ecosystem biomass and productivity (Vincent et al., 2008). They take advantage of the more stable environment and of the enhanced supply of nutrients by sedimentation of particles from above and by more active bacterial decomposition and recycling processes, compared to the water column environment. The lake floor photosynthetic communities may be more limited by light than by nutrients (Bonilla et al., 2005).

Climate change is the major environmental driver affecting Arctic freshwater ecosystems (Prowse and Reist, 2013). The duration of freshwater ice cover is strongly controlled by climate. The lake ice cover duration in the Northern Hemisphere (1846-1995) has declined: freeze-up comes later, break-up comes earlier and the ice cover duration has decreased (Prowse et al., 2011). Rivers are also showing the same trend although there are regional differences (Prowse et al., 2011). In Arctic freshwater ecosystems, the duration of ice cover has decreased by almost two weeks over the last 150 years, with earlier break-ups and later freeze-ups (Prowse and Brown, 2010). Hence, lakes with seasonal ice cover have a longer ice-free season while lakes with perennial ice covers are becoming ice free during summer (Prowse et al., 2011). These reductions in lake ice cover duration modify thermal conditions that may lead to enhanced evaporation and, in some cases, the loss of shallow lakes (Prowse et al., 2011). In addition, these conditions can lead to enhanced mixing, making Arctic lakes sinks for contaminants (Prowse et al., 2011). Loss of ice cover will also likely lead to increased methane emissions and expose the biota to an increased level of ultraviolet radiation (Prowse et al., 2011). Apart from climate change, other environmental stressors are increasingly relevant for Arctic aquatic ecosystems such as pollution (point source and long-range atmospheric transport), altered hydrologic regimes related to impoundment and diversion of freshwater, water quality degradation due to enhanced mining, and oil and gas activities, and anthropogenic introduction of invasive species via more transport in the North (Prowse and Reist, 2013).

9.2 Glacier ice

Arctic glacier ice comprises mountain glaciers (i.e. ice bodies whose shape and size are controlled by bedrock topography), ice caps (i.e. dome-shaped ice bodies that entirely submerge the underlying rock) and the Greenland Ice Sheet (i.e. an ice sheet is an ice cap). If all glaciers, ice caps and the Ellesmere Ice Sheet were to completely melt, the global sea level would rise by 7.9 m (Dahl-Jensen et al., 2011; Sharp et al., 2011). 250,000 km³ of ice is locked up in mountain

glaciers and ice caps (Sharp et al., 2011). The LIA region contains glaciers and ice caps in the mountains on Devon and Ellesmere islands, which are nourished in part by moisture from the NOW polynya, and glaciers at the periphery of Greenland (these glaciers are not connected to the Greenland Ice Sheet). These glacial features drain ice mass away from the accumulation areas, where snowfall exceeds surface melt, to ablation areas where melting exceeds accumulation. Where the ablation areas of ice reach the ocean, icebergs are calved. The Greenland Ice Sheet is a massive ice cap of nearly 3,000 m thick. It is the largest body of freshwater ice in the Northern Hemisphere; it is composed of 2.93 million km³ of ice (Dahl-Jensen et al., 2011). The Greenland Ice Sheet gains ice by snow falling onto its surface, and loses ice either at the surface, where it is melted by warm air and winds, or from the edge, where it breaks off as chunks of solid ice or flows into the ocean as meltwater. In contrast to sea ice, glacier ice is formed on land but may end up in the ocean. Glaciers and ice sheets contribute to the river and lake systems of the Arctic to which they provide freshwater while melting. Nutrients and sediment are carried with the melting ice into rivers, lakes and the ocean.

Similar to trends observed for sea ice, lake and river ice cover, glacier ice is also rapidly declining (Dahl-Jensen et al., 2011; Sharp et al., 2011). Almost all Arctic glaciers have retreated over the past 100 years and the rate of loss has increased during the last decade across most regions (Sharp et al., 2011). The Greenland Ice Sheet is also losing ice in a series of fast-flowing glaciers that discharge to the ocean through fiords along the coast. These glaciers have increased their rate of flow and discharge an increased volume of ice (Dahl-Jensen et al., 2011; Nick et al., 2013). The warming of the ocean water that is in contact with the outflowing end of these glaciers would play a role in these rapid changes. The total loss of ice from Arctic glaciers and ice caps since 2000 (150 Gt/y) is in the same range as the ice loss estimated from the Greenland Ice Sheet (~200 Gt/y) (Dahl-Jensen et al., 2011; Sharp et al., 2011). However, the volume of the ice sheet is almost 12 times larger than the global volume of glaciers and ice caps.

The implications of land ice melt are numerous (Dahl-Jensen et al., 2011; Sharp et al., 2011). Freshwater is added to the ocean, which reduces the salinity and density of the surface water and, thereby enhances the water column stratification, especially in fiords and in coastal locations. These physical changes may have implications for marine food webs and thereby fisheries. The composition and production at the base of the food web will be altered and these changes will ultimately affect fish, birds and marine mammals. Moreover, new land areas are exposed and the global sea level is rising, affecting the populations living close to the coast (Dahl-Jensen et al., 2011; Sharp et al., 2011). Global mean sea level rose by 0.19 m over the period 1901-2010 (IPCC, 2013). Global mean sea level rise will keep rising during this century and at an increasing rate compared to those observed over 1971-2010 due to increased ocean warming (thermal expansion) and increased loss of mass from glaciers and ice sheets (IPCC, 2013). By 2100, the rise in the global sea level is projected to be between 0.52 and 0.98 m (IPCC, 2013). Also, it is important to note that in a few decades, in many parts of the Arctic, when glacier area will be greatly reduced, glacier runoff will decline. This will have implications for water supplies, water quality, hydroelectric power generation, coastal habitats and ocean circulation patterns (Sharp et al., 2011). Finally, iceberg production represents hazards to shipping and offshore activities.

9.3 Permafrost

Permafrost, or permanently frozen ground, is soil, sediment, or other rock material that remains at or below 0°C for two or more consecutive years (National Snow and Ice Data Centre, 2013c). Permafrost underlies the vast majority of the surface of the terrestrial Arctic and it can occur beneath offshore Arctic continental shelves (National Snow and Ice Data Centre, 2013c). At the soil surface, there is an active layer that freezes and thaws seasonally. Under this active layer, a transient layer can remain frozen in some summers and, underneath it, there is permafrost (Callaghan et al., 2011a). Taliks, unfrozen zones within permafrost, can occur, for example, under large water bodies (Callaghan et al., 2011a). Terrestrial permafrost thickness ranges from less than 1 meter to greater than 1,500 meters in the north of the Arctic region (National Snow and Ice Data Centre, 2013c). The active layer thickness is influenced by climate and local factors and vary from less than 0.5 m in vegetated, organic terrain to more than 10 m in areas of exposed bedrock (Callaghan et al., 2011a). The proportion of the landscape underlain by permafrost becomes greater with increasing latitude from the southern limits of the permafrost zone to the High Arctic (Callaghan et al., 2011a). The LIA is located well north of the continuous (90-100% of area) permafrost boundary.

Permafrost is intimately linked with biodiversity and ecosystem processes in the Arctic (Callaghan et al., 2011a). On one hand, permafrost influences soil temperature, drainage, nutrient availability, rooting depth and plant stability. It also provides a habitat for viable ancient microorganisms that live within permafrost. On the other hand, vegetation moderates ground surface temperature by insulating and protecting permafrost directly or indirectly by trapping snow. No species are dependent on permafrost and no ecosystems are limited by the presence of permafrost, as tundra can be underlain by permafrost or not. However, the presence of permafrost is playing a key role in plant species composition as it restricts the types of plants that can grow.

As a result of increased air temperature, the permafrost is degrading rapidly in most Arctic regions (IPCC, 2013). Temperatures in the permafrost have risen by up to 2 °C over the last three decades, although there are large regional variabilities (Callaghan et al., 2011a), and the southern limit of permafrost has moved northward in Russia and Canada (Callaghan et al., 2011a). This thawing trend is projected to continue and by 2100, the area currently underlain by permafrost near the surface (upper 3.5 m) would decrease by 37-81% (IPCC, 2013).

Permafrost thawing is having drastic impacts on the built and natural environments (Callaghan et al., 2011a). Arctic infrastructure (e.g. schools, hospitals, roads, airports) is greatly damaged and the design of any future development will need to take into account the instability of the permafrost. Also, permafrost thawing on mountain slopes can lead to rock slope instability and landslides. In addition, coastal erosion is enhanced since the Arctic coastline is composed of unconsolidated material rich in ice. With permafrost thawing during summer, the coasts are especially sensitive to the action of waves and experience high annual erosion rate. Moreover, the outcomes of thawing permafrost are at the opposite for hydrology; landscape dryness is increasing in the boreal forest

and ponds are drying, while waterlogging occurs in some flat areas of the Subarctic. This is because permafrost degrades in a continuum from rising temperatures in frozen ground (which increases the unfrozen water content and reduces the load-bearing strength of the ground) to complete thawing of ice-rich ground (which causes the surface to subside and creates depressions in the ground, termed 'thermokarst'). Biodiversity and ecosystem processes on land and in aquatic ecosystems are being affected by these changes in hydrology. Finally, permafrost thawing has a critical impact in greenhouse gases emissions. Recent research have demonstrated that permafrost soils (both terrestrial and beneath continental shelves) hold large pools of carbon, mostly in the form of methane (CH₄) and nitrous oxide (N₂O), and that the emission of these two powerful greenhouse gases from thawed permafrost could greatly increase radiative forcing and trigger abrupt climate change (Callaghan et al., 2011a).

10. Terrestrial biodiversity

This section examines Arctic terrestrial biodiversity. Soil microbial biodiversity, vegetation and animal biodiversity for terrestrial ecosystems (except aquatic ecosystems) are first described, then, aquatic biodiversity is presented.

10.1 Soil microbial biodiversity

Arctic soils are generally shallow and low productive. The heterogeneity of the soil cover is substantial and greatly influences the distribution of the soil biota occurring in relation to the small-scale topographic variations (Callaghan, 2005). The soil biota comprises invertebrates, fungi and prokaryotes (bacteria and archaea). Despite the critical role that these organisms play for the functioning of ecosystems by being responsible of carbon and nutrient fluxes, they are still poorly understood in the soil of the tundra compared with other species (Callaghan, 2005).

Recent progresses in molecular ecology have rarely been applied to Arctic terrestrial studies. Nevertheless, a molecular technique investigated the upper limit for variation of prokaryote diversity as compared with other systems. This technique revealed that Arctic polar desert and tundra soils contain a considerable level of prokaryote diversity; similar to boreal forest soils and much higher than arable soils (Callaghan, 2005). However, conventional inventories reveal that species number of all groups of soil microorganisms is lower in the Arctic than further south (Callaghan, 2005). Most groups of prokaryotes and fungi are represented in the soil of the tundra but some that are common elsewhere are rare or absent in the tundra. Soil microbial communities in the tundra vary seasonally; it is dominated by fungi during winter while certain bacteria become more important during spring, summer and fall, and the importance of fungi declines (Buckeridge et al., 2013). The soil nutrient status and environmental differences between winter and the other seasons explain these community differences (Buckeridge et al., 2013). Also, Arctic soils hold

large reserves of microorganisms. The harsh Arctic climate limits the metabolic activity of Arctic soil microorganisms.

Microorganisms are highly adaptive, tolerant of most environmental conditions and have short generation times that help to adapt to changes in environmental conditions. The main impact of climate change on Arctic soil microorganisms will likely be an increase in metabolic activity, to a similar level as the one of the boreal soils (Callaghan, 2005). Warmer temperatures, increase in atmospheric CO₂ concentration and a higher availability of nutrient will likely contribute to this. Increased in microorganisms activity implies accelerate soil organic matter decomposition (Koyama et al., 2013).

10.2 Vegetation

Vegetation in the Arctic

Environmental and climatic conditions are extreme for Arctic vegetation and control the plant communities that can grow. Summer temperature is the most important factor that influences Arctic vegetation (CAVM Team, 2003). The mean July temperatures are near 0°C on the northernmost Arctic islands. At these low temperatures, plants are at their metabolic limits, and small differences in the total amount of summer warmth make large differences in the amount of energy available for maintenance, growth, and reproduction. Higher summer temperatures cause the size, horizontal cover, abundance, productivity, and variety of plants to increase. Environmental factors such as landscape, topography, soil chemistry, soil moisture, and the history of plant colonization also influence the distribution of plant communities in the Arctic (CAVM Team, 2003). Most plants found in the Arctic are dwarf shrubs, herbs, lichens and mosses that grow close to the ground, and they cover the land surface that is not ice-covered (5.05 millions km² are covered by vegetation out of 7.11 millions km² of total land surface) (Walker et al., 2005). With decreasing latitude (moving from the High Arctic to the Low Arctic), the amount of warmth available for plant growth increases significantly, allowing the size, abundance, and variety of plants to increase as well (CAVM Team, 2003).

The circumpolar Arctic is subdivided along latitudinal subzones (Figure 4) and longitudinal floristic provinces (Figure 31). The latitudinal north-south axis reflects the present climate and vegetation gradient divided into five different subzones. A, B and C delineate bioclimate subzones of the High Arctic, while D and E are located in the Low Arctic (Table 4). Very steep bioclimate gradients occur in mountains and these areas are therefore mapped as elevation belts (CAVM Team, 2003). There is a clear increase in species numbers from the northernmost High Arctic subzone A (102 species) to the southernmost Low Arctic subzone E (2180 species) (Daniëls et al., 2013). The longitudinal east-west axis reflects different conditions in the past such as glaciations, land bridges and north-south trending mountain ranges (particularly in Asia). These influences have limited the exchange of species between parts of the Arctic (Daniëls et al., 2013). Species numbers per floristic province vary widely from approximately 200 species for the heavily glaciated and northern floristic province Ellesmere – North Greenland to more than 800 species for Beringian Alaska (Daniëls et al., 2013).

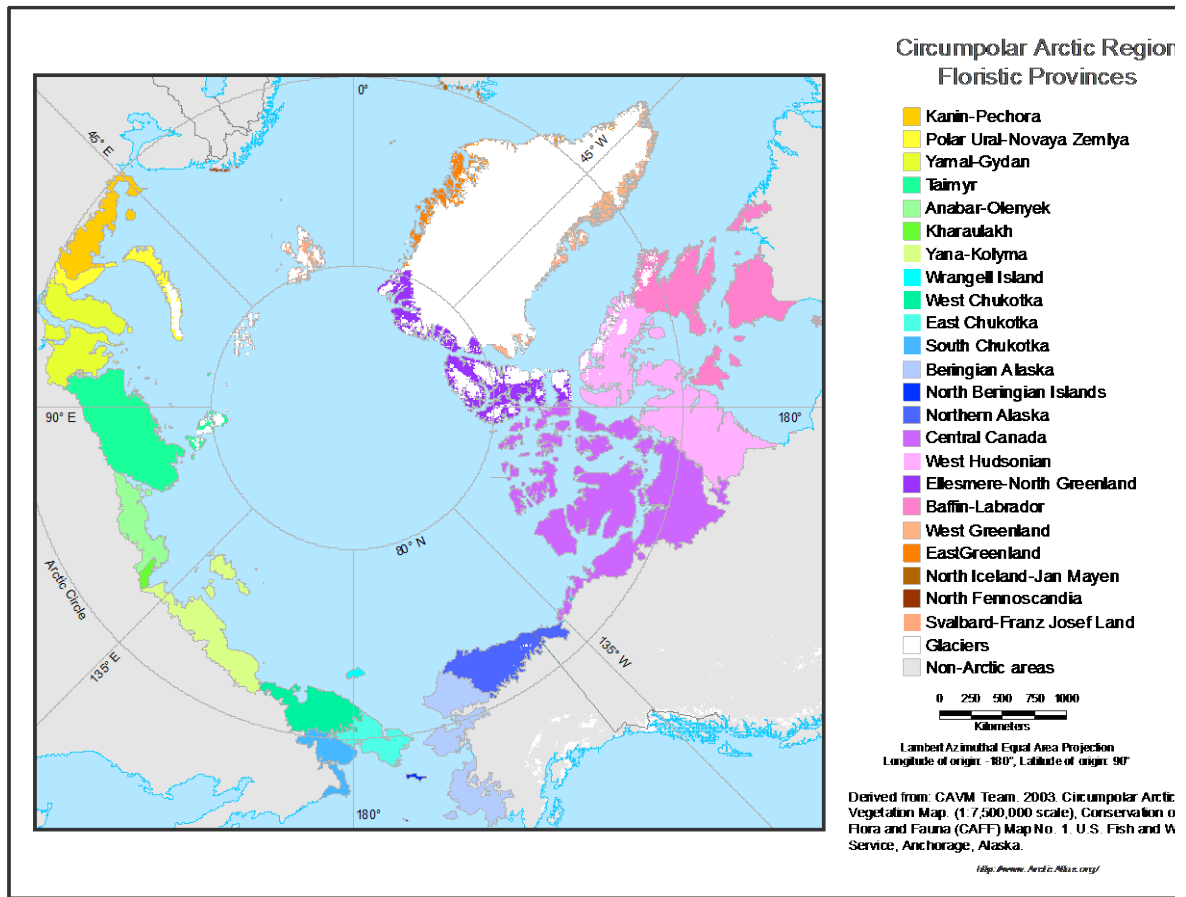


Figure 30. The floristic provinces of the circumpolar Arctic region (CAVM Team, 2003).

Table 4. Vegetation properties in each bioclimate subzone from CAVM Team (2003). Note that the subzone A is also known as polar desert, subzone B as Arctic tundra, subzones C and D as typical tundra and, subzone E as southern tundra. Alternatively, subzone A can also be named the Arctic herb subzone (absence of sedges and woody plants); B, the northern Arctic dwarf shrub subzone; C, the middle Arctic dwarf shrub subzone; D, the southern Arctic dwarf shrub subzone and E, the Arctic shrub subzone.

Subzone	Mean July Temp ¹ (°C)	Summer warmth index ² (°C)	Vertical structure of plant cover ³	Horizontal structure of plant cover ³	Major plant growth forms ⁴	Dominant vegetation unit (see Detailed Vegetation Descriptions for species)	Total phyto-mass ⁵ (t ha ⁻¹)	Net annual production ⁶ (t ha ⁻¹ yr ⁻¹)	Number of vascular plant species in local floras ⁷
A	0-3	<6	Mostly barren. In favorable microsites, 1 lichen or moss layer <2 cm tall, very scattered vascular plants hardly exceeding the moss layer	<5% cover of vascular plants, up to 40% cover by mosses and lichens	b, g, r, cf, of, ol, c	B1, G1	<3	<0.3	<50
B	3-5	6-9	2 layers, moss layer 1-3 cm thick and herbaceous layer, 5-10 cm tall, prostrate dwarf shrubs <5 cm tall	5-25% cover of vascular plants, up to 60% cover of cryptogams	npds, dpds, b, r, ns, cf, of, ol	P1, G1	5-20	0.2-1.9	50-100
C	5-7	9-12	2 layers, moss layer 3-5 cm thick and herbaceous layer 5-10 cm tall, prostrate and hemi-prostrate dwarf shrubs <15 cm tall	5-50% cover of vascular plants, open patchy vegetation	npds, dpds, b, ns, cf, of, ol, ehds* * in acidic areas	G2, P2	10-30	1.7-2.9	75-150
D	7-9	12-20	2 layers, moss layer 5-10 cm thick and herbaceous and dwarf-shrub layer 10-40 cm tall	50-80% cover of vascular plants, interrupted closed vegetation	ns, nb, npds, dpds, deds, neds, cf, of, ol, b	G3, S1	30-60	2.7-3.9	125-250
E	9-12	20-35	2-3 layers, moss layer 5-10 cm thick, herbaceous/ dwarf-shrub layer 20-50 cm tall, sometimes with low-shrub layer to 80 cm	80-100% cover of vascular plants, closed canopy	dls, ts*, ns, deds, neds, sb, nb, rl, ol *in Beringia	G4, S1, S2	50-100	3.3-4.3	200 to 500

¹ based on Edlund (1996) and Matveyeva (1998).

² Sum of mean monthly temperatures greater than 0°C, modified from Young (1971).

³ Chernov and Matveyeva (1997).

⁴ b - barren; c - cryptogam; cf - cushion or rosette forb; deds - deciduous erect dwarf shrub; dls - deciduous low shrub; dpds - deciduous prostrate dwarf shrub; g - grass; ehds - evergreen hemiprostrate dwarf shrub; nb - nonsphagnoid bryophyte; neds - nondeciduous erect dwarf shrub; npds - nondeciduous prostrate dwarf shrub; ns - nontussock sedge; of - other forb; ol - other lichen; r - rush; rl - reindeer lichen; sb - sphagnoid bryophyte; ts - tussock sedge. Underlined codes are dominant.

⁵ Based on Bazilevich, Tishkov and Vilcheck (1997), aboveground + belowground, live + dead.

⁶ Based on Bazilevich, Tishkov and Vilcheck (1997), aboveground + belowground.

⁷ Number of vascular species in local floras based mainly on Young (1971).

Approximately 3% (~5900 species) of known plant species occur in the Arctic (Callaghan, 2005). Vascular plants (2,218 species), bryophytes (mosses and liverworts; 900 species) and lichens (1,750 species) are the main structural components of terrestrial vegetation and ecosystems (Daniëls et al., 2013). Vascular plants and bryophytes are the two main groups of terrestrial plants and as primary producers, they perform photosynthesis and support all organisms of higher trophic levels. Vascular plant diversity of the Arctic is relatively poor. Approximately 2,218 vascular plant species are recognized in the Arctic which represent less than 1% of the known vascular plant species in the world (Daniëls et al., 2013). The majority of these Arctic vascular plant species have a circumpolar distribution (Daniëls et al., 2013). Bryophytes cover less land surface than vascular plants in the Arctic (Schofield, 1972) and they strongly differ in life cycle, structure and physiology (Daniëls et al., 2013). Turfs dominate the bryophyte growth form in the Arctic (Schofield, 1972). Bryophyte diversity is moderate in the Arctic although species number could increase in the course of future studies. The estimated species number of Arctic bryophyte is 900 species, significantly less than 1,750 lichen species and 2,218 vascular plants (Daniëls et al., 2013). High Arctic sites have fewer species of bryophyte than Low Arctic areas (Daniëls et al., 2013). Also, almost 80%

of these species have a circumpolar distribution (Daniëls et al., 2013). Bryophyte contribute to vegetation biomass in stable, wet-to-moist sites, and they add to species richness of many vegetation types in other habitats as very few vegetation type in the Arctic occur without bryophytes (Daniëls et al., 2013). Single shoots occur almost everywhere, and particularly in the High Arctic (Daniëls et al., 2013). Vascular plant endemism is well developed in the Arctic as 5% of the Arctic vascular plant species are endemic to the Arctic (Daniëls et al., 2013). Interestingly, the relative percentage of vascular plant species endemic to the Arctic decreases from the High Arctic to the Low Arctic (Daniëls et al., 2013). In contrast, Arctic endemism is not strongly pronounced for bryophytes (Daniëls et al., 2013). No species in the Arctic are currently considered as invasive, although some are at risk of becoming it with increasing human traffic combined with climate change (Daniëls et al., 2013).

Plants have always played a central role in the lives and cultures of Arctic indigenous peoples (Daniëls et al., 2013). Vascular plants are consumed and used for medicines. The use of bryophytes is little known and therefore, probably very restricted.

Vegetation in the LIA

The LIA region encompasses three bioclimate subzones. Islands between the Peary Channel and the M'Clure Strait, at the northwestern margin of the Canadian Arctic Archipelago, are characterized by subzone A, the northern coast of Ellesmere Island and Greenland, and territories on each shore of the Parry Channel, by subzone B, and the interior of Ellesmere Island and Devon Island, by subzone C. Two floristic provinces are found within LIA. Northern Greenland, Ellesmere Island, Axel Heiberg Island and Devon Island are part of the Ellesmere – North Greenland province. The other islands of the Canadian Arctic Archipelago north of the Parry Channel are included in the central Canada province. Appendix III presents a detailed overview of all sub-categories of vegetation types found in the LIA.

Climate change impacts on vegetation

The main impacts of climate change on the Arctic vegetation is greening, shrub expansion and floristic changes (Daniëls et al., 2013). Greenness is measured by indices such as the Normalized Difference Vegetation Index (NDVI), a measure of vegetation photosynthetic capacity. Most studies report a significant increase in greenness in the circumpolar Arctic that correlates with the general warming of this region (Henry et al., 2012). Large NDVI changes (10-15%) occurred in the Canadian High Arctic (part of LIA) (Bhatt et al., 2010). Increases in greenness are also reported to be linked to the loss of coastal sea ice (Bhatt et al., 2010). When there is less ice, air temperatures warm over land and the primary production of tundra ecosystem increases. This greening is accompanied with shifts in vegetation communities. Key plant events (such as leaf bud burst and flowering) and growth are stimulated by warmer temperature (Aft et al., 1999). Warming also increases shrub cover and height in the tundra ecosystems along the southern Low Arctic (Myers-Smith et al., 2011). This shrub expansion may result in important feedbacks effects. For instance, the darker and denser canopy will lower the albedo, increasing the amount of solar

radiation absorbed, and will lead to increased warming (Chapin et al., 2005). Also, taller shrubs enhance snow depth, which insulate the soil during winter, which result in greater microbial activity and greater nutrient availability (Sturm et al., 2005). In addition, the increased presence of shrubs will have implications for herbivores such as the caribou that feed on lichens, herbaceous and woody plants (Henry et al., 2012). There is no clear evidence of treeline advance. However, seedlings and saplings show the potential for increases in tree density within and beyond this zone of transition (Henry et al., 2012). Changes will also occur as plants with southern distributions will move into the Arctic as climate warms (Callaghan, 2005). These more aggressive species will compete with Arctic species and possibly represent the main threat to Arctic plant diversity (Callaghan, 2005). The heterogeneity of habitats in the Arctic and the high genotypical and phenotypical variability of Arctic plants will certainly result in the evolution of adaptations to benefit from higher temperatures and longer growing seasons. There is no evidence that any Arctic plant species has become extinct in the last 250 years (Elven, 2011). However, species with a very low abundance and a restricted distribution are the most vulnerable to ongoing climate change. Also, the loss of habitats induced by climate change may reduce the range of many plant species. This could cause losses of genetic diversity within species and therefore, hamper their capacity to adapt and persist in a changing climate (Alsos et al., 2012).

10.3 Terrestrial fauna

Biodiversity of Arctic terrestrial fauna

The species richness of Arctic terrestrial animals (6,000 species) is similar to the one of Arctic plants (~5900 species), and accounts for around 2% of the global total (Callaghan, 2005). The most diverse group of Arctic animals are insects with 3,300 species. Vertebrates are less diverse with 322 species in total, of which 75 are mammals, 240 are birds, 2 are reptiles and 5 are amphibians. Spiders (300 species), mites (700 species), springtails (400 species), nematodes (500 species), oligochaetes (700 species), molluscs (a few species) and protozoans (an unknown number of species) are also present. Similar to Arctic plants, diversity of Arctic animals declines with latitude and temperature (Callaghan, 2005). However, patterns of animal distribution are more diverse than for plants. As a consequence of the lower number of species present at high latitudes, dominance is more important in these regions (Callaghan, 2005). Arctic terrestrial food chains are short and simpler than further south. There are typically a couple of plant species involved (mainly grasses, sedges and willows), along with an herbivore (mammal or bird) and a top predator (mammal or bird) (Jensen and Christensen, 2003).

Terrestrial Arctic animals possess different adaptations that enable them to cope with low winter temperature and conserve energy. As an example, warm-blooded animals have thick coats of fur or feathers, they store fat and they reduce metabolism during winter (Callaghan, 2005). Numerous vertebrate animals escape harsh conditions by moving over long or short distances (Callaghan, 2005). Moreover, Arctic animals would be mostly generalist in terms of food and habitat selection, and this might be explained by the low presence of competitors and the unpredictable food resource availability (Callaghan, 2005). Some predators are also scavenging if and when

opportunities arise. In winter, carrion is the mainstay of Arctic foxes. They trail polar bears on the sea ice to eat the remains of seal kills, and they trail wolves on land for the same prey reason. These activities must be pursued circumspectly, as both polar bears and wolves will kill and eat Arctic foxes (Sale, 2006). Ivory gulls scavenge on carrion from polar bear kills (Sale, 2009).

Terrestrial fauna of the LIA

Terrestrial mammal species reported for LIA are listed at Appendix I. The terrestrial predator community of the LIA consists of Arctic wolf (*Canis lupus arctos*), Arctic fox (*Vulpes lagopus*), (red fox, *Vulpes vulpes*, on Devon Island) and stoat (*Mustela erminea*). Aerial predators in the LIA are rough-legged hawk (*Buteo lagopus*), gyrfalcon (*Falco rusticolus*), peregrine falcon (*Falco peregrinus*), snowy owl (*Bubo scandiacus*), jaegers and skuas (Stercorariidae), gulls (Laridae) and raven (Corvidae). There are many species of shorebirds that prey on invertebrates and molluscs on land, shorelines and tidal mud flats. Polar bears are summer season terrestrial predators and scavengers in the seasonal sea ice regions.

Caribou



Caribou. © P.Nicklen National Geographic Stock
WWF-Canada

Rangifer tarandus is called caribou in North America and reindeer in Europe. It is a conspicuous Arctic terrestrial species with a circumpolar distribution in the tundra and taiga zones of northern Europe, Siberia and North America (Figure 32). They have supported many cultures for thousands of years through meat and fat, and skins for clothing. Caribou is found throughout LIA; the subspecies Peary caribou (*Rangifer tarandus pearyi*) is found on the islands of the Canadian Arctic Archipelago and coastal northwestern Greenland (Government of Canada, 2013b; Jensen and Christensen, 2003). This subspecies is small (males measure 1.7 m in length on

average), have relatively short legs, they are almost completely white and they have small antlers (Government of Canada, 2013b). Peary caribou migrate seasonally between islands to maximize their use of the available habitat. During summer, they feed on dense vegetation in the slopes of river valleys and upland plains, while during winter they occur in areas where the snow is shallow. Caribou is an important prey species for many Arctic carnivores such as the golden eagles, wolves, and polar bears. The caribou is listed under the category of 'least concern' of the IUCN Red List due to a wide circumpolar distribution and presumed large populations (Henttonen and Tikhonov, 2008).

The number of mature individuals of Peary caribou in the population of the Queen Elizabeth Islands is 2100 (Government of Canada, 2013b), the Inglefield/Pruhoe Land population and the Olrik Fiord population in Greenland had an estimated population size of 2,300 in 1999, and an unknown number, respectively (Greenland Institute of Natural Resources, 2013). The best current

estimate of the total Peary Caribou population, including calves, is 7890 (Government of Canada, 2013b). The Peary caribou population is declining; the total population has declined by 72% since 1980, and the population on the Queen Elizabeth Islands has declined by about 37% (Government

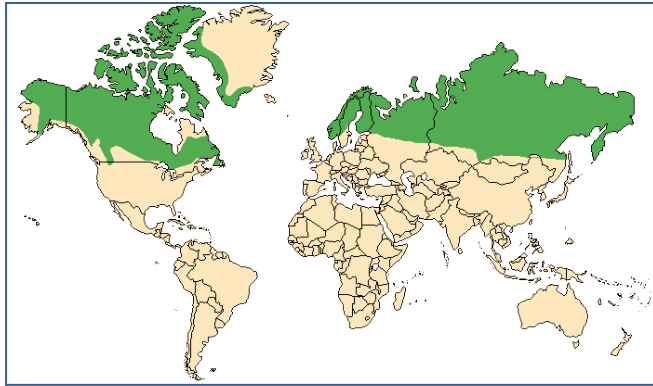


Figure 31. Distribution of caribou (Ultimate ungulate.com, 2012, compiled from Burt and Grossenheider, 1976; Whitehead, 1993)

of Canada, 2013b). The Peary caribou has been assessed as endangered under both the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) and the Species At Risk Act (SARA) (Government of Canada, 2013b). The main threat to this caribou population would be winters with heavy and persistent snow accumulation, in association with freezing rain and warm periods that cause the formation of ice crusts over vegetation. For this reason, climate change could lead to the disappearance of this population (Government of Canada, 2013b). Industrial development is still absent

in the Queen Elizabeth Islands and northwestern Greenland. However, future industrial operations could hamper seasonal migrations and cause disruptions during critical periods of their life cycle (Government of Canada, 2013b). Certain Peary caribou herds are characterized by low number and low genetic diversity, which reduce their ability to adapt to environmental stresses (Government of Canada, 2013b).

Lemming

The Northern Collared (or Arctic) lemming (*Dicrostonyx groenlandicus*) is an important species in the High Arctic ecosystem and it is widely distributed throughout the LIA. It copes with the severe winters by positioning its nest and tunnels under the snow. The Arctic lemming feeds on willow and grasses while it is the most important prey species for Arctic fox, stoat and snowy owls. Skuas, jaegers, gyrfalcon and raven also feed on lemmings. The lemming population follows a cyclical pattern and crashes at times, which influences especially the population of stoats. As an example, two races of Arctic foxes occur in Greenland: the white Arctic foxes are found primarily inland, and the blue Arctic foxes are associated with the coastal zone (Jensen and Christensen, 2003). The white Arctic foxes feed on lemmings and show much greater population fluctuations than the blue Arctic foxes that feed on stable food sources (Jensen and Christensen, 2003).

Musk ox

Musk ox (*Ovibos moschatus*) have lived in the Arctic for many thousands of years and they are survivors of the last ice age. They live in the Arctic tundra in Canada, Alaska, and Greenland (throughout LIA). These animals are well adapted to the Arctic climate with their long thick, shaggy fur that keeps them warm. Additional adaptations to the harsh Arctic climate are short legs and large, rounded hooves that allow them to move easily through shallow snow. These large

mammals (up to 360 kg) feed on roots, mosses and lichens and they supplement their diet with Arctic flowers and grasses during summer. Musk ox live in herds of two to three dozen animals and they use cooperation to deal with predation by wolves and dogs. When they are threatened, they form a circle, protecting their young in the middle, and they show their sharp horns outward. They are an integral part of the Inuit lifestyle as they provide large quantities of meat, and warm versatile insulating fur.

Impacts of climate change on terrestrial fauna

Current climate change is having observed impacts on Arctic terrestrial animals. Among them, alterations of freeze-thaw cycles lead to ice-crust formation that reduce the insulating properties of the snowpack, and alter temperature, oxygen and CO₂ conditions for animals living below the snow (Callaghan, 2005). In addition, ice crusts make vegetation inaccessible to herbivores, such as the caribou (Callaghan, 2005). Inuit are also reporting changes in animal behaviours (WWF, 2013a).

Future climate change will impact terrestrial animals in several ways (Callaghan, 2005). A projected deeper snow cover in winter is likely to limit the ability of the caribou to access winter pastures and to escape from predators (Callaghan, 2005). Migrant species may also be particularly vulnerable if climate change interferes with migration routes and staging sites. Some animal species time their reproduction to the seasonal peak in food resource availability. Future climate change might lead to mismatch if there is disruption in animal behaviour or change in timing of food availability. With future increase in summer temperature, interspecific interactions (competition, predation and parasitism) may be intensified (Callaghan, 2005). Species with temperate distributions will likely invade the Arctic and compete with Arctic species. The large and aggressive red fox would likely spread north, probably at the expense of the Arctic fox (Tannerfeldt et al., 2002). In addition, generalist predators that are currently absent in the Arctic are likely to move northward as ecosystem productivity increases (Callaghan, 2005). Also, longer growing seasons may be an advantage for species that come to the Arctic during the short summer season to feed and reproduce.

The main response of Arctic animal species to climate change impacts would be relocation rather than adaptation (Callaghan, 2005), since the geographic ranges of terrestrial species are generally well correlated with bioclimatic variables. Relocation possibilities vary from one region to another and are also restricted by geographical barriers. With the increasing length of the open water season, crossing between islands will become harder and will reduce the connectivity in habitats and isolate local populations. Hybridization of Arctic species will likely increase with melting sea ice as Arctic species spend more time with more temperate species (i.e. polar bears spend more time in the same environment that grizzlies). However, in most cases, hybridization tends to reduce individual genomic diversity and species diversity (Kelly et al., 2010). The rate of climate change would be too rapid for Arctic vertebrates to adapt through evolution.

10.4 Aquatic biodiversity

Arctic aquatic biodiversity

Aquatic biodiversity is known to decrease with increasing latitude, likely reflecting the increasingly harsh conditions (Prowse and Reist, 2013). Also, Arctic aquatic environments often have a simplified food web structure compared to temperate latitudes (Vincent et al., 2008). They range from simple with flagellates, ciliates and rotifers at the highest trophic level, to more complex with well-developed zooplankton and fish communities (Vincent et al., 2008). Shallow lakes and ponds exhibit extreme seasonality in temperature, water levels and light conditions, which preclude the presence of higher trophic levels (Prowse and Reist, 2013). The level of nutrients available in the lake (if it is oligotrophic, mesotrophic or eutrophic) and biogeography would likely influence the food web structure and diversity (Vincent et al., 2008). The microbial water column diversity of some Arctic lakes was reported to be very rich despite their extreme locations (Charvet et al., 2012; Comeau et al., 2012).

At the base of the food web, phytoplankton in polar lakes include bacteria, eukaryotic algae and ciliated protists (Lizotte, 2008). Between 20 to 150 species of phytoplankton are found per lake in the Arctic and species number was found to be correlated with latitude, altitude or water temperature (Moore, 1979; Prowse and Reist, 2013). Species composition would be mainly determined by water chemistry (Forsström et al., 2009). Chrysophytes were reported to dominate the phytoplankton communities of High Arctic lakes (Charvet et al., 2012). However, picocyanobacteria could be the most abundant cell types in these waters (Van Hove et al., 2008). Zooplankton are important components of Arctic lakes as they represent the highest trophic level of the foodweb in lakes without fish. Their abundance is therefore only controlled by food supply and their ability to survive in cold conditions (Rautio et al., 2008). Rotifers, copepods, cladocerans, fairy shrimps (Anostraca) and mysids are the main components of the zooplanktonic community of Arctic lakes and ponds (Rautio et al., 2008). The distribution of zooplankton species in Arctic lakes is largely dependant on geographic location and correlates with the distance from locations that escaped glaciation in the Pleistocene period (Rautio et al., 2008). Zooplankton feed preferably on phytoplankton but they can also feed on benthic microbial mats in shallow lakes (Rautio et al., 2008). Some species live on the edge of their environmental tolerance while others have adapted to life at low temperatures, short growing season, long periods of ice cover, and low food supply (Rautio et al., 2008). In lakes with fish, predation controls the zooplankton community, as fish are size-selective in their feeding. Zooplankton therefore tends to be small and transparent in order to escape predation in these lakes (O'Brien et al., 2004; Rautio et al., 2008). Different species of fish have different impacts on the zooplanktonic community (O'Brien et al., 2004).

Arctic lakes display low fish abundance and diversity. Within the Arctic, eastern Canadian Arctic and Greenland are the regions with the lowest diversity because they were deglaciated last during the last ice age and that they still retain large ice sheets (Christiansen and Reist, 2013). Five fish families (carps and minnows, trouts and salmons, sculpins, perches, and lampreys), out of the 17-19 present, comprise most of the Arctic freshwater diversity (Christiansen and Reist, 2013). Some

lampreys, and some trouts and salmon are anadromous, meaning that they undertake regular migrations between marine waters, to benefit from the productive marine coastal environments for feeding, and freshwater for reproduction, juvenile growth and over-wintering. These species are especially important for subsistence fisheries by local communities. About 127 species of fish occur in freshwater Arctic and sub-Arctic environments, which represent around 1% of the global fish estimate on the planet (Christiansen and Reist, 2013). Nonetheless, this estimate certainly underestimates Arctic freshwater fish diversity, as it does not consider the important diversity that occurs below the species level. Out of these 127 species, 83-85 are obligate freshwater forms, 39 are anadromous and 2 species are catadromous (fishes which migrate from freshwater into the sea to spawn) (Christiansen and Reist, 2013). Arctic char (*Salvelinus alpinus*) is the freshwater fish the most northerly distributed as it is the only species to occur north of 75°N latitude, and in the LIA (Christiansen and Reist, 2013). Lake A, a coastal lake located at 83°N on the northern coast of Ellesmere Island inhabits anadromous Arctic char population (Veillette et al., 2012). This fish species is widely distributed throughout many habitats and exhibit different life-history strategies that vary with latitude, resulting in high adaptability (Power et al., 2008). Some populations are resident in lakes and they show complex variety of life-history tactics: they vary in growth and feeding patterns, and occupy distinct niches. Other populations are anadromous. Lake char (*Salvelinus namaycush*) is also present in many lakes in the south of the Canadian Arctic Archipelago (Power et al., 2008).

The well-developed benthic microbial mats at the bottom of Arctic lakes, streams and ponds are dominated by cyanobacteria, but other algal groups such as chlorophytes and chromophytes are also present (Jungblut et al., 2009). The benthic invertebrate community is abundant in Arctic lakes and is mostly composed of insect larvae (chironomids), oligochaete worms, snails, mites and turbellarians (Rautio et al., 2008). The only macrophytes present in Arctic lakes are benthic mosses (Jungblut et al., 2009).

Impacts of climate change on aquatic biodiversity

Climate change has been identified as the main threat to Arctic freshwater ecosystems, and to their related biological and functional diversity (Prowse and Reist, 2013). Since freshwater biodiversity typically declines sharply poleward (because of lower temperatures), the responses of aquatic organisms to climate change by migrating northward is likely to be straightforward (Prowse and Reist, 2013). As an example, freshwater fish would move northward along river corridors and anadromous fish would migrate in marine waters northward as the climatic constraints lessen (Christiansen and Reist, 2013). This will increase fish diversity of Arctic lakes and rivers. Increased summer air temperature and precipitation would have positive effects on the condition of anadromous fish and would increase their overall abundance, survival and growth, mainly because of increased marine productivity (Reist et al., 2006). Shifts in ice cover regimes will have cascading effects on the biological communities. The longer duration of ice-free conditions may increase primary productivity due to improved light conditions, and to enhanced nutrient availability caused by wind-induced mixing and entrainment of nutrients into the euphotic zone (the surface layer with enough light for net photosynthesis), and catchment geochemical

inputs (Prowse et al., 2011). Shifts in algae and invertebrates are also associated with decreased ice cover conditions (Smol et al., 2005). Changes in the timing of freeze-up and break-up of lakes will also affect biological aspects linked with seasonality. As an example, the seasonal succession of plankton is strongly coupled with the freeze-up and the break-up of ice cover and summer thermal stratification. Also, an earlier break-up may advance spring phytoplankton bloom and the associated zooplankton biomass peak. Cold-water fish species, such as the Arctic char, will likely reduce their habitat as temperature warms (Prowse and Reist, 2013). Reductions in river ice cover will likely result in fewer ice-dam flood events and less severe break-up ice scouring.

11. Protected areas

Certain areas of the Arctic are currently under some form of protected status. Interactive mapping platforms showing these areas are available online at www.protectedplanet.net (the World Database on Protected Areas (WDPA), a joint project of IUCN and UNEP), and at www.arkgis.org (Arctic Geographical Information System, by WWF). Protected areas are a key tool to maintain and conserve Arctic biodiversity and the functioning landscapes upon which species rely on for survival (Barry and McLennan, 2010). They have been established in strategically important and representative areas in order to help to maintain crucial ecological and physical features (e.g. seabird colonies, caribou migration and calving areas) (Barry and McLennan, 2010). Arctic protected areas are also important for global biodiversity conservation as Arctic habitats provide essential resources for many bird and mammal species that migrate to the Arctic seasonally (Barry and McLennan, 2010). Arctic protected areas also play a role in holding values for societies and allowing traditional uses and lifestyles (CAFF, 2002). In many Arctic countries, protected areas are co-managed with indigenous and local peoples, through which access to resources is maintained and knowledge is shared (Barry and McLennan, 2010). Arctic protected areas provide significant long-term economic benefits, for example by tourism, in term of revenues and employment to the countries and to local communities (CAFF, 2002). Arctic protected areas are also important for education and recreation (Livingston, 2011). The Arctic contains most of the last remaining pristine and undisturbed landscapes. Protected areas in this region are therefore critical for research and monitoring as they can be used as benchmarks where human-induced changes are minimal (Livingston, 2011). However, increasing pressures from industrial development including the oil, gas, mining, forestry and transportation sectors, might modify the situation. Protected areas will face the challenge of resisting industrial pressures even if they offer economic benefits and job opportunities (CAFF, 2002).

Around 11% of the Arctic, 3.5 million km² divided in 1,127 protected areas, had some form of protected status in 2009 (Barry and McLennan, 2010). Obviously, the nature and level of protection, and governance of these areas vary between the different Arctic countries. Although this level of protection is considerable, it is important to note that the North-East Greenland National Park accounts for over a quarter of the protected territory, and that, although over 40%

of Arctic protected areas have a coastal component (Barry and McLennan, 2010), the marine environment is not well represented (CAFF, 2002). Therefore, the area of Arctic protected areas should be increased and the Aichi Biodiversity Target aims for at least 17% of terrestrial and inland water, and 10% of coastal and marine protected areas worldwide by 2020 (Convention on Biological Diversity, 2013). The Aichi Biodiversity Target also stresses the role of areas of particular importance for biodiversity, such as High Arctic environment, and the importance of connectivity between protected areas to facilitate species migration.

With ongoing climate change and increasing human impacts in the Arctic, it is urgent to assess the effectiveness of terrestrial protected areas as a conservation tool. Also, a changing climate motivates the identification and the advancement of the protection of large areas of ecologically important marine, terrestrial and freshwater habitats (CAFF, 2013a). It is critical to ensure environmental conservation outside of the actual protected areas boundaries as the northward shift of species or greening of the Arctic may move the target ecological features outside of the original protected area (Barry and McLennan, 2010). Areas critical for sensitive life stages of Arctic species may also be located outside of protected areas (CAFF, 2013a). Arctic biodiversity associated with sea ice, glaciers and permafrost is especially vulnerable to changing environmental conditions and CAFF recommend to safeguard areas where High Arctic species have greater chance to survive in the future for climatic and geographical reasons, such as certain islands and mountainous regions (CAFF, 2013a, b). These areas would act as a refuge for these specialized species. This recommendation is one of the main *raison d'être* of the LIA project.

There are several protected areas in LIA and its vicinity, which cover terrestrial and marine environments (Figure 33). Moreover, Canada is currently in the process of establishing a national marine protected area near Lancaster Sound (Parks Canada, 2013a). Lancaster Sound is the eastern entrance to the Northwest Passage, the sea route through Canada's Arctic Archipelago. This area is crucial for marine mammals including seals, narwhals, belugas, bowhead whales, walrus and polar bears. Lancaster Sound is also bordered by huge seabird breeding colonies, with populations in the hundreds of thousands. In addition, Qausuittuq is a proposed national park that includes most of Bathurst Island and a number of islands west of Bathurst Island, and is north of the Polar Bear Pass National Wildlife area (Parks Canada, 2012). This area has been chosen to represent the Western High Arctic Natural Region. This park would help to protect the endangered Peary caribou and other wildlife. The following paragraphs briefly describe each of the protected areas located in the LIA.

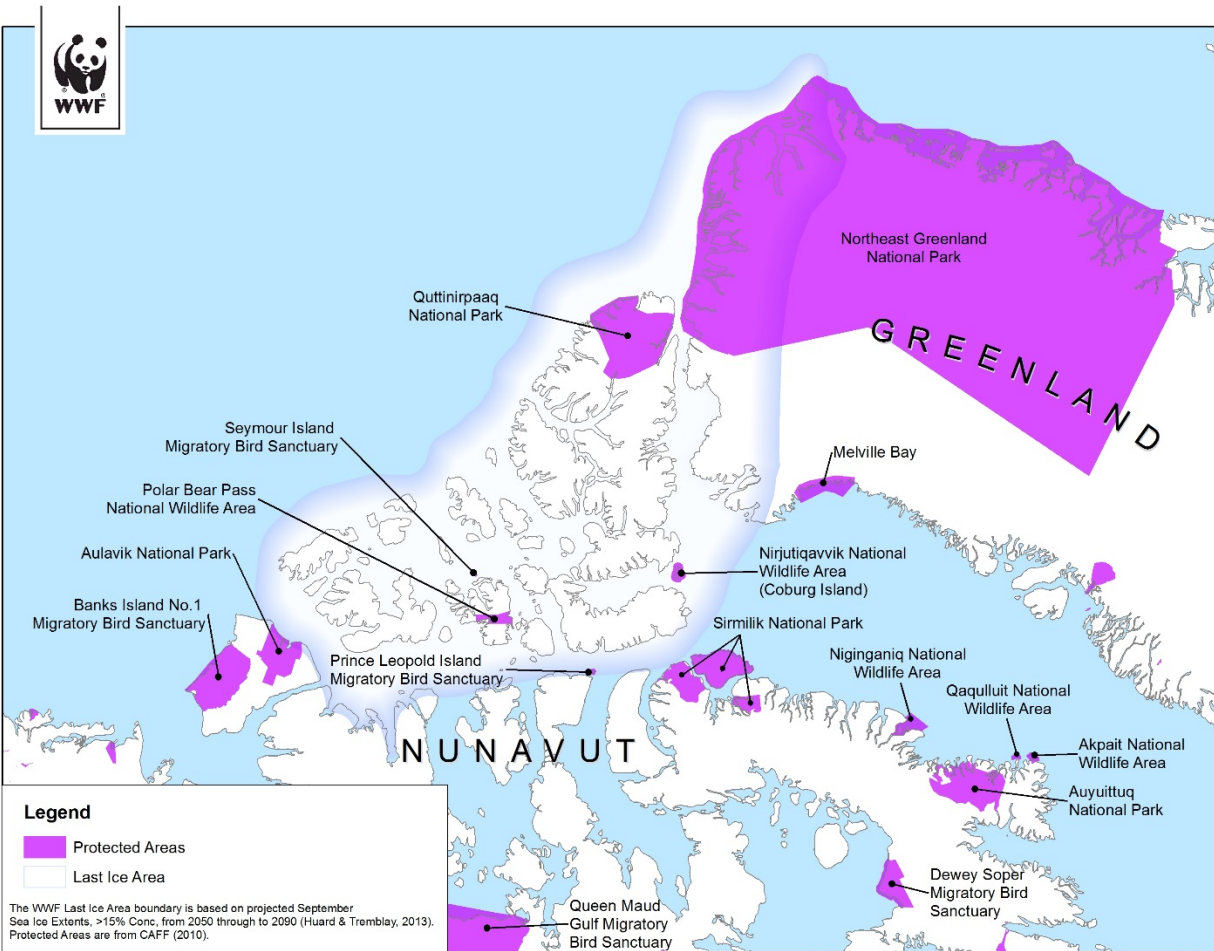


Figure 32. Protected areas in LIA and its vicinity (Protected Planet, 2013).

North-East Greenland National Park

The North-East Greenland National Park is the largest (with an area of 972,000 km²) and most northerly national park in the world. It extends three nautical miles into the adjacent sea. The Greenland Government established it in 1992, 15 years after it was appointed a UNESCO biosphere reserve. Mineral exploration is possible within this park (Tejsner and Frost, 2012). It is the only national park in Greenland and it encompasses the entire northeastern coastline of 18,000 km, and interior sections of Greenland. The Sirius Dog Sledge Patrol, Danish Navy, monitors the coastline of the park and is stationed at Daneborg, located in the National Park. Also, the research station Zackenberg is located within the park. There are no permanent Inuit settlements within the park.

Melville Bay Nature Reserve

This reserve borders with LIA. It is a large bay off the coast of northwestern Greenland. It is located to the north of the Upernavik Archipelago and opens to the southwest into Baffin Bay. It was

established in 1977. Melville Bay Nature Reserve has an area of 7,957 km², of which 5,193 km² are marine (Wood, 2007). The Greenland Government is currently drafting a new regulation for the nature reserve with a clearer definition of activities allowed within the reserve (e.g. traditional hunting) (Tejsner and Frost, 2012).

Quttinirpaaq National Park

The Quttinirpaaq (“top of the world” in Inuktitut) National Park is located on the northeastern part of Ellesmere Island. It is the northernmost park in Canada and the second largest, after Wood Buffalo National Park. It covers 37,775 km², of which 2,670 km² are marine (Wood, 2007). It was established as Ellesmere Island National Park Reserve in 1988, and the name was changed to Quttinirpaaq in 1999, when Nunavut was created, and became a national park in 2000 (Parks Canada, 2013b). Quttinirpaaq is pending an application as a UNESCO world heritage site (UNESCO, 2013). Most of Quttinirpaaq National Park is classified as an Arctic desert.

Sirmilk National Park

Located near Pond Inlet, Sirmilik (“the place of glaciers” in Inuktitut) National Park is composed of three separate areas at the north end of Baffin Island: most of Bylot Island, the area between Oliver Sound and Paquet Bay, and the Borden Peninsula east of Arctic Bay. Sirmilik National Park represents the Northern Eastern Arctic Lowlands Natural Region and portions of the Lancaster Sound Marine Region (Parks Canada, 2013c). This park was created in 2001 and has a global area of 22,252 km². Although this park does not include a marine portion, it is surrounded by ocean.

Aulavik National Park

Aulavik (“place where people travel” in Inuvialuktun) National Park is located on Banks Island and was established in 1992. This park protects 12,274 km of Arctic Lowlands (Environment Canada, 2013a). This park encompasses a variety of landscapes from fertile river valleys to polar deserts, is home to the Peary caribou and has the highest density of musk ox in the world.

Nirjutiqavvik National Wildlife Area (Coburg Island)

Nirjutiqavvik National Wildlife Area includes Coburg Island and its surrounding marine areas, and is located between Ellesmere Island and Devon Island. It was established in 1995. It encloses 1,650 km², including a marine portion with intertidal components of 1,283 km². This national wildlife area is one of the most important seabird nesting areas in the Canadian Arctic. It supports around 385,000 seabirds, predominantly Thick-billed Murres and Black-legged Kittiwakes. Northern Fulmars, Glaucous Gulls, Black Guillemots and Atlantic Puffins also nest on Princess Charlotte Monument Island (Environment Canada, 2013b). This area is also important for polar bear, walrus, ringed seal, bearded seal and migrating beluga and narwhal (Environment Canada, 2013b).

Polar Bear Pass National Wildlife Area (Bathurst Island)

Polar Bear Pass National Wildlife Area is located on Bathurst Island, in the heart of the Canadian Arctic Archipelago. It has an area of 2,636 km² (including 214 km² of marine environments) and was created in 1985. This protected area was created because it supports significant wildlife populations and important archaeological sites (Environment Canada, 2013c). Polar Bear Pass National Wildlife Area supports more than 54 species of birds including 30 breeding species (mostly waterfowl and shorebirds), Arctic fox, Arctic wolf, lemmings, musk ox, the Peary Caribou, and polar bears travel through the area in spring and summer.

Prince Leopold Island Migratory Bird Sanctuary

This migratory bird sanctuary is located on Prince Leopold Island within Lancaster Sound, at the junction of Prince Regent Inlet and Barrow Strait. It was established in 1992 and covers 311 km², including a marine portion of 243 km². This area is host to huge seabird colonies of murres, kittiwakes, fulmars and guillemots and its surrounding waters represent a major seabird feeding area (Environment Canada, 2013a).

Seymour Island Migratory Bird Sanctuary

This bird sanctuary is part of the Berkeley group of islands and is located approximately 30 km north of Bathurst Island. It was designated in 1975 and this protected area is small (28 km² including a marine portion of 20 km²). The island is approximately 3 km long, and raised beaches cover most of the island. Seymour Island supports the largest Ivory Gull colony in Canada. The Ivory Gull is an endangered species (Environment Canada, 2013a).

12. Additional potential stressors

Although the Arctic is still sparsely populated, it is experiencing pressure from numerous sources. Climate change is a prominent driver affecting the entire Arctic. The climatic impacts for marine and terrestrial environments, and their related biodiversity, have been addressed throughout the different sections of this report. Additional important factors that threaten the integrity of Arctic ecosystems are enhanced mining and oil and gas activities, increased shipping, and contaminants by local pollution or long-range transport. These anthropogenic stressors are also likely to interplay and have cumulative effects. A companion report by WWF on the non-renewable resources of the LIA looks more closely at the economic probability of exploitation of these resources. The text on mineral resources below is from the summary section of that report.

12.1 Oil and gas exploitation, and mining

Large known and predicted hydrocarbons occur in the LIA although there is no current exploration or production except for some seismic surveys by Conoco south of the Greenland LIA. Most of the past exploration emphasis has been in the Paleozoic and Mesozoic strata in the central Sverdrup Basin. Future exploration may test the play fairways along the southern rim of the Sverdrup Basin and the Arctic Fold Belt where there is significant hydrocarbon potential.

In the Greenland LIA hydrocarbon potential occurs in major offshore sedimentary basins, notably the large basins offshore west Greenland and east Greenland. To date no fields have been discovered and no commercial development occurs on the Greenland continental margin. Assessment studies indicate that there is significant potential for large resources in the offshore basins particularly in the West Greenland-East Canada Province.

The geological setting of the LIA naturally favours hydrocarbon georesources over mineral resources. The latest known period of widespread mineralization in the area predates the Paleozoic sedimentary rocks, therefore rocks of this age or younger may be discounted as sources of metalliferous deposits. Most of the mineral exploration activities occur in Archean rocks in the southern part of the LIA particularly on Baffin Island where the geology is more conducive for mineralization. A number of zinc-lead deposits and occurrences have been delineated in the Greenland part of the LIA with the Citronen Fjord deposit being in an advanced stage of exploitation. The Mary River iron ore project on Baffin Island is scheduled to begin commercial production in 2014.

There are many technical and environmental obstacles which will complicate Arctic and LIA development. Technical challenges arise from extreme climatic conditions that necessitate specific requirements for equipment, materials and construction operations. Environmental concerns are particularly associated with accidents and pollution that may damage delicate Arctic ecosystems and local people's livelihoods. The main obstacle, however, is the lack of sufficient infrastructure to confirm viability, economy and safety of LIA operations.

Climate warming presents challenges for resource development and infrastructure design in the LIA. Georesource activity is likely to experience savings due to reduced sea-ice extent and a longer shipping season. However, continued warming will increase the rate of permafrost thawing which in turn will alter ground conditions. This will adversely affect structures and increase the cost and maintenance of tailings impoundments, buildings, pipelines, airfields, and other installations which support resource activity. Structures must be designed to ensure that contaminants and acid-rock drainage are not discharged to the environment.

Large scale pollution is the primary environmental concern for georesource activity in the LIA. In Arctic environments pollution both onshore and offshore persist longer than anywhere else. Responder's time and efforts will be hampered by harsh environmental conditions, a near total

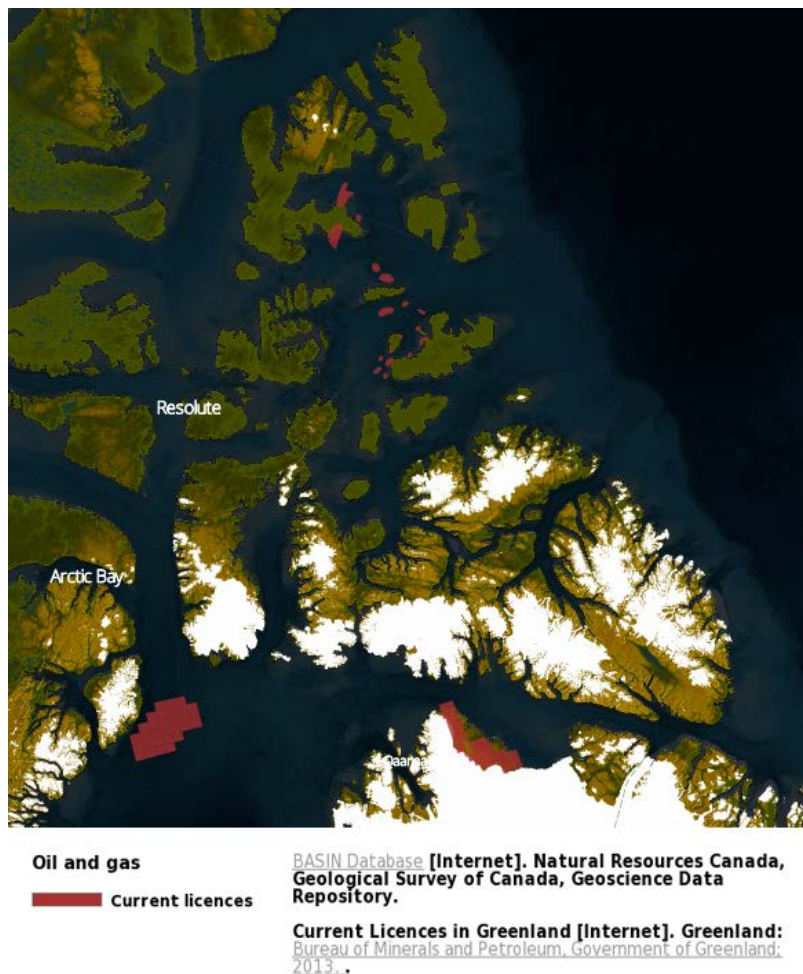


Figure 33. Location of current oil and gas rights in the Canadian Arctic Archipelago. Interactive map available at arkgis.org.

waves and rough weather conditions, and ocean currents will spread the pollutants over extensive areas. In the Arctic, low temperatures and scarce sunlight over much of the year will slow evaporation rates as well as the physical, chemical and biological breakdown of pollutants. Thus, hazardous compounds released during an emergency may remain in Arctic ecosystems for long periods of time, aggravating the risk of bioaccumulation.

The natural containment provided by ice may offer some relief. In open water, slicks can spread and drift so quickly that shoreline impingement may occur before a response can be initiated. Ice, however, may confine oil spills and provide time to mount a response. Due to the cold temperatures and reduced wave energies in ice fields, spilled oil will weather more slowly, which may extend the window-of-opportunity for some countermeasures. Extreme Arctic conditions present a number of challenges to mounting safe and effective oil spill response actions. To overcome these challenges responders must develop action plans with an understanding not only of the physical environment but also with a basic understanding of the effect this environment will have on the fate and behavior of spilled oil (Potter et al. 2012).

lack of infrastructure and long distances. The environmental and ecological impact of Arctic contamination would depend on its timing and location relative to patterns of breeding, spawning and species migration. Sea birds, marine mammals, and fish larvae are particularly vulnerable to larger oil spills and other industrial contaminants.

Oil spill prevention is the ultimate goal, but, in the event of a spill, operators must strive to ensure that the response is robust, efficient and well-adapted to local conditions. Ice in its various forms can make it more difficult to detect oil, and to encounter, contain and recover oil slicks with booms, skimmers, and other countermeasures (Glover and Dickins 1999). The current technologies and infrastructure for recovery of oil from the surface perform poorly in high

Reports from both industry and government groups in the polar states have addressed strategies and techniques for handling pollutants in a variety of ice conditions. With very little infrastructure in the LIA from which to stage an effective recovery program it becomes obvious that Canada and Greenland are poorly equipped to handle such catastrophes. The rich and unspoiled ecosystems of the LIA will always be at risk from industrial activity. A comprehensive, international policy on clean-up response techniques, mitigation policies and liability recommendations is required.

Conclusions

The LIA is a frontier region for petroleum and mineral exploration. Commodity forecasts, for both petroleum and minerals, predict a steady increase of demand for georesources and subsequent increase of prices over the next 20 to 25 years. New technology and data will make parts of the LIA more prospective. Given the long lead times necessary to meet regulatory requirements, a lack of strategic infrastructure, economic factors and insufficient scientific data large scale production of resources in the LIA is unlikely to occur within the next 20 to 30 years. New large discoveries in more temperate environments are of more interest for industry investment.

The most probable targets for future georesource development in the LIA are:

1. Hydrocarbons – Development of West Greenland-East Canada Province is possible in 20 to 25 years if current seismic studies delineate large-scale offshore structures (Gautier 2008). All the recent surveys are south of the LIA. The Greenland continental margin may be more prospective than the Sverdrup Basin due to infrastructure factors.
2. Zinc – Citronen mine site production is possible in 10 to 15 years if current activity demonstrates significant reserves (Ironbark 2011).
3. Iron ore – Limited production at Mary River may begin in 2014 but large scale mining is probably 15 to 20 years away (Nunavut Geoscience Exploration Overview 2012).

12.2 Shipping

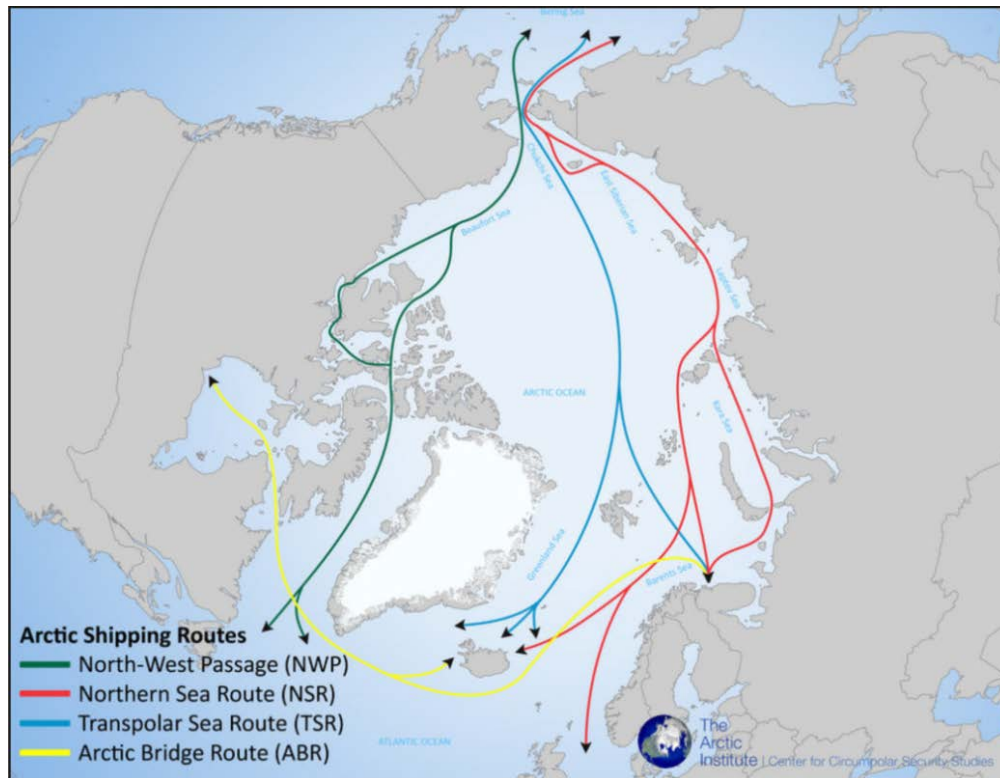
An increase in Arctic shipping through the LIA is expected by 2020, due to a surge of ecotourism voyages and the development of several large-scale mining projects such as Citronen Fjord in northeastern Greenland and the Mary River project on Baffin Island. By 2050, Arctic shipping in LIA waters could increase by a factor of six, if large-scale georesource production occurs (CIGI 2013). As maritime activities continue to increase, the levels of resupply to northern communities will also increase as populations grow. Problematically, only 10 percent of Canada's Arctic waters are charted to modern standards, according to the Canadian Hydrographic Service, and few navigational aids are available (Humbert and Raspotnik 2012).

New technology such as ice management systems provide more efficient ways to conduct operations by extending the operating season while mitigating ecological, environmental, and safety risks. Systems for ice management address the complex challenges associated with operating in the harsh but fragile Arctic environment and provide ice visualization, analysis, tracking and risk mitigation tools for offshore Arctic operations (Ion Geophysical 2013).

In 2007, the Canadian government said it would address the lack of deepwater port infrastructure in the Canadian LIA by committing \$100 million dollars to turn the port at the old Nanisivik mine on Baffin Island into a deepwater facility. Due to budget constraints in March 2013 the government announced a major downsizing of northern development leading to a reassessment of infrastructure investment (CIGI 2013).

The increasing gap between service requirements and capabilities, such as equipment transportation and spill response measures, in the LIA highlights the concerns of resource operators. The lack of infrastructure including road and rail networks, deepwater ports, paved runways, geology and topographic maps —impedes safe transportation, and makes exploration and resource development extremely difficult, risky and more expensive.

One of the Arctic's most important contributions to the northern Canadian and Greenlandic economies will be the Trans-Arctic waterways. Arctic states have recognized that the new waterways will be an opportunity to re-define their national boundaries and expand commercial operations. Three potential Trans-Arctic routes are being considered for formerly inaccessible regions (Figure 22). The shortest comparable routes, for instance, through the Panama or Suez Canals, or around the Cape of Good Hope, are more than twice the distance of the longest Arctic route (Parliament of Canada Info Series PRB 08-07E, 2008). The Northwest Passage route transits the LIA and will be crucial for future georesource activities.



Polar view of the major trans-arctic shipping routes. The Bering Strait is a natural choke point for shipping. Source: Humbert and Raspotnik 2012.

As cited in the Ottawa Citizen, January 4, 2014 the future may be here now. Most studies suggested that commercial shipping through the Northwest Passage would not occur for many years yet. However, in September 2013 the Danish owned Nordic Orion bulk carrier made history when it hauled 15,000 tonnes of coal from Vancouver to Finland through the North West Passage. It took four days less than it would have by transiting the Panama Canal and the greater sea depths allowed the Orion to carry 25% more coal. Shipping through the passage saved the company \$200,000. Talks are underway between Transport Canada and various shippers to increase such voyages. Unlike Russia, where shippers have more than 400 ice class carriers, Canada has not made upgrading Arctic infrastructure and shipping activities a priority. To take advantage of newly open Arctic shipping lanes Canada and Greenland must make significant investments in shipping facilities and define regulations required for safe transportation through the LIA.



Figure 34. Ship traffic density in the LIA region illustrated by a scale from yellow (low traffic) to red (high traffic). Ship traffic density indicates the intensity of shipping as a function of the size and number of ship tracks in a 5 x 5 km grid. The ship traffic observations are made through the satellite based Automatic Identification System (AIS), which provides the identification of the spatial location of a vessel at a given time. Automatic System AIS data are provided by The Norwegian Coastal Administration www.havbase.no 2012 and further processed by DNV and WWF. Map made by arkgis (www.arkgis.org).

The impacts of shipping can be deleterious for marine biodiversity. The increase in transport augments the risks of the introduction of invasive species by ballast waters that could disrupt the ecosystems. Also, noise and direct contact from ships can induce disturbance or harm marine mammals and fish. Oil and gas spills could also have dramatic effects on this sensitive region. Some of these impacts are expected to be addressed to some extent by the forthcoming Polar Code of the International Maritime Organization, but not all.

12.3 Contaminants

The Arctic is not as clean as it should be based on its remote location, few in-situ industrial activities and direct sources pollution and contaminants. Unfortunately, the Arctic is a sink for man-made contaminants (Macdonald,

2005). Contaminants, originating from temperate industrial centres, travel by long-range-transport within the atmosphere, oceans, rivers and migratory animals (AMAP, 2009). When the contaminants that travelled by atmospheric currents arrive in the Arctic, they reach the ground and surface water because of cold condensation.

Contaminants found in the Arctic include the persistent organic pollutants (POPs), heavy metals (such as mercury, cadmium and lead) and radionuclides (radioactive atoms). Current trends in contaminant burden in the Arctic environment vary among these different classes of compounds. There was a general decline in the concentrations of legacy POPs (PCBs, DDTs, HCB, chlordane, dieldrin, toxaphene, dioxins) in the 1990's as a result of their reduced usage (AMAP, 2009). Emerging and current-use POPs (include brominated flame retardants (BFRs), fluorinated compounds, PCNs, endosulphan) are not yet regulated by international agreements. Nevertheless, BFRs are starting to decline in the environment due to national regulations (AMAP, 2009). However, trends in mercury concentrations over time vary from one region to another and from one type of environment (such as the atmosphere, lakes, biota) to another (AMAP, 2011). Reductions in mercury emissions from human activities over the last 30 years is reflected by decreasing mercury levels in the High Arctic atmosphere, although mercury levels in most animals

are not showing this trend (AMAP, 2011). Cadmium and lead were generally found to decline (AMAP, 2009). Radionuclides level in the environment would also be declining (AMAP, 2009).

Contaminants impose an additional stress on Arctic ecosystems as they enter and move through Arctic food webs. Many of these chemicals bio-amplify (i.e. concentrations in higher trophic levels are greater than at the base of the food web) and reach very high levels in top predators such as the polar bears and people. Contaminants can cause chronic and acute health effects on species over the short and long term. Climate change is also interacting with contaminant transport pathways (AMAP, 2009). For instance, higher temperatures in temperate industrial centres will increase the volatilization of contaminants, these will travel by atmospheric transport to the Arctic, and there will be a greater delivery of contaminants to the Arctic (AMAP, 2009).

13. Concluding remarks

The LIA region encompasses an exceptional variety of marine and terrestrial ecosystems. The Arctic environment is currently facing multiple threats with climate change being the most prominent. Climate change is associated with drastic changes in the marine environment such as loss in sea ice cover, warmer water temperature, ocean acidification, and shifts in the marine food webs. The terrestrial environment sees its snow cover altered, lakes and rivers ice cover decline, glaciers retreat, the Greenland Ice Sheet is losing ice, and permafrost is melting. Species with specialized life histories, as those in association with ice and snow, may struggle for persistence in the future as their strong ties with the cryosphere make them less resilient to change. Sea ice obligate and associated species will need to adapt to other habitats and prey species, or may shift their range northwards with the decline in sea ice cover. However, the North is not an endless frontier – there is no further North left after 90°N. Where species depend on terrestrial habitats in part of their lifecycle (such as polar bears which den on land), northward shifts are even more limited as land terminates at around 82°N. Furthermore, the rate of change currently occurring in the Arctic is extremely fast, pushing the adaption capability of species to their limits.

The LIA area needs to be monitored and indicators of change could be very useful for this. Indicators are features that are sensitive to shifts. Polynyas (Smith Jr and Barber, 2007) and epishelf lakes (Veillette et al., 2008) were suggested to be effective indicators in the High Arctic and they are currently present in the LIA. There is a need for better understanding of the productivity of the high Arctic, the current density and distribution of life there, and the operation of its systems. This is being addressed by ongoing scientific research (such as that sponsored by ArcticNet) but coverage of this region of the High Arctic is still partial at best due to the difficulty and expense of conducting research in the region, and the vast area to cover.

While defining management regimes for the LIA, special attention should be paid to critical habitats such as migration routes, foraging, breeding and resting areas of Arctic species. Also, economic

activities need to be managed in a way that needs of local communities are fulfilled within the limits of biodiversity and ecosystem functions capacity. Most importantly, attention needs to be paid to projected future states of the Arctic when defining management regimes. What has worked within a relatively stable environment over the past several decades may not work with the extremely rapid environmental, economic, and social change that the Arctic is now experiencing. Monitoring and further investigation of the ice ecosystem of the LIA are useful contributions but action to conserve those ecosystems must not be contingent on a full and complete scientific understanding of those systems, otherwise any interventions may be too late.

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Appendix I List of mammal species

Species Name		Sub-species	North Greenland	Ellesmere and Devon Islands	Canadian Archipelago
English	Scientific				
Marine mammals					
Whales					
Beluga	Delphinapterus leucas		√	√	
Bowhead Whale	Balaena mysticetus		√	√	
Narwhal	Monodon monoceros		√	√	√
Orca	Orcinus orca			√	
Pinnipeds					
Bearded Seal	Erignathus barbatus			√	
Harp Seal	Phoca groenlandica			√	
Ringed Seal	Pusa hispida			√	
Walrus	Odobenus rosmarus	O.r. rosmarus Atlantic	√	√	
Polar bear					
Polar Bear	Ursus maritimus		√	√	√
Terrestrial mammals					
Arctic Fox	Alopex lagopus		√	√	√
Arctic Hare	Lepus arcticus		√	√	√
Musk Ox	Ovibos moschatus		√	√	√
Northern Collared Lemming	Dicrostonyx groenlandicus		√	√	√
Red Fox	Vulpus vulpus			√	
Reindeer	Rangifer tarandus	R.t. groenlandicus Barren-ground and <i>R.t. pearyi</i>	√ R.t. groenlandicus Barren-ground	√ R.t. pearyi	√ R.t. pearyi

Stoat	Mustela erminea		√	√	√
Wolf	Canis lupus	C.l. arctos	√	√	√
Wolverine	Gulo gulo	G.g. luscus		√	√

Mammals present in LIA (Sale, 2006).

Appendix II List of bird species

English Name	Scientific Name	Range
Red-throated Diver	<i>Gavia stellata</i>	Throughout Canadian LIA
Northern Fulmar	<i>Fulmarus glacialis</i>	Southeast Ellesmere Island, southwest Devon Island
Snow Goose	<i>Anser caerulescens</i>	All islands directly along the Parry Channel, southern Ellesmere Island
Brent Goose	<i>Branta bernicla</i>	Northern Ellesmere Island, southern Devon Island
Common Eider	<i>Somateria mollissima</i>	Devon and Cornwallis islands
King Eider	<i>Somateria spectabilis</i>	Throughout LIA
Long-tailed Duck	<i>Clangula hyemalis</i>	Throughout LIA
Rough-legged Buzzard	<i>Buteo lagopus</i>	All islands directly along the Parry Channel
Gyrfalcon	<i>Falco rusticolus</i>	Greenland (north-east, north, north-west), Ellesmere, Devon, Melville, Prince Patrick islands
Rock Ptarmigan	<i>Lagopus muta</i>	Throughout LIA (except northern Ellesmere)
Sandhill Crane	<i>Grus canadensis</i>	Southern Devon and Cornwallis islands
Ringed Plover	<i>Charadrius hiaticula</i>	Eastern Devon and eastern Ellesmere islands
American Golden Plover	<i>Pluvialis dominica</i>	Southern Devon Island
Grey Plover	<i>Pluvialis squatarola</i>	Melville Island
Baird's Sandpiper	<i>Calidris bairdii</i>	Throughout LIA, except northernmost Greenland
Knot	<i>Calidris canutus</i>	Throughout LIA
Pectoral Sandpiper	<i>Calidris mealnotos</i>	All islands directly along the Parry Channel
Purple Sandpiper	<i>Calidris maritima</i>	Devon and southern Ellesmere islands
Sanderling	<i>Calidris alba</i>	Throughout LIA
Buff-breasted Sandpiper	<i>Tryngites subruficollis</i>	Southern Devon and Cornwallis islands
Ruddy Turnstone	<i>Arenaria interpres</i>	Throughout LIA
Grey Phalarope	<i>Phalaropus fulicarius</i>	All islands directly along the Parry Channel
Arctic Skua	<i>Stercorarius parasiticus</i>	Southern Ellesmere, Devon, Cornwallis, and Badhurst islands

Long-tailed Skua	<i>Stercorarius longicaudus</i>	Throughout LIA, except northeast Greenland
Pomarine Skua	<i>Stercorarius pomarinus</i>	Devon Island
Glaucous Gull	<i>Larus hyperboreus</i>	Throughout LIA
Iceland Gull	<i>Larus glaucoides</i>	Southeast Ellesmere and southeast Devon islands
Thayer's Gull	<i>Larus thayeri</i>	Ellesmere, Axel Heiberg, Devon, and Cornwallis islands
Sabine's Gull	<i>Xema sabini</i>	Northeast and northwest Greenland
Black-legged Kittiwake	<i>Rissa tridactyla</i>	Southeast Ellesmere and southeast Devon islands
Ivory Gull	<i>Pagophila eburnea</i>	Throughout LIA
Ross' Gull	<i>Rhodostethia rosea</i>	Southeast Ellesmere Island
Arctic Tern	<i>Sterna paradisaea</i>	Throughout LIA
Brünnich's Guillemot	<i>Uria lomvia</i>	Southeast Ellesmere Island
Black Guillemot	<i>Cepphus grylle</i>	South and southeast Ellesmere, northern Devon and Cornwallis islands
Snowy Owl	<i>Bubo scandiacus</i>	Throughout LIA (except northernmost Greenland)
Shore Lark	<i>Eremophila alpestris</i>	All islands directly along the Parry Channel, and southern Ellesmere Island
Northern Wheatear	<i>Oenanthe oenanthe</i>	Ellesmere (except the northern part), and Devon islands
Common Raven	<i>Corvus corax</i>	Throughout LIA
Lapland Bunting	<i>Calcarius lapponicus</i>	Southern Ellesmere Island, and all islands directly along the Parry Channel
Snow Bunting	<i>Plectrophenax nivalis</i>	Throughout LIA
Arctic Redpoll	<i>Carduelis hornemanni</i>	Greenland (north-east, north, north-west), Ellesmere, and Devon islands

Birds of LIA (Sale, 2006).

Main breeding colonies	Sensitivity*	Nr. seabirds	Key species
Cape Vera	Moderate	> 20,000	Northern fulmar
Coburg Island	High	> 400,000	Thick-billed murre, Black-legged kittiwake, Northern fulmar
Baillie-Hamilton Island	Moderte	> 5,000	Black-legged kittiwake
Hobhouse Inlet	Moderate	> 40,000	Northern fulmar
Browne Island	Moderate	> 4,000	Black-legged kittiwake
Cape Liddon	Moderate	> 20,000	Northern fulmar
Prince Leopold Island	High	> 400,000	Thick-billed murre, Black-legged kittiwake, Northern fulmar
Other important bird areas	Function		Key species
Cheyne Islands	Polynya = productive area		Ross's gull
Eastern Devon Island	Breeding colonies		Ivory gull, Iceland gull, Glaucous gull
Eastern Jones Sound	Foraging area, breeding ground Atlantic puffin		Atlantic puffin
Eastern Lancaster Sound	Food stopover on migration, breeding colonies		Northern fulmar, Black-legged kittiwake, Thick-billed murre
Hell Gate and Cardigan Strait	Polynya = productive area, breeding colonies		Black guillemot, Northern fulmar, Common eider
Inglefield Mountains, Ellesmere Island	Nunataks, highest nr breeding colonies Ivory gull		Ivory gull
Nasaruvaalik (Unnamed) Island	Breeding colonies		Common eider, Arctic tern, Ross's gull
Nirjutiqavvik (Coburg Island)	Breeding colonies		Black-legged kittiwake and Thick-billed murre
Seymour Island	Canada's largest Ivory gull colony		Ivory gull
Skruis Point, Devon Island	Breeding colonies		Black guillemot
Sydkap Ice Field, Ellesmere Island	Ivory gull breeding colonies		Ivory gull

Main breeding colonies and other areas of importance to seabirds in the Canadian Arctic Archipelago (Environment Canada, 2005; Environment Canada, 2012). * Sensitivity to human disturbances such as close approach, garbage, oil spills

Appendix III Vegetation characteristics

CAVM Code	Vegetation Type	Description	Rank (area)
B1	Barrens - cryptogam, herb barren	<p>Dry to wet barren landscapes with very sparse, very low-growing plant cover. Scattered herbs, lichens, mosses, and liverworts.</p> <p>Dry to wet barren desert-like landscapes mainly in Subzone A and on some coarse-grained, often calcareous sediments in subzones B and C. Sparse (2-40%) horizontal plant cover, and very low vertical structure (generally <2 cm tall) with a single layer of plants where they occur. Dry herb barrens composed of few scattered vascular plants are present over much of the landscape. Snow-fl ush communities are often a conspicuous component, forming dark streaks on the otherwise barren lands, composed largely of bryophytes and cryptogamic crusts. In upland areas, vascular plant cover is generally very sparse (<2%), mainly scattered individual plants often in crevices between stones or small (< 50 cm diameter) cryoturbated polygons. Sedges (Cyperaceae), dwarf shrubs, and peaty mires are normally absent.</p> <p>Dominant plants: The most common vascular plants are cushion forbs (<i>Papaver dahlianum</i> ssp . <i>polare</i>, <i>Draba</i>, <i>Potentilla hyperarctica</i> a, <i>Saxifraga oppositifolia</i> n) and graminoids (<i>Alopecurus alpinus</i>, <i>Deschampsia borealis/brevifolia</i>, <i>Poa abbreviata</i>, <i>Puccinellia angustata</i>, <i>Phippsia</i> , <i>Luzula nivalis</i> a , <i>L. confusa</i> a), lichens (<i>Caloplaca</i> , <i>Lecanora</i>, <i>Ochrolechia</i>, <i>Pertusaria</i>, <i>Mycobilimbia</i>, <i>Collema</i>, <i>Thamnolia</i>, <i>Cetraria</i>, <i>Flavocetraria</i>, <i>Cetrariella</i>, <i>Stereocaulon</i>), mosses (<i>Racomitrium</i>, <i>Schistidium</i>, <i>Orthothecium</i> n , <i>Ditrichum</i> n , <i>Distichium</i> n , <i>Encalypta</i>, <i>Pohlia</i>, <i>Bryum</i>, <i>Polytrichum</i>), liverworts (e.g., <i>Gymnomitrium</i>, <i>Cephaloziella</i>), and cyanobacteria.</p>	3
B3b	Barrens - noncarbonate mountain complex	<p>Mountain vegetation on noncarbonate bedrock. 2 layers: moss layer 1-3 cm thick, herbaceous layer 5-10 cm tall; prostrate dwarf shrubs <5 cm tall.</p> <p>Dry acidic tundra complexes on mountains and plateaus with noncarbonate bedrock. Vegetation changes with elevation in the mountains, forming elevation belts whose vegetation is physiognomically similar to that of bioclimate subzones with comparable summer climate. Mesic zonal microsites are relatively uncommon. More common are plant communities growing on wind-swept, rocky ridges, screes, and dry fell- elds, alternating with snowbed plant communities.</p>	6

B3c	Barrens - noncarbonate mountain complex	Mountain vegetation on noncarbonate bedrock. 2 layers: moss layer 1-3 cm thick, herbaceous layer 5-10 cm tall; prostrate dwarf shrubs <5 cm tall. Dry acidic tundra complexes on mountains and plateaus with noncarbonate bedrock. Vegetation changes with elevation in the mountains, forming elevation belts whose vegetation is physiognomically similar to that of bioclimate subzones with comparable summer climate. Mesic zonal microsites are relatively uncommon. More common are plant communities growing on wind-swept, rocky ridges, screes, and dry fell-fields, alternating with snowbed plant communities.	5
B3n	Barrens - noncarbonate mountain complex	Nunatak area	10
B4b	Barrens - carbonate mountain complex	Mountain vegetation on carbonate bedrock. 2 layers: moss layer 1-3 cm thick, herbaceous layer 5-10 cm tall; prostrate dwarf shrubs <5 cm tall. Dry calcareous tundra complexes on mountains and plateaus with limestone or dolomite bedrock. Vegetation changes with elevation in the mountains, forming elevation belts whose vegetation is physiognomically similar to that of bioclimate subzones with comparable summer climate. Mesic zonal microsites are relatively uncommon. More common are plant communities growing on wind-swept, rocky ridges, screes, and dry fell-fields, alternating with snowbed plant communities.	7
B4c	Barrens - carbonate mountain complex	Mountain vegetation on carbonate bedrock. 2 layers: moss layer 1-3 cm thick, herbaceous layer 5-10 cm tall; prostrate dwarf shrubs <5 cm tall. Dry calcareous tundra complexes on mountains and plateaus with limestone or dolomite bedrock. Vegetation changes with elevation in the mountains, forming elevation belts whose vegetation is physiognomically similar to that of bioclimate subzones with comparable summer climate. Mesic zonal microsites are relatively uncommon. More common are plant communities growing on wind-swept, rocky ridges, screes, and dry fell-fields, alternating with snowbed plant communities.	8
G1	Graminoid tundras _ rush/grass, forb, cryptogam tundra	Moist tundra with moderate to complete cover of very low-growing plants. Mostly grasses, rushes, forbs, mosses, lichens, and liverworts. Moist tundra on fine-grained, often hummocky soils in subzones A and B. Plant cover is moderate (40-80%), and the vegetation forms a single layer generally 5-10 cm tall. This is the zonal vegetation in Subzone A, often occurring in somewhat more protected areas with moderate snow cover. Except for the greater density of plants, particularly rushes and grasses, it is similar in composition to cryptogam, cushion-forb barrens.	4

		<p>Dominant plants: Grasses (e.g., <i>Alopecurus alpinus</i>, <i>Dupontiafi sheri</i>, <i>Deschampsia borealis/brevifolia</i>, <i>Poa abbreviata</i>, <i>P. arctica</i>) and rushes (<i>Luzula nivalis a</i>, <i>L. confusa a</i>) are usually the dominant vascular plants. Forbs (<i>Cardamine bellidifolia a</i>, <i>Cerastium regelii n</i>, <i>Minuartia rossii n</i>, <i>Papaver dahlianum ssp. polare</i>, <i>Potentilla hyparctica a</i>, <i>Saxifraga oppositifolia n</i>, <i>Ranunculus hyperboreus</i>, <i>Draba n</i>, <i>Stellaria n</i>, <i>Oxyria digyna</i>) are abundant. Mosses are common (<i>Aulacomnium turgidum</i>, <i>Tomentypnum nitens n</i>, <i>Ditrichum n</i>, <i>Oncophorus wahlenbergii</i>, <i>Polytrichum</i>, <i>Racomitrium a</i>, <i>Schistidium</i>) and lichens (<i>Lecanora</i>, <i>Biatora</i>, <i>Pertusaria</i>, <i>Ochrolechia</i>, <i>Thamnolia</i>, <i>Cetrariella</i>, <i>Flavoce-traria</i>, <i>Stereocaulon n</i>), and liverworts. Cryptogamic crusts composed of cyanobacteria and black crustose lichens are common. In Subzone B, prostrate dwarf shrubs (<i>Dryas n</i>, <i>Salix polaris</i>, <i>S. arctica n</i>) and sedges (e.g., <i>Carex aquatilis</i>, <i>Eriophorum</i>) are present but not dominant.</p>	
G2	Graminoid tundras - graminoid, prostrate dwarf-shrub, forb tundra	<p>Moist to dry tundra, with open to continuous plant cover. Sedges are dominant, along with prostrate shrubs < 5 cm tall. Moist to dry tundra in Subzone C and warmer parts on fine-grained, often hummocky circumneutral soils with moderate snow. This is the zonal vegetation on nonacidic soils. Plant cover is moderate (40-80%) and 5-15 cm tall. The diversity of plant communities is much greater than in Unit G1 and includes <i>Cassiope tetragona</i> snowbeds, well-developed mires, and streamside plant communities.</p> <p>Dominant plants: Sedges (<i>Carex misandra</i>, <i>C. lugens/arctisibirica/ bigelowii</i>, <i>C. rupestris</i>, <i>Eriophorum triste</i>, <i>Kobresia myosuroides</i>, <i>C. aquatilis ssp. stans</i> (moister sites)), rushes (<i>Luzula nivalis a</i>, <i>L. confusa a</i>), and prostrate dwarf-shrubs (<i>Salix polaris</i>, <i>S. rotundifolia</i>, <i>S. arctica</i>, <i>S. reticulata</i>, <i>Dryas</i>). Other common plants include grasses (<i>Alopecurus alpinus</i>, <i>Puccinellia vahliana</i>, <i>P. wrightii</i>, <i>Poa arctica</i>), forbs (<i>Potentilla hyparctica a</i>, <i>Cardamine bellidifolia a</i>, <i>Draba nivalis</i>, <i>Saxifraga cernua</i>, <i>S. hirculus</i>, <i>Stellaria</i>, <i>Pedicularis capitata</i>, <i>Papaver</i>), mosses (<i>Racomitrium lanuginosum a</i>, <i>Oncophorus wahlenbergii</i>, <i>Campylium stellatum</i>, <i>Aulacomnium turgidum</i>, <i>Warnstorfi a sarmentosa</i>, <i>Hylocomium splendens</i>, <i>Polytrichum</i>), liverworts (<i>Tetralophozia setiformis a</i>, <i>Anastrophyllum minutum a</i>), and lichens (<i>phaerophorus globosus a</i>, <i>Cladonia rangiferina a</i>, <i>Cladonia pyxidata</i>, <i>Thamnolia</i>, <i>Dactylina arctica</i>, <i>Flavocetraria</i>, <i>Masonhalea richardsonii</i>).</p>	2
P1	Prostrate-shrub tundras - prostrate dwarf-shrub, herb tundra	<p>Dry tundra with patchy vegetation. Prostrate shrubs < 5 cm tall (such as <i>Dryas</i> and <i>Salix arctica</i>) are dominant, with graminoids and forbs. Lichens are also common.</p> <p>Dry tundra of the Middle Arctic (sensu Polunin 1951; polar semideserts of Bliss 1997). The vegetation is open or patchy (20-80% cover), with plants 5-10 cm tall. Vascular plants cover about 5-25%, lichens and mosses cover 30-60%. On nonacidic substrates the dominant zonal vegetation is <i>Dryas - Salix arctica</i> communities; on acidic substrates it is <i>Luzula - Salix arctica</i>.</p>	1

		<p>Dominant plants: Prostrate dwarf-shrubs (<i>Dryas</i> n, <i>Salix arctica</i>, <i>S. polaris</i>, <i>S. rotundifolia</i>, <i>S. phlebophylla</i> a) are dominant. Other common plants include sedges (<i>Eriophorum triste</i>, <i>Carex rupestris</i> n), rushes (<i>Luzula confusa</i> a , <i>L. nivalis</i> a , <i>Juncus biglumis</i>) , grasses (<i>Alopecurus alpinus</i> a (Subzone B), <i>Deschampsia</i>), forbs, (<i>Saxifraga hirculus</i>, <i>S. caespitosa</i> a , <i>S. oppositifolia</i> n , <i>Novosieversia glacialis</i> n , <i>Oxytropis</i> n), mosses (<i>Ditrichum fl exicaule</i> n , <i>Distichium</i> n , <i>Sanionia uncinata</i>, <i>Encalypta</i> , <i>Pohlia</i>, <i>Polytrichum</i>, <i>Hylocomium splendens</i>, <i>Aulacomnium turgidum</i>, <i>Tomentypnum nitens</i> n), and lichens (<i>Thamnolia</i>, <i>Flavocetraria</i>). In Subzone C this vegetation is much richer in vascular species, particularly sedges, grasses, and forbs.</p>	
W1	Wetlands - sedge/grass, moss wetland	<p>Wetland complexes in the colder areas of the Arctic, dominated by sedges, grasses, and mosses.</p> <p>Dominant plants: Sedges (<i>Carex aquatilis</i>, <i>Eriophorum triste</i>, <i>E. scheuchzeri</i>), grasses (<i>Arctophila fulva</i>, <i>Alopecurus alpinus</i>, <i>Pleuropogon sabinei</i> , <i>Dupontia fi sheri</i>, <i>Poa pratensis</i>), mosses (e.g., <i>Calliergon giganteum</i>, <i>Warnstorfi a sarmentosa</i>, <i>Cinclidium arcticum</i>, <i>Hamatocaulis vernicosus</i>, <i>Campylium stellatum</i>, <i>Plagiomnium ellipticum</i>, <i>Bryum pseudotriquetrum</i>), and forbs (e.g., <i>Cardamine pratensis</i>, <i>Cerastium regelii</i>, <i>Caltha arctica</i>, <i>Bistorta vivipara</i> , <i>Saxifraga cernua</i>, <i>S. foliolosa</i>, <i>Pedicularis sudetica</i>). Grasses (<i>Pleuropogon</i>, <i>Dupontia</i>, <i>Alopecurus</i>) are important. Elevated microsites have moist graminoid, prostrate dwarf-shrub, forb, moss tundra species such as <i>Eriophorum triste</i>, <i>Carex misandra</i>, <i>C. membranacea</i>, <i>C. atrofusca</i>, <i>Kobresia simpliciuscula</i>, <i>Salix arctica</i>, <i>S. reticulata</i>, and <i>Tomentypnum nitens</i>.</p>	9

Characteristics of vegetation types of Ellesmere and Devon Island (CAVM Team, 2003), available at www.arcticatlas.org/maps/themes/cp/cpvq.

CAVM Code	Vegetation Type	Description	Rank (area)
B1	Barrens - cryptogam, herb barren	<p>Dry to wet barren landscapes with very sparse, very low-growing plant cover. Scattered herbs, lichens, mosses, and liverworts.</p> <p>Dry to wet barren desert-like landscapes mainly in Subzone A and on some coarse-grained, often calcareous sediments in subzones B and C. Sparse (2-40%) horizontal plant cover, and very low vertical structure (generally <2 cm tall) with a single layer of plants where they occur. Dry herb barrens composed of few scattered vascular plants are present over much of the landscape. Snow-flush communities are often a conspicuous component, forming dark streaks on the otherwise barren lands, composed largely of bryophytes and cryptogamic crusts. In upland areas, vascular plant cover</p>	2

		<p>is generally very sparse (<2%), mainly scattered individual plants often in crevices between stones or small (< 50 cm diameter) cryoturbated polygons. Sedges (Cyperaceae), dwarf shrubs, and peaty mires are normally absent.</p> <p>Dominant plants: The most common vascular plants are cushion forbs (<i>Papaver dahlianum</i> ssp . <i>polare</i>, <i>Draba</i>, <i>Potentilla hyparctica</i> a, <i>Saxifraga oppositifolia</i> n) and graminoids (<i>Alopecurus alpinus</i>, <i>Deschampsia borealis/brevifolia</i>, <i>Poa abbreviata</i>, <i>Puccinellia angustata</i>, <i>Phippsia</i> , <i>Luzula nivalis</i> a , <i>L. confusa</i> a), lichens (<i>Caloplaca</i> , <i>Lecanora</i>, <i>Ochrolechia</i>, <i>Pertusaria</i>, <i>Mycobilimbia</i>, <i>Collema</i>, <i>Thamnolia</i>, <i>Cetraria</i>, <i>Flavocetraria</i>, <i>Cetrariella</i>, <i>Stereocaulon</i>), mosses (<i>Racomitrium</i>, <i>Schistidium</i>, <i>Orthothecium</i> n , <i>Ditrichum</i> n , <i>Distichium</i> n , <i>Encalypta</i>, <i>Pohlia</i>, <i>Bryum</i>, <i>Polytrichum</i>), liverworts (e.g., <i>Gymnomitrium</i>, <i>Cephaloziella</i>), and cyanobacteria.</p>	
B2	Barrens - cryptogam barren complex (bedrock)	<p>Areas of exposed rock and lichens interspersed with lakes and more vegetated areas, as found on the Canadian Shield. Bedrock covered with lichens, usually mixed with many lakes and the zonal vegetation. The largest areas are on Precambrian granite and gneiss bedrock of the Canadian Shield, but also in the high elevation areas of Siberia, northeast Asia, Alaska, and Greenland. Areas between bedrock outcrops commonly have dwarf shrubs and fruticose lichens.</p> <p>Dominant plants: Saxicolous lichens (<i>Lecidia</i>, <i>Lecanora</i>, <i>Buellia</i>, <i>Porpidia</i>, <i>Rhizocarpon</i> , <i>Umbilicaria</i>, <i>Parmelia</i>, <i>Xanthoria</i> n , <i>Caloplaca</i> n , <i>Aspicilia</i> n) cover the rock surfaces. <i>Betula</i>, <i>Ledum palustre</i> ssp . <i>decumbens</i>, <i>Arctous alpina</i>, <i>Cassiope tetragona</i>, <i>Vaccinium</i>, the grass <i>Hierochloë alpina</i>, and terricolous lichens (<i>Cladonia</i>, <i>Cladina</i>, <i>Flavocetraria</i>, <i>Masonhalea richardsonii</i>, <i>Stereocaulon</i>, <i>Bryocaulon divergens</i>, <i>Alectoria ochroleuca</i>) grow between the bedrock outcrops.</p>	3
B3b	Barrens - noncarbonate mountain complex	<p>Mountain vegetation on noncarbonate bedrock. 2 layers: moss layer 1-3 cm thick, herbaceous layer 5-10 cm tall; prostrate dwarf shrubs <5 cm tall.</p> <p>Dry acidic tundra complexes on mountains and plateaus with noncarbonate bedrock. Vegetation changes with elevation in the mountains, forming elevation belts whose vegetation is physiognomically similar to that of bioclimate subzones with comparable summer climate. Mesic zonal microsites are relatively uncommon. More common are plant communities growing on wind-swept, rocky ridges, screes, and dry fell-fields, alternating with snowbed plant communities.</p>	7
B3c	Barrens - noncarbonate mountain complex	<p>Mountain vegetation on noncarbonate bedrock. 2 layers: moss layer 1-3 cm thick, herbaceous layer 5-10 cm tall; prostrate dwarf shrubs <5 cm tall.</p> <p>Dry acidic tundra complexes on mountains and plateaus with noncarbonate bedrock. Vegetation changes with elevation in the mountains, forming elevation belts whose vegetation is physiognomically similar to that of bioclimate subzones with comparable summer climate. Mesic zonal microsites are relatively uncommon. More common are plant</p>	5

		communities growing on wind-swept, rocky ridges, screes, and dry fell-fields, alternating with snowbed plant communities.	
B4b	Barrens - arbonate mountain complex	Mountain vegetation on carbonate bedrock. 2 layers: moss layer 1-3 cm thick, herbaceous layer 5-10 cm tall; prostrate dwarf shrubs <5 cm tall. Dry calcareous tundra complexes on mountains and plateaus with limestone or dolomite bedrock. Vegetation changes with elevation in the mountains, forming elevation belts whose vegetation is physiognomically similar to that of bioclimate subzones with comparable summer climate. Mesic zonal microsites are relatively uncommon. More common are plant communities growing on wind-swept, rocky ridges, screes, and dry fell-fi elds, alternating with snowbed plant communities.	4
G1	Graminoid tundras - rush/grass, forb, cryptogam tundra	Moist tundra with moderate to complete cover of very low-growing plants. Mostly grasses, rushes, forbs, mosses, lichens, and liverworts. Moist tundra on fi ne-grained, often hummocky soils in subzones A and B. Plant cover is moderate (40-80%), and the vegetation forms a single layer generally 5-10 cm tall. This is the zonal vegetation in Subzone A, often occurring in somewhat more protected areas with moderate snow cover. Except for the greater density of plants, particularly rushes and grasses, it is similar in composition to cryptogam, cushion-forb barrens. Dominant plants: Grasses (e.g., <i>Alopecurus alpinus</i> , <i>Dupontiafi sheri</i> , <i>Deschampsia borealis/brevifolia</i> , <i>Poa abbreviata</i> , <i>P. arctica</i>) and rushes (<i>Luzula nivalis a</i> , <i>L. confusa a</i>) are usually the dominant vascular plants. Forbs (<i>Cardamine bellidifolia a</i> , <i>Cerastium regelii n</i> , <i>Minuartia rossii n</i> , <i>Papaver dahlianum ssp . polare</i> , <i>Potentilla hyparctica a</i> , <i>Saxifraga oppositifolia n</i> , <i>Ranunculus hyperboreus</i> , <i>Draba n</i> , <i>Stellaria n</i> , <i>Oxyria digyna</i>) are abundant. Mosses are common (<i>Aulacomnium turgidum</i> , <i>Tomentypnum nitens n</i> , <i>Ditrichum n</i> , <i>Oncophorus wahlenbergii</i> , <i>Polytrichum</i> , <i>Racomitrium a</i> , <i>Schistidium</i>) and lichens (<i>Lecanora</i> , <i>Biatora</i> , <i>Pertusaria</i> , <i>Ochrolechia</i> , <i>Thamnolia</i> , <i>Cetrariella</i> , <i>Flavoce-traria</i> , <i>Stereocaulon n</i>), and liverworts. Cryptogamic crusts composed of cyanobacteria and black crustose lichens are common . In Subzone B, prostrate dwarf shrubs (<i>Dryas n</i> , <i>Salix polaris</i> , <i>S. arctica n</i>) and sedges (e.g., <i>Carex aquatilis</i> , <i>Eriophorum</i>) are present but not dominant.	1
G2	Graminoid tundras graminoid, prostrate dwarf- shrub, forb tundra	Moist to dry tundra, with open to continuous plant cover. Sedges are dominant, along with prostrate shrubs < 5 cm tall. Moist to dry tundra in Subzone C and warmer parts on fi ne-grained, often hummocky circumneutral soils with moderate snow. This is the zonal vegetation on nonacidic soils. Plant cover is moderate (40-80%) and 5-15 cm tall. The diversity of plant communities is much greater than in Unit G1 and includes <i>Cassiope tetragona</i> snowbeds, well-developed mires, and streamside plant communities.	8

		Dominant plants: Sedges (<i>Carex misandra</i> , <i>C. lugens/arctisibirica/ bigelowii</i> , <i>C. rupestris</i> , <i>Eriophorum triste</i> , <i>Kobresia myosuroides</i> , <i>C. aquatilis</i> ssp. <i>stans</i> (moister sites)), rushes (<i>Luzula nivalis</i> a , <i>L. confusa</i> a), and prostrate dwarf-shrubs (<i>Salix polaris</i> , <i>S. rotundifolia</i> , <i>S. arctica</i> , <i>S. reticulata</i> , <i>Dryas</i>). Other common plants include grasses (<i>Alopecurus alpinus</i> , <i>Puccinellia vahliana</i> , <i>P. wrightii</i> , <i>Poa arctica</i>), forbs (<i>Potentilla hyparctica</i> a , <i>Cardamine bellidifolia</i> a , <i>Draba nivalis</i> , <i>Saxifraga cernua</i> , <i>S. hirculus</i> , <i>Stellaria</i> , <i>Pedicularis capitata</i> , <i>Papaver</i>), mosses (<i>Racomitrium lanuginosum</i> a , <i>Oncophorus wahlenbergii</i> , <i>Campylium stellatum</i> , <i>Aulacomnium turgidum</i> , <i>Warnstorfi</i> a sarmentosa, <i>Hylocomium splendens</i> , <i>Polytrichum</i>), liverworts (<i>Tetralophozia setiformis</i> a , <i>Anastrophyllum minutum</i> a), and lichens (<i>phaerophorus globosus</i> a , <i>Cladina rangiferina</i> a , <i>Cladonia pyxidata</i> , <i>Thamnolia</i> , <i>Dactylina arctica</i> , <i>Flavocetraria</i> , <i>Masonhalea richardsonii</i>).	
W1	Wetlands - sedge/grass, moss wetland	Wetland complexes in the colder areas of the Arctic, dominated by sedges, grasses, and mosses. Dominant plants: Sedges (<i>Carex aquatilis</i> , <i>Eriophorum triste</i> , <i>E. scheuchzeri</i>), grasses (<i>Arctophila fulva</i> , <i>Alopecurus alpinus</i> , <i>Pleuropogon sabinei</i> , <i>Dupontia fi sheri</i> , <i>Poa pratensis</i>), mosses (e.g., <i>Calliergon giganteum</i> , <i>Warnstorfi</i> a sarmentosa, <i>Cinclidium arcticum</i> , <i>Hamatocaulis vernicosus</i> , <i>Campylium stellatum</i> , <i>Plagiomnium ellipticum</i> , <i>Bryum pseudotriquetrum</i>), and forbs (e.g., <i>Cardamine pratensis</i> , <i>Cerastium regelii</i> , <i>Caltha arctica</i> , <i>Bistorta vivipara</i> , <i>Saxifraga cernua</i> , <i>S. foliolosa</i> , <i>Pedicularis sudetica</i>). Grasses (<i>Pleuropogon</i> , <i>Dupontia</i> , <i>Alopecurus</i>) are important. Elevated microsites have moist graminoid, prostrate dwarf-shrub, forb, moss tundra species such as <i>Eriophorum triste</i> , <i>Carex misandra</i> , <i>C. membranacea</i> , <i>C. atrofusca</i> , <i>Kobresia simpliciuscula</i> , <i>Salix arctica</i> , <i>S. reticulata</i> , and <i>Tomentypnum nitens</i> .	6

Characteristics of vegetation types of the Canadian Arctic Archipelago (CAVM Team, 2003), available at www.arcticatlas.org/maps/themes/cp/cpvg.

CAVM Code	Vegetation Type	Description	Rank (area)
B1	Barrens - cryptogam, herb barren	Dry to wet barren landscapes with very sparse, very low-growing plant cover. Scattered herbs, lichens, mosses, and liverworts. Dry to wet barren desert-like landscapes mainly in Subzone A and on some coarse-grained, often calcareous sediments in subzones B and C. Sparse (2-40%) horizontal plant cover, and very low vertical structure (generally <2 cm tall) with a single layer of plants where they occur. Dry herb barrens composed of few scattered vascular plants are present over much of the landscape. Snow-flush communities are often a conspicuous component, forming dark	4

		<p>streaks on the otherwise barren lands, composed largely of bryophytes and cryptogamic crusts. In upland areas, vascular plant cover is generally very sparse (<2%), mainly scattered individual plants often in crevices between stones or small (< 50 cm diameter) cryoturbated polygons. Sedges (Cyperaceae), dwarf shrubs, and peaty mires are normally absent.</p> <p>Dominant plants: The most common vascular plants are cushion forbs (<i>Papaver dahlianum</i> ssp . <i>polare</i>, <i>Draba</i>, <i>Potentilla hyperarctica</i> a, <i>Saxifraga oppositifolia</i> n) and graminoids (<i>Alopecurus alpinus</i>, <i>Deschampsia borealis/brevifolia</i>, <i>Poa abbreviata</i>, <i>Puccinellia angustata</i>, <i>Phippsia</i> , <i>Luzula nivalis</i> a , <i>L. confusa</i> a), lichens (<i>Caloplaca</i> , <i>Lecanora</i>, <i>Ochrolechia</i>, <i>Pertusaria</i>, <i>Mycobilimbia</i>, <i>Collema</i>, <i>Thamnolia</i>, <i>Cetraria</i>, <i>Flavocetraria</i>, <i>Cetrariella</i>, <i>Stereocaulon</i>), mosses (<i>Racomitrium</i>, <i>Schistidium</i>, <i>Orthothecium</i> n , <i>Ditrichum</i> n , <i>Distichium</i> n , <i>Encalypta</i>, <i>Pohlia</i>, <i>Bryum</i>, <i>Polytrichum</i>), liverworts (e.g., <i>Gymnomitrium</i>, <i>Cephaloziella</i>), and cyanobacteria.</p>	
B3b	Barrens - noncarbonate mountain complex	<p>Mountain vegetation on noncarbonate bedrock. 2 layers: moss layer 1-3 cm thick, herbaceous layer 5-10 cm tall; prostrate dwarf shrubs <5 cm tall.</p> <p>Dry acidic tundra complexes on mountains and plateaus with noncarbonate bedrock. Vegetation changes with elevation in the mountains, forming elevation belts whose vegetation is physiognomically similar to that of bioclimate subzones with comparable summer climate. Mesic zonal microsites are relatively uncommon. More common are plant communities growing on wind-swept, rocky ridges, screes, and dry fell-fields, alternating with snowbed plant communities.</p>	1
B4b	Barrens -carbonate mountain complex	<p>Mountain vegetation on carbonate bedrock. 2 layers: moss layer 1-3 cm thick, herbaceous layer 5-10 cm tall; prostrate dwarf shrubs <5 cm tall.</p> <p>Dry calcareous tundra complexes on mountains and plateaus with limestone or dolomite bedrock. Vegetation changes with elevation in the mountains, forming elevation belts whose vegetation is physiognomically similar to that of bioclimate subzones with comparable summer climate. Mesic zonal microsites are relatively uncommon. More common are plant communities growing on wind-swept, rocky ridges, screes, and dry fell-fi elds, alternating with snowbed plant communities.</p>	2
P1	Prostrate-shrub tundras - prostrate dwarf-shrub, herb tundra	<p>Dry tundra with patchy vegetation. Prostrate shrubs < 5 cm tall (such as <i>Dryas</i> and <i>Salix arctica</i>) are dominant, with graminoids and forbs. Lichens are also common.</p> <p>Dry tundra of the Middle Arctic (sensu Polunin 1951; polar semideserts of Bliss 1997). The vegetation is open or patchy (20-80% cover), with plants 5-10 cm tall. Vascular plants cover about 5-25%, lichens and mosses cover 30-60%. On nonacidic substrates the dominant zonal vegetation is <i>Dryas</i> - <i>Salix arctica</i> communities; on acidic substrates it is <i>Luzula</i> - <i>Salix arctica</i>.</p>	3

	<p>Dominant plants: Prostrate dwarf-shrubs (<i>Dryas</i> n, <i>Salix arctica</i>, <i>S. polaris</i>, <i>S. rotundifolia</i>, <i>S. phlebophylla</i> a) are dominant. Other common plants include sedges (<i>Eriophorum triste</i>, <i>Carex rupestris</i> n), rushes (<i>Luzula confusa</i> a , <i>L. nivalis</i> a , <i>Juncus biglumis</i>) , grasses (<i>Alopecurus alpinus</i> a (Subzone B), <i>Deschampsia</i>), forbs, (<i>Saxifraga hirculus</i>, <i>S. caespitosa</i> a , <i>S. oppositifolia</i> n , <i>Novosieversia glacialis</i> n , <i>Oxytropis</i> n), mosses (<i>Ditrichum fl exicaule</i> n , <i>Distichium</i> n , <i>Sanionia uncinata</i>, <i>Encalypta</i> , <i>Pohlia</i>, <i>Polytrichum</i>, <i>Hylocomium splendens</i>, <i>Aulacomnium turgidum</i>, <i>Tomentypnum nitens</i> n), and lichens (<i>Thamnolia</i>, <i>Flavocetraria</i>). In Subzone C this vegetation is much richer in vascular species, particularly sedges, grasses, and forbs.</p>	
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Characteristics of vegetation types of the northern Greenland (CAVM Team, 2003), available at www.arcticatlas.org/maps/themes/cp/cpvg.