Arctic Biodiversity Assessment

Synthesis

CAFF
Conservation of Arctic Flora and Fauna

ARCTIC COUNCIL

» **Nowadays all of the tundra is on the move now.
Many forest animals are coming to tundra now.
Moose is moving towards the tundra proper nowadays.**

Alexey Nikolayevich Kemlil, a Chukchi reindeer herder from Turvaurgin in northeastern Sakha-Yakutia, Siberia;
T. Mustonen in litt.

» **I too, have noticed changes to the climate in our area. It has progressed with frightening speed especially the last few years. In Iqaluktutiaq, the landscape has changed. The land is now a stranger, it seems, based on our accumulated knowledge. The seasons have shifted, the ice is thinner and weaker, and the streams, creeks and rivers have changed their characteristics.**

Analok, Cambridge Bay, Victoria Island, Nunavut;
Elders Conference on Climate Change 2001.

Cover photo: Muskoxen are hardy animals that had a circumpolar distribution in the Pleistocene, but Holocene climate changes along with heavy hunting may have contributed to its disappearance in the Palearctic and from Alaska and Yukon. In modern times, humans have reintroduced muskoxen to Alaska and the Taymyr Peninsula together with a number of places where the species did not occur in the Holocene.
Photo. Lars Holst Hansen/ARC-PIC.com

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Arctic Biodiversity Assessment

Status and trends in Arctic biodiversity

Synthesis

CAFF
Conservation of Arctic Flora and Fauna

ARCTIC COUNCIL

Arctic Biodiversity Assessment

Status and trends in Arctic biodiversity: Synthesis
Conservation of Arctic Flora and Fauna (CAFF), Arctic Council, 2013

The report and associated materials can be downloaded for free at www.arcticbiodiversity.is

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Jacob's ladder flowering in the Arctic summer.
Photo: Erik Thomsen.

PREFACE

by CAFF and Steering Committee Chairmen

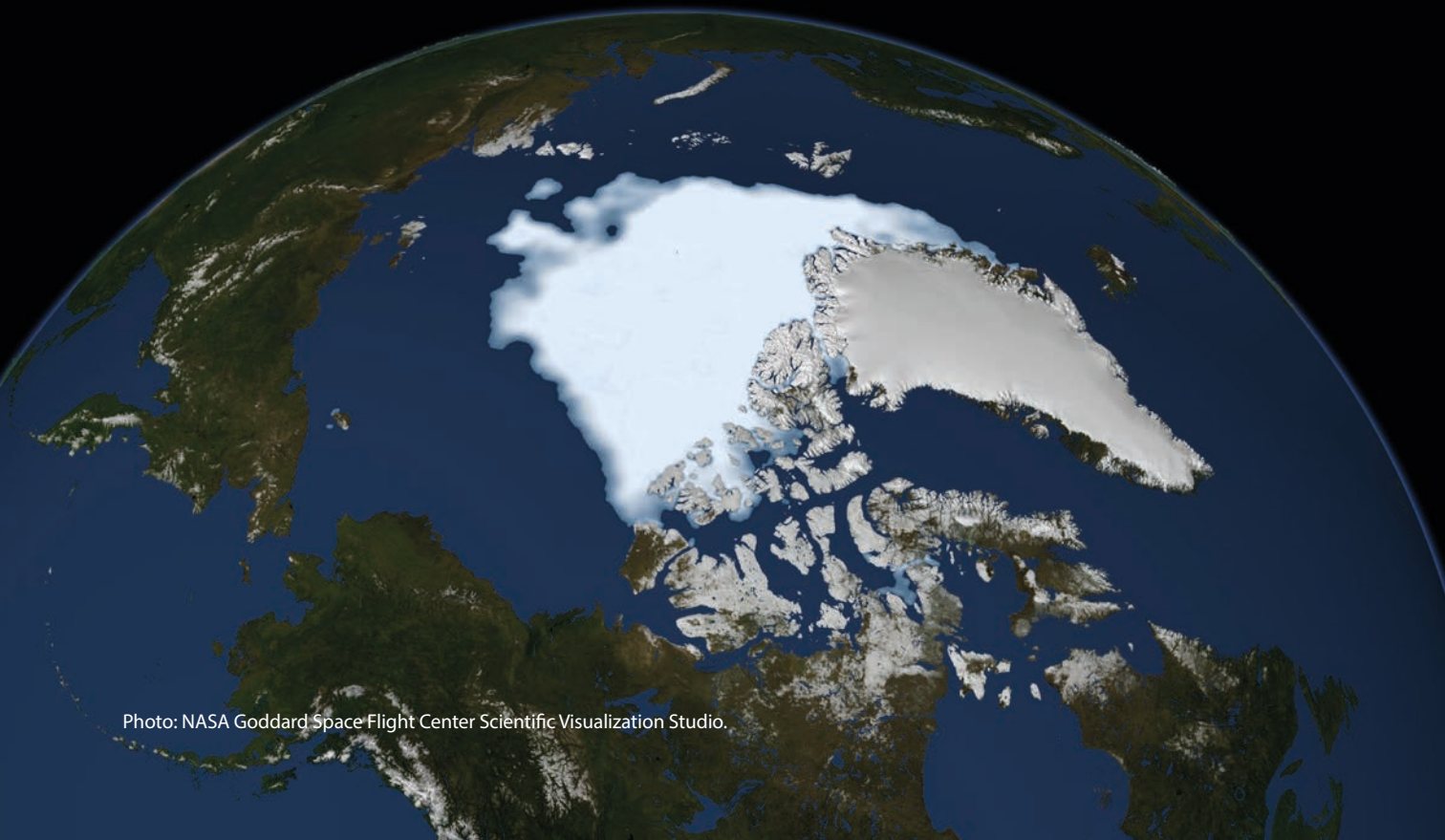


Photo: NASA Goddard Space Flight Center Scientific Visualization Studio.

The eyes of the world are turning northwards. In recent years, interest in the Arctic has increased dramatically within and outside of Arctic countries. This is reflected in the amount of attention given to Arctic biodiversity. While the landscapes and wildlife have been the subject of explorers, scientists, artists and photographers as well as the home of a variety of peoples for a long time, until recently Arctic biodiversity did not feature very prominently in national or international policy work. This, however, is changing, as the unique values of Arctic nature are increasingly discussed at high levels. At the same time, more and more attention has been paid to the interface between science and policy to ensure that policy is built on the best science available.

We are therefore very happy and proud to present the Arctic Biodiversity Assessment (ABA), which has been seven years in the making. It is the result of the contributions from 252 scientists together with holders of traditional knowledge. The chapters in the main document have been peer-reviewed by over 100 scientists from all over the Arctic and the rest of the world. We are very grateful for the efforts they have made to ensure the quality of this assessment. We would especially like to thank Chief Scientist Hans Meltofte and the lead authors of the chapters.

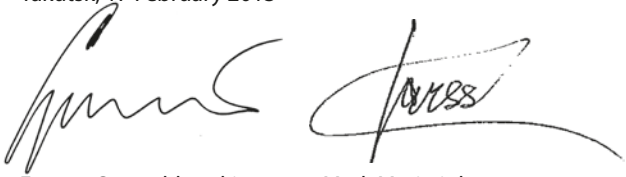
In order to communicate the findings presented in this scientific work and to inform policy makers, the board of the Arctic Council's working group on the Conservation of Arctic Flora and Fauna (CAFF) has prepared a summary of the key findings and developed policy recommendations. The key findings and recommendations have been provided in a separate document, which we trust will be useful for all those who make decisions that may affect Arctic biodiversity.

The Arctic is home to a vast array of biodiversity, including many globally significant populations. Included among these are 30% of the world's shorebird species, two thirds of the global numbers of geese, several million reindeer and caribou, and many unique mammals, such as the polar bear. During the short summer breeding season, almost 200 species of birds arrive from almost all parts of the world, connecting the Arctic with the rest of the globe. We therefore hope that the ABA will be consulted frequently within as well as outside of the Arctic.

Biodiversity is life. It is the very foundation of our existence on Earth. In the Arctic, links between biodiversity and traditional ways of life are often seen more clearly than in many other parts of the world. These are examples of ecosystem services, the benefits that we receive from nature. Many ecosystems and ecosystem functions in the Arctic remain largely unstudied and involve little-known organisms, especially microbes. The ABA presents current knowledge also on these processes and organisms and thus provides a base for further work.

But biodiversity is more than a means for humankind to survive. The unique nature of the Arctic is not just an asset for us to use. It is also a source of wonder, enjoyment and inspiration to people living in the Arctic and across the globe. It has intrinsic values that cannot be measured. We sincerely hope that the ABA will not only create the baseline reference for scientific understanding about Arctic biodiversity, but that it also may inspire people to take effective actions on the conservation of Arctic flora and fauna. We hope it gives people reasons to love Arctic nature as much as we do.

Yakutsk, 17 February 2013



Evgeny Syroechkovskiy
Chair of CAFF

Mark Marissink
Chair of the ABA
Steering Committee

FOREWORD

by the Chief Scientist

Until recently, most Arctic biodiversity was relatively unaffected by negative impacts from human activities. Only over-exploitation of certain animal populations posed serious threats, such as the extermination of Steller's sea cow, the great auk, the Eskimo curlew and a number of whale populations in recent centuries, in addition to the contribution that humans may have made to the extermination of terrestrial mega-fauna in prehistoric times.

Human impacts, however, have increased in modern times with increasing human populations in much of the Arctic, modern means of rapid transport, modern hunting and fishing technology, increasing exploration and exploitation of mineral resources, impacts from contaminants and, most importantly, with climate change, which is more pronounced in the Arctic than elsewhere on the globe.

There is no inherited capacity in human nature to safeguard the Earth's biological assets – moral and intellectual strength are needed to achieve conservation and wise use of living resources through cultural and personal ethics and practices. Sustainability is a prerequisite for such balance, but it does not come without restraint and concerted efforts by all stakeholders, supported by mutual social pressure, legislation and law enforcement.

The king eider is one of the fascinating species endemic to the Arctic. Photo: Patrick J. Endres/ AlaskaPhotoGraphics.com

The Arctic is changing rapidly with shorter winters, rapidly melting sea ice, retreating glaciers and expanding sub-Arctic vegetation from the south. If greenhouse gas emissions are not reduced, Arctic biodiversity will be forever changed, and much may disappear completely.

On 18 May 2011, 50 prominent thinkers, among them 15 Nobel Prize winners, issued The Stockholm Memorandum, which among other things states that:

Science indicates that we are transgressing planetary boundaries that have kept civilization safe for the past 10,000 years. Evidence is growing that human pressures are starting to overwhelm the Earth's buffering capacity. Humans are now the most significant driver of global change, propelling the planet into a new geological epoch, the Anthropocene. We can no longer exclude the possibility that our collective actions will trigger tipping points, risking abrupt and irreversible consequences for human communities and ecological systems. We cannot continue on our current path. The time for procrastination is over. We cannot afford the luxury of denial. We must respond rationally, equipped with scientific evidence.

Among the many current and projected stressors on Arctic biodiversity addressed in this report is that of invasive species. However, if we want to do something about the many problems facing nature and biodiversity in the Arctic, we need to focus on the impacts of the most globally 'invasive species' of all: *Homo sapiens*.

Copenhagen, 8 February 2013

Hans Meltofte
Chief Scientist

SUMMARY

Arctic biodiversity – the multitude of species and ecosystems in the land north of the tree line together with the Arctic Ocean and adjacent seas – is an irreplaceable cultural, aesthetic, scientific, ecological, economic and spiritual asset. For Arctic peoples, biodiversity has been the very basis for their ways of life through millennia, and is still a vital part of their material and spiritual existence. Arctic fisheries and tourism are also of particularly high value for the rest of the world, and so are the millions of Arctic birds and mammals migrating to virtually all parts of the globe during winter.

The Arctic is home to more than 21,000 species of often highly cold-adapted mammals, birds, fish, invertebrates, plants and fungi (including lichens) – together with large numbers of undescribed endoparasites and microbes. These include charismatic and iconic species such as polar bears *Ursus maritimus*, narwhals *Monodon monoceros*, walrus *Odobenus rosmarus*, caribou/reindeer *Rangifer tarandus*, muskoxen *Ovibos moschatus*, Arctic fox *Vulpes lagopus*, ivory gull *Pagophila eburnea* and snowy owls *Bubo scandiaca* together with marine and terrestrial ecosystems such as vast areas of lowland tundra, wetlands, mountains, extensive shallow ocean shelves, millennia-old ice shelves and huge seabird cliffs.

The functional significance of different groups of organisms in maintaining the integrity, structure,

Perennial as well as seasonal sea ice make up an important habitat for Arctic marine ecosystems, where polynyas and leads make room for diverse species assemblages of birds and marine mammals. Walruses in a lead in the summer sea ice in Baffin Bay. Photo: B&C Alexander/ArcticPhoto.com

services and health of Arctic ecosystems, however, is generally greatest among those we understand least. Microorganisms are key elements of Arctic ecosystems, yet they have been little studied.

Anthropogenically driven climate change is by far the most serious threat to biodiversity in the Arctic, and there is an immediate need to implement actions to reduce this stressor. Due to a range of feedback mechanisms, the 2 °C upper limit of human-induced warming, chosen by world leaders, is projected to result in an air temperature increase of between 2.8 and 7.8 °C in the Arctic, likely resulting in severe disruptions to Arctic biodiversity.

Climate change is the most likely explanation for shifts already visible in several parts of the Arctic, as documented by both scientists and Arctic residents. These include northward range expansions of many species and changes in ecosystems likely resulting from habitat warming and/or drying of the substrate associated with warming and earlier snow melt, together with development of new oceanic current patterns.

Future global warming will result in further northward shifts in the distribution of a great many species. This will include boreal species and ecosystems encroaching on areas currently characterized as the low Arctic, and low Arctic species and ecosystems encroaching on areas currently characterized as the high Arctic.

Northward movement of boreal species may increase the number of species found in the Arctic, but this does not represent a net gain in global biodiversity. The additions will primarily be species that are already common in southern habitats, some of which may outcompete or displace unique assemblages of Arctic species with the risk of severe range reductions and possible extinctions.

Terrestrial habitats in the Arctic are bounded to the north by marine ecosystems. Therefore, northward ecosystem shifts are expected to reduce the overall geographic extent of terrestrial Arctic habitats – in particular for high Arctic habitats. Arctic terrestrial ecosystems may disappear in many places, or only survive in alpine or island 'refugia'.

Arctic freshwater ecosystems are undergoing rapid change in response to the influence of both environmental and anthropogenic stressors. The distribution and number of lakes, ponds, wetlands and riverine networks are being altered with significant implications to the structure, function and diversity of associated biological communities.

Also in the marine Arctic, climate-induced effects on species and ecosystems, associated with a decrease in sea ice extent and duration, are already being observed. Of key concern is the rapid loss of multi-year ice in the central Arctic basins and changes in sea ice dynamics on the extensive Arctic shelves, which affect the biodiversity and productivity of marine ecosystems.

A secondary effect of increased CO_2 in the atmosphere is ocean acidification resulting from increased dissolved CO_2. Since the solubility of CO_2 is higher in cold than warm waters, Arctic marine ecosystems are especially prone to acidification, and there are already signs of such changes in the Arctic Ocean. This is an important threat to calcareous organisms, and thereby may have cascading impacts on marine ecosystems including potential impacts on biodiversity and fisheries.

Until the second half of the 20th century, overharvest was the primary threat to a number of Arctic mammals, birds and fishes. A wide variety of conservation and management actions have helped alleviate this

pressure in many areas to such an extent that many populations are recovering, although pressures on others persist.

Since the middle of the 20th century, a variety of contaminants have bioaccumulated in several Arctic predator species to levels that threaten the health and fecundity of both animals and humans. However, due to concerted global action to reduce the release of contaminants, there are, as yet, few demonstrated effects on Arctic species at the population level. Lack of data may mask such impacts, however. New contaminants, and changing fluxes of others, continue to be introduced to Arctic ecosystems and related food webs with unknown ecosystem effects.

Arctic habitats are among the least anthropologically disturbed on Earth, and huge tracts of almost pristine tundra, mountain, freshwater and marine habitats still exist. While climate change is the most geographically extensive and potentially harmful anthropogenic impacts at present, regionally ocean bottom trawling, non-renewable resource development and other intensive forms of land use pose serious challenges to Arctic biodiversity.

Pollution from oil spills at sites of oil and gas development and from oil transport is a serious local level threat particularly in coastal and marine ecosystems. A major oil spill in ice-filled waters would be disastrous to marine mammals, birds and other biota, because containing and cleaning up oil spills in broken ice is very difficult, particularly under problematic weather, light and ice conditions.

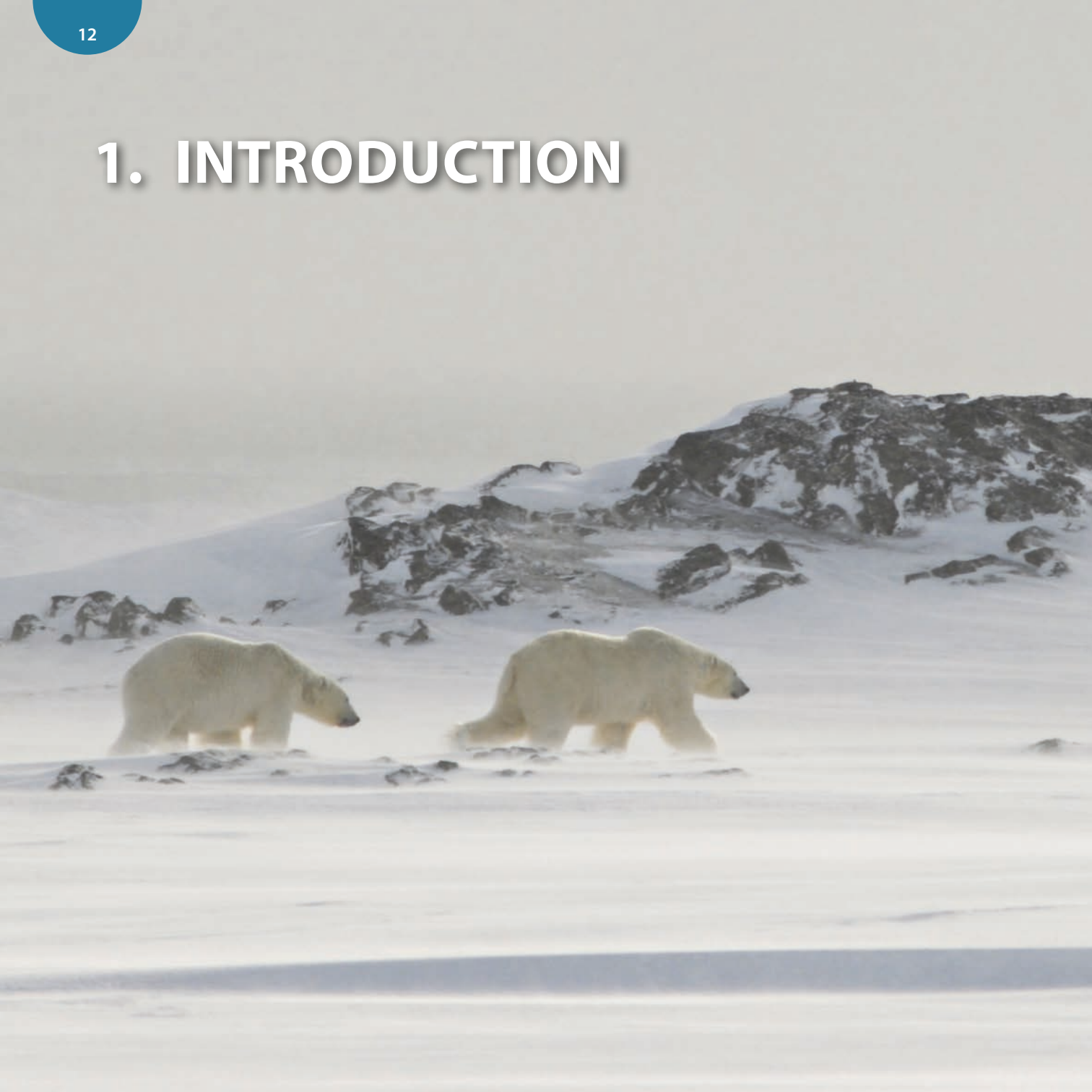
Many Arctic species spend much of the year outside the Arctic; e.g. Arctic waterbirds are highly dependent on a network of staging and wintering areas in wetlands in many parts of the world. These habitats are experiencing severe development pressure and in some cases overharvest, particularly in East Asia, but also in other parts of the world.

At present, few human-introduced alien species, including pathogens and disease vectors, are spreading unchecked and putting Arctic species under pressure. However, the pathways by which invasive species spread, such as shipping and resource development corridors are rapidly expanding and may dramatically increase the rate of introduction. Many potentially disruptive alien species are also found in sub-Arctic regions and will probably spread northwards along with other species in a warming climate.

There is an enormous deficit in our knowledge of species richness in many groups of organisms, and monitoring in the Arctic is lagging far behind that in other regions of the world. Even for the better-studied Arctic species and ecosystems we have insufficient data on trends in distribution, abundance and phenology and too few natural history specimens for retrospective and baseline analyses. Also the functioning of Arctic ecosystems is insufficiently understood making it difficult to implement ecosystem-based monitoring and management. Hence, there is a critical lack of essential data and scientific understanding necessary to improve the planning and implementation of biodiversity conservation or monitoring strategies in the Arctic.

The multitude of changes in Arctic biodiversity – driven by climate and other anthropogenic stressors – will have profound effects on the living conditions of peoples in the Arctic, including the diversity of indigenous languages, cultures and the range of services that humans derive from Arctic biodiversity. While the ecosystem changes may provide new opportunities, they will also require considerable adaptation and adjustment.

1. INTRODUCTION



The Arctic holds some of the most extreme habitats on Earth, with species and peoples that have adapted through biological and cultural evolution to its unique conditions. A homeland to some, and a harsh if not hostile environment to others, the Arctic is home to iconic animals such as polar bears *Ursus maritimus*, narwhals *Monodon monoceros*, caribou/reindeer *Rangifer tarandus*, muskoxen *Ovibos moschatus*, Arctic fox *Vulpes lagopus,* ivory gull *Pagophila eburnea* and snowy owls *Bubo scandiaca*, as well as numerous microbes and invertebrates capable of living in extreme cold, and large intact landscapes and seascapes with little or no obvious sign of direct degradation from human activity. In addition to flora and fauna, the Arctic is known for the knowledge and ingenuity of Arctic peoples, who thanks to great adaptability have thrived amid ice, snow and winter darkness.

The purpose of this Arctic Biodiversity Assessment (ABA) is to synthesize and assess the status and trends of biodiversity in the Arctic and provide a first and much-needed description of the state of biodiversity in the Arctic (see Box 1 for this assessment's definition of the Arctic). It creates a baseline for global and regional assessments of Arctic biodiversity, and is a basis for informing and guiding future Arctic Council work. It provides up-to-date knowledge, identifies data and knowledge gaps, describes key mechanisms driving change and presents science-based suggestions for action to address major pressures.

Polar bears are iconic species of the Arctic, representing the fascination for wildlife in the cold northern region shared by people living in the Arctic as well as beyond.
Photo: Wild Arctic Pictures/shutterstock.com

The ABA identifies current status together with historical trends in abundance and distribution where available, and includes projections of future change informed by scientific literature. It draws on a vast number of scientific publications, supplemented by 'eye witness' observations from indigenous peoples in the context of Traditional Ecological Knowledge (TEK). The ABA has been through comprehensive peer review to ensure the highest standard of analysis and unbiased interpretation. The results are a benchmark against which to help measure and understand the significance of future change, without which the scope and gravity of future changes will be less clearly identifiable, undermining our ability to reduce harm.

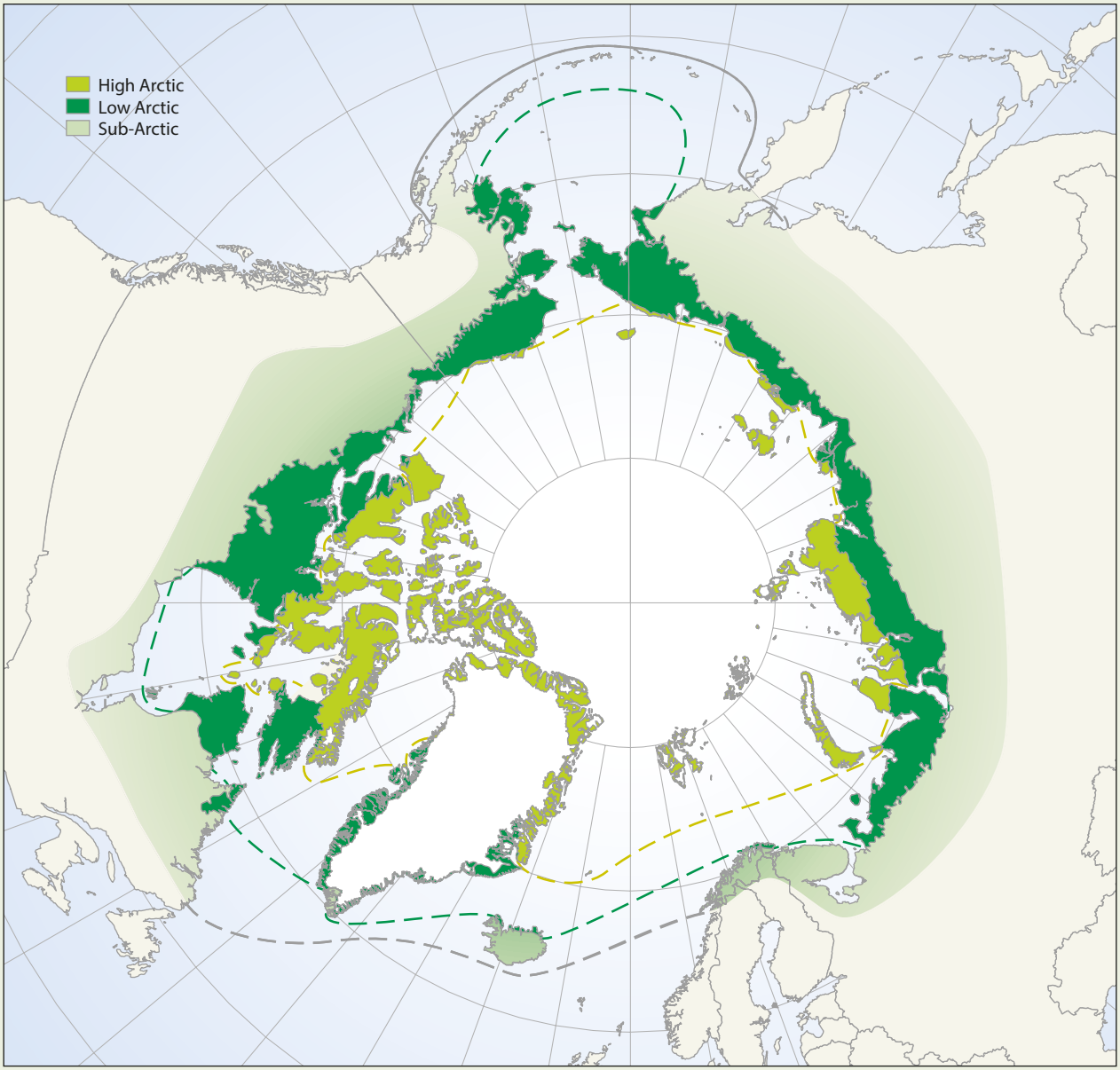
Change in the Arctic comes in many forms and from a variety of sources. Several of these stressors have been the subject of intense research and assessments documenting the effects and impacts of human activity regionally and globally, and seeking ways to conserve the biological and cultural wealth of the Arctic in the face of considerable pressures to develop its resources. These assessments have focused primarily on effects and impacts from a range of present and future stressors, such as global warming (ACIA 2005, AMAP 2009a, AMAP 2011a), oil and gas activities (AMAP 2009b), social change (AHDR 2004), marine shipping (AMSA 2009) and environmental contaminants (AMAP 1998, 2004, 2010, 2011b). The ABA, in contrast, looks not at the stressors but at the biodiversity being stressed.

Box 1. Definition of the Arctic

For this assessment a more scientific definition of the Arctic was needed than the CAFF boundaries, which are defined as much by political boundaries as by climatic and biological zoning, and therefore vary considerably among the Arctic nations. That such a clear definition is a prerequisite for a meaningful account of Arctic biodiversity can be illustrated by the highly varying numbers of 'Arctic' bird species found in the literature. By including huge tracts of boreal forest and woodland into the Arctic, as politically defined by CAFF, figures of up to "450 Arctic breeding bird species" have been quoted (Zöckler 1998, Trouwborst 2009) as compared with the c. 200 species given in the present report based on a stricter ecological definition (Ganter & Gaston, Chapter 4).

The name Arctic derives from the ancient Greek word *Arktikós*, meaning the land of the North. It relates to *Arktos*, the Great Bear, which is the star constellation close to the Pole Star. There are several definitions of the Arctic. From a geophysical point of view, the Arctic may be defined as the land and sea north of the Arctic Circle, where the sun does not set on the summer solstice and does not rise on the winter solstice. From an ecological point of view, it is more meaningful to use the name for the land north of the tree line, which generally has a mean temperature below c. 10-12 °C for the warmest month, July (Jonasson *et al.* 2000). With this definition, the Arctic land area comprises about 7.1 million km^2, or some 4.8% of the land surface of Earth (Box 1 Fig. 1).

Box 1 Figure 1. Map of the top of the northern hemisphere with the high and low Arctic zones delineated according to the Circumpolar Arctic Vegetation Map (CAVM Team 2003), together with a tentative demarcation of the sub-Arctic. Lines indicating similar marine zones are sketched.


High Arctic
Low Arctic
Sub-Arctic

(Box 1. continued)

Similarly, the Arctic waters are defined by characteristics of surface water masses, i.e. the extent of cold Arctic water bordering temperate waters including 'gateways' between the two biomes. The Arctic Ocean covers about 10 million km^2 (see Michel, Chapter 14 for details).

The open landscapes of the Arctic are often named tundra, which originates from the Saami words for barren habitats, *tūndar* or *tunturi*. In general, the low Arctic has much more lush vegetation than the high Arctic, where large lowland areas may be almost devoid of vegetation, like the Arctic deserts of the northernmost lands in the world.

The sub-Arctic or forest tundra is the northernmost part of the boreal zone, i.e. the area between the timberline and the tree line.* Hence, the sub-Arctic is not part of the Arctic, just as the sub-tropics are not part of the tropics. Like the Arctic, the word *boreal* is derived from Greek: *Boreas* was the god of the cold northern winds and bringer of winter. Related zones are found in mountainous areas outside of the Arctic as sub-alpine, low-alpine and high-alpine biomes.

This assessment follows the Circumpolar Arctic Vegetation Map's (CAVM Team 2003) definition of the Arctic, since this map builds on scientific criteria for Arctic habitats.

Furthermore, inclusion of tree-covered sub-Arctic habitats would have expanded the volume of species and ecosystems beyond achievable limits. Yet, different chapters may cover additional bordering areas as needed to provide scientific and ecological completeness. The entire Arctic tundra region (sub-zones A-E on the CAVM) is addressed as comprehensively as possible in terms of species and ecosystem processes and services.

Oceanic tundra (e.g. the Aleutian Islands), the sub-Arctic and other adjacent areas are addressed as appropriate in regard to (1) key ecosystem processes and services, (2) species of significance to the Arctic tundra region, (3) influences on the Arctic tundra region, and (4) potential for species movement into the current Arctic tundra region, e.g. due to global change.

For the separation between the high Arctic and the low Arctic, we follow the simplest division which is between sub-zones C and D on the CAVM (Box 1 Fig. 1). The southern limit of the sub-Arctic is 'loose', since work on a CAFF Circumpolar Boreal Vegetation Map is pending (CBVM 2011). Contrary to the Arctic zones on land, the boundaries at sea are tentative, and on Box 1 Fig. 1 they are indicated only with rough boundaries between the different zones.

* While the tree line is the limit of often scattered tree growth or forest tundra, the timberline is the limit of harvest of useable timber.

The ABA consists of four components: (1) *Arctic Biodiversity Trends 2010 – Selected Indicators of Change*, which provided a preliminary snapshot of status and trends of Arctic biodiversity (Box 2), (2) the Arctic Biodiversity Assessment, Status and Trends in Arctic Biodiversity, a comprehensive, peer-reviewed scientific assessment of Arctic biodiversity, and scientific synthesis, (3) *Indigenous observations of change* (under development) and (4) *Arctic Biodiversity Assessment: Summary for Policy Makers*.

A key challenge for conservation in the Arctic is to shorten the gap between data collection and policy response. The Arctic Council has recognized this challenge and in recent years, through the working group for Conservation of Flora and Fauna (CAFF), has worked towards developing a solution. This approach has focused on not just developing a classical assessment but also addressing the collection, processing and analysis of data on a continuous basis. The ABA is not just a one-time, static assessment, but rather provides a baseline of current knowledge, closely linked to the development of the Circumpolar Biodiversity Monitoring Program (CBMP) as the engine for ongoing work, including the production of regular and more flexible regional and circumpolar assessments and analyses.

Box 2.
Arctic Biodiversity Trends 2010: selected indicators of change

The *Arctic Biodiversity Trends 2010: selected indicators of change* report was the first product produced from the Arctic Biodiversity Assessment. Released in 2010, it was Arctic Council's response to the United Nations International Year of Biodiversity in 2010. At the same time it was a contribution to the Convention on Biological Diversity (CBD)'s Third Global Biodiversity Outlook to measure progress towards the CBD's target "to achieve, by 2010, a significant reduction of the current rate of biodiversity loss at the global, regional, and national levels as a contribution to poverty alleviation and to the benefit of all life on Earth."

The report presented a broad spectrum of changes in Arctic ecosystems and biodiversity and provided a snapshot of the trends being observed in Arctic biodiversity today. It highlighted the potentially significant consequences of changes taking place in the Arctic and provided evidence that some anticipated impacts on Arctic biodiversity were already occurring.

The report was based on a suite of 22 indicators developed by the Circumpolar Biodiversity Monitoring Program (CBMP) to cover major species groups with wide distributions across Arctic ecosystems. These indicators include those closely associated with biodiversity use by indigenous and local communities, as well as those with relevance to decision-makers.

Conservation action based on the findings of the ABA will not happen in a vacuum. All Arctic Council states have made commitments that, directly or indirectly, help protect biodiversity and ecosystems through a number of conventions as well as bi- and multi-lateral agreements, including the Convention on Biological Diversity (CBD), United Nations (UN) Framework Convention on Climate Change (UNFCCC), Convention to Combat Desertification (CCD), Bonn Convention (Convention on the Conservation of Migratory Species of Wild Animals; CMS), Ramsar Convention on Wetlands of International Importance, UN Educational, Scientific and Cultural Organization (UNESCO), World Heritage Convention (WHC) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). Each Arctic Council country is a Party to at least one of these conventions and has, thereby, made commitments that have the effect of protecting and restoring biodiversity (Box 3).

This synthesis draws on the evidence, findings and suggested actions presented in the peer-reviewed technical chapters of the ABA. It provides an overview of their primary findings and the extensive cross-sectoral scientific literature, and presents suggestions for priority actions on conservation and research. It starts with a description of the characteristics of Arctic biodiversity, outlines the interactions between humans and Arctic wildlife through millennia, provides a brief summary of the conclusions of each chapter and then discusses challenges facing biodiversity by describing stressors from both within and outside the Arctic.

Box 3. International conventions on biodiversity issues and the Arctic

Six international conventions focus on biodiversity issues: the Convention on Biological Diversity, the Convention on Conservation of Migratory Species, the Convention on International Trade in Endangered Species of Wild Fauna and Flora, the International Treaty on Plant Genetic Resources for Food and Agriculture, the Ramsar Convention on Wetlands, and the World Heritage Convention. While each of these conventions has distinct and specific aims and commitments, they share common goals of biodiversity conservation and sustainable use.

All Arctic Council countries work through one or several of these conventions to develop and implement national and international policies for the conservation and sustainable use of biodiversity. Collectively, these conventions aim to ensure the conservation and sustainable use of migratory species, areas of natural heritage, wetlands, plant genetic resources and the protection of endangered species. These conventions are complementary to the Arctic Council's efforts to address the conservation of Arctic biodiversity and to promote practices that ensure the sustainability of the Arctic's living resources.

In relation to the United Nations Convention on Biological Diversity (CBD), a Resolution of Cooperation between CAFF and the CBD, signed in 2010, encourages the two organizations to provide and use information and opportunities to promote the importance of Arctic biodiversity. This has led to many opportunities to provide Arctic-specific information into CBD processes (CAFF 2012), and will directly contribute to the achievement of the Strategic Plan for Biodiversity 2011-2020 adopted by CBD Parties in 2010.

The Strategic Plan for Biodiversity 2011-2020 is comprised of a shared vision, a mission, strategic goals and 20 ambitious yet achievable targets, collectively known as the Aichi Targets. The mission calls for effective and urgent action to halt the loss of biodiversity in order to ensure that, by 2020, ecosystems are resilient and continue to provide essential services, thereby securing the planet's variety of life, and contributing to human well-being, including the eradication of poverty.

The 2013 Arctic Biodiversity Assessment will provide data and information on the status and trends of biological diversity in the Arctic to the Fourth Global Biodiversity Outlook and will also contribute to the achievement of the Strategic Plan for Biodiversity 2011-2020 and the Aichi Targets. The Aichi Targets of direct relevance to the findings of the Arctic Biodiversity Assessment are:

- **Target 5**
  By 2020, the rate of loss of all natural habitats, including forests, is at least halved and where feasible brought close to zero, and degradation and fragmentation is significantly reduced.

- **Target 6**
  By 2020 all fish and invertebrate stocks and aquatic plants are managed and harvested sustainably, legally and applying ecosystem based approaches, so that overfishing is avoided, recovery plans and measures are in place for all depleted species, fisheries have no significant adverse impacts on threatened species and vulnerable ecosystems and the impacts of fisheries on stocks, species and ecosystems are within safe ecological limits.

- **Target 9**
  By 2020, invasive alien species and pathways are identified and prioritized, priority species are controlled or eradicated, and measures are in place to manage pathways to prevent their introduction and establishment.

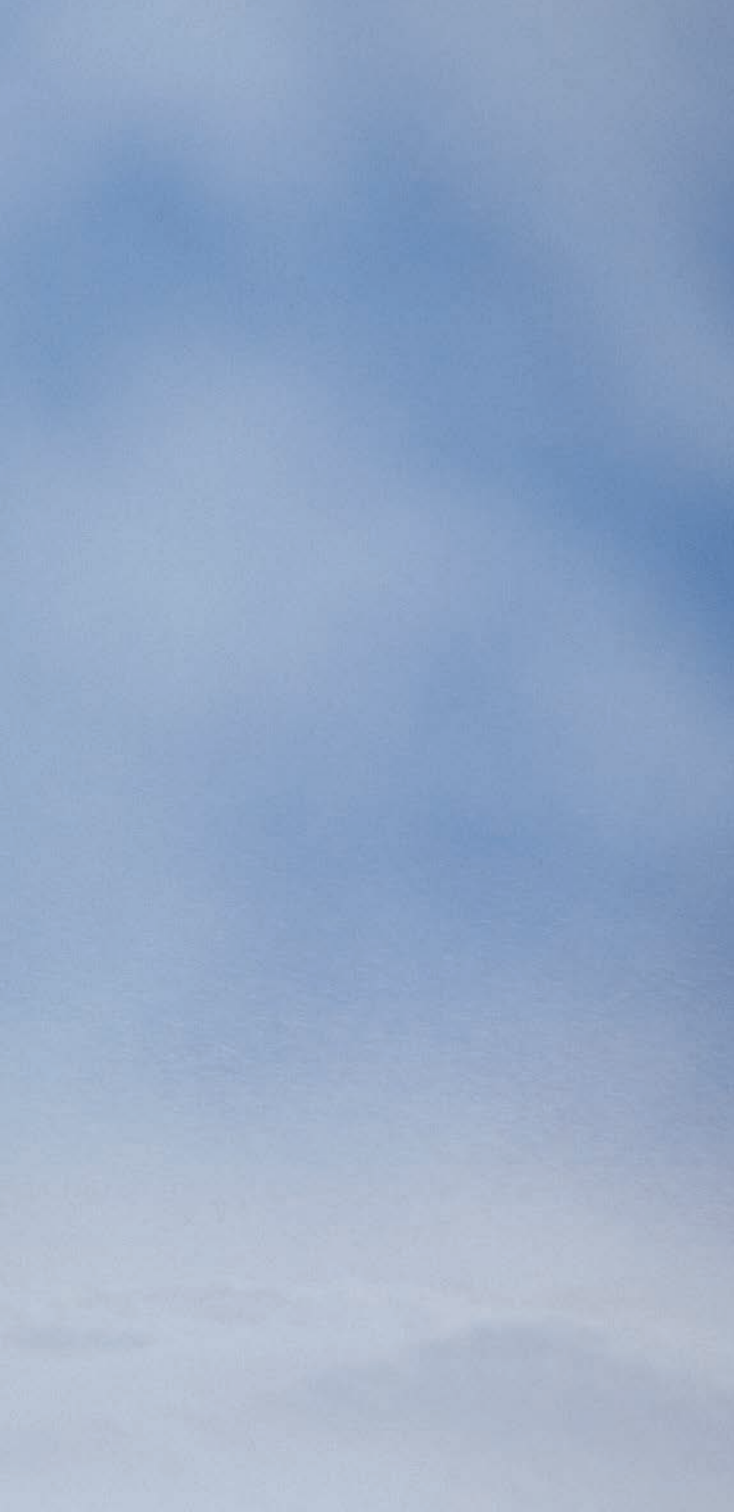
- **Target 10**
  By 2015, the multiple anthropogenic pressures on coral reefs, and other vulnerable ecosystems impacted by climate change or ocean acidification are minimized, so as to maintain their integrity and functioning.

- **Target 11**
  By 2020, at least 17 per cent of terrestrial and inland water, and 10 per cent of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, are conserved through effectively and equitably managed, ecologically representative and well connected systems of protected areas and other effective area-based conservation measures, and integrated into the wider landscapes and seascapes.

- **Target 12**
  By 2020, the extinction of known threatened species has been prevented and their conservation status, particularly of those most in decline, has been improved and sustained.

- **Target 14**
  By 2020, ecosystems that provide essential services, including services related to water, and contribute to health, livelihoods and well-being, are restored and safeguarded, taking into account the needs of women, indigenous and local communities, and the poor and vulnerable.

2. CHARACTERISTICS OF ARCTIC BIODIVERSITY



The Arctic is made up of the world's smallest ocean surrounded by a relatively narrow fringe of island and continental tundra (Box 4). Extreme seasonality and permafrost, together with an abundance of freshwater habitats ranging from shallow tundra ponds fed by small streams to large deep lakes and rivers, determine the hydrology, biodiversity and general features of the Arctic's terrestrial ecosystems. Seasonal and permanent sea ice are the defining features of the Arctic's marine ecosystems.

The Arctic tundra, freshwaters and seas support more than 21,000 species of plants, fungi and animals – even when endoparasites[1] and microorganisms are excluded, of which thousands of species may remain undescribed (Tab. 1). Although they are less rich in species than other biomes on Earth (see for example, vascular plant richness in Fig. 1), Arctic terrestrial and marine ecosystems provide room for a range of highly adapted and particularly cold-resistant species, as well as species that fill multiple ecological niches.

The Arctic fox is highly adapted to cold and snow by short extremities, winter whiteness and insulation through fur. Photo: Carsten Egevang/ARC-PIC.com

1 A parasite that lives within another organism.

Box 4.
Two very different polar areas

The Antarctic continent has been isolated from the rest of the world's land masses for about 23 million years (Trewby 2002), and together with an almost total ice cover for 15 million years this has left the Antarctic with a very sparse terrestrial fauna and flora. While the Antarctic continent is huge and almost totally ice covered, the Arctic is made up of the world's smallest ocean surrounded by a relatively narrow zone of island and continental tundra at the edge of the two large northern continents. This means that the Arctic has a rich terrestrial fauna and flora derived from the Eurasian and North American continents and including many species that were widespread at lower latitudes during the Pleistocene. Indeed, about 14,000 terrestrial Arctic species are known to science – even when endoparasites and microorganisms are excluded. The periodic advances and retreats of Arctic continental ice sheets during the Pleistocene caused many local extinctions, but also created intermittent dispersal barriers and population bottlenecks, accelerating divergent evolution of some taxa (see Christiansen & Reist, Chapter 6 and Josefson & Mokievsky, Chapter 8).

One of the results of this is that the Arctic – in contrast to the Antarctic – is inhabited by a variety of terrestrial mammalian predators. The absence of this faunal element from the Antarctic allowed millions of flightless penguins to breed on the continental land mass – a behavior which would be precluded in the Arctic by the presence of Arctic foxea, wolves and polar bears. Not even massive harvest by humans during the last century altered the apparently genetically fixed confidence of much of the Antarctic fauna, so that one can approach the animals almost to within touching range. The presence of land predators in the Arctic meant that the 'northern penguin', the flightless great auk *Piguinus impennis* only lived at the margins of the Arctic, on islands where polar bears, wolves, Arctic foxes and humans were absent – until European mariners reached their breeding grounds a few centuries ago and drove them to extinction.

While the Arctic is very much richer in terrestrial biodiversity than the Antarctic, this is not so for marine life. With c. 7,600 marine species, the Arctic has similar species richness to the Antarctic, even though the species composition of the marine phytoplankton and sea-ice algal communities is different between the two polar regions. The open southern ocean that has encircled the Antarctic for millions of years has allowed many Antarctic marine taxa to disperse around the entire continent. Given the greater extent of the ice-free southern ocean, compared with Arctic waters, it is not surprising that the total numbers of marine organisms living in Antarctic waters exceed those of similar Arctic species. For example, the most numerous seal species in the world is the Antarctic crabeater seal *Lobodon carcinophaga* with an estimated population in the region of 50 to 80 million individuals (Shirihai 2008); while at least 24 Antarctic and sub-Antarctic seabird species number more than 1 million individuals, 'only' about 13 Arctic and sub-Arctic seabirds reach this level (cf. Cramp 1983-1989, Williams 1995, Brooke 2004, Shirihai 2008, Ganter & Gaston, Chapter 4). In contrast to Antarctica, Arctic marine waters are separated into Pacific and Atlantic zones, each with its own evolutionary history, so that many Arctic genera are represented by different species in the two ocean basins. In addition, marine food webs differ between the two polar regions (Smetacek & Nicol 2005). Taken together, ecosystem structure, sea extent and the presence of humans and mammalian predators in the Arctic have resulted in great differences in structure, composition and functioning between both marine and terrestrial ecosystems in the Arctic and Antarctic regions.

Table 1. Selected characteristics of species occurring in the Arctic, by taxonomic group. On top of these come an estimated total of at least 7,100 described and as-yet undescribed endoparasites and several thousand groups of microorganisms.

Group	Species occurring in the Arctic	Ratio of worldwide total	Mainly Arctic species	IUCN Endangered, Vulnerable, or Near Threatened	Extinct in modern times
Terrestrial mammals	67	1%	18	1	0
Marine mammals	35	27%	11	13	1
Terrestrial and freshwater birds	154[a]	2%	81[a]	17	0
Marine birds	45[a]	15%	24[a]	3	0
Amphibians/reptiles	6	< 1%	0	0	0
Freshwater and diadromous fishes	127	1%	19		
Marine fishes	c. 250[b]	1%	63	4[c]	
Terrestrial and freshwater invertebrates	> 4,750				
Marine invertebrates	c. 5,000				
Vascular plants	2,218	< 1%	106[d]	0	0
Bryophytes	c. 900	6%			
Terrestrial and freshwater algae	> 1,700				
Marine algae	> 2,300				
Non-lichenized fungi	c. 2,030	4%	< 2%		
Lichens	c. 1,750	10%	c. 350		
Lichenocolous fungi	373	> 20%			

a) Includes only birds that breed in the Arctic. b) Excludes the sub-Arctic Bering, Barents and Norwegian Seas. c) Most marine fish species have not been assessed by IUCN. d) Includes Arctic endemics only.

Species richness is unevenly distributed over the Arctic and varies both with latitude and longitude and Pleistocene glacial history. It is also to some extent taxon specific. In most organism groups, species richness declines from the low to high Arctic. Areas that were unglaciated during the last ice age possess higher richness of vascular plants, bryophytes, diadromous and freshwater fishes and terrestrial mammals (Reid *et al.*, Chapter 3, Christiansen & Reist, Chapter 6, Daniëls *et al.*, Chapter 9). The area around the Bering Strait and eastern Siberia is particularly rich in species (e.g. plants, terrestrial invertebrates, shorebirds and mammals), probably due to the existence of unglaciated refugia during the Quarternary (Fig. 2) in combination with isolation east and west of the strait and on islands during interglacial periods with elevated sea levels (Payer *et al.*, Chapter 2, Reid *et al.*, Chapter 3, Ganter & Gaston, Chapter 4, Hodkinson, Chapter 7, Daniëls *et al.*, Chapter 9, Ims and Ehrich, Chapter 12). Marine fish have very high richness in the Bering Sea, but much lower richness on the Arctic side of the Bering Strait sill (Christiansen & Reist, Chapter 6). While Iceland and Greenland have

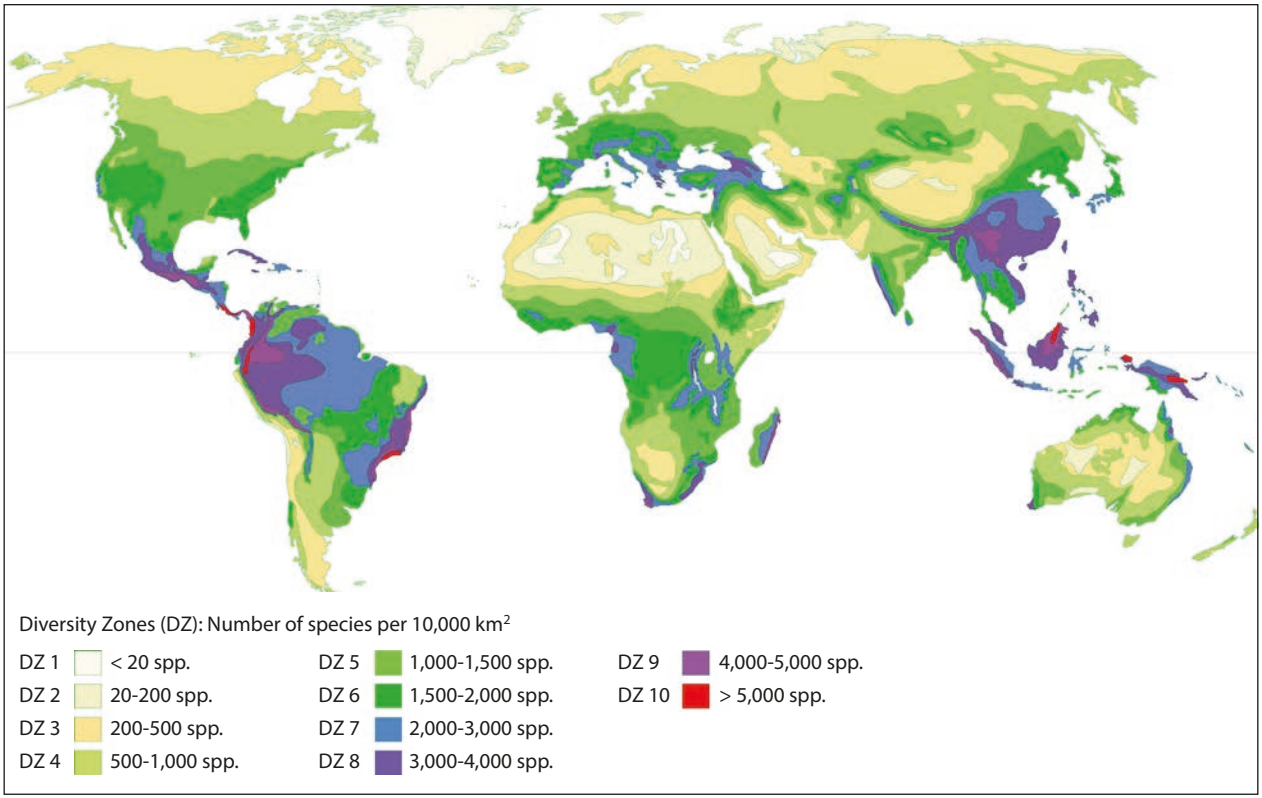


Figure 1. World species richness in vascular plants (from Settele *et al.* 2010; printed with permission from Pensoft Publishers).

particularly low diversity of freshwater fish and terrestrial mammals, Greenland is rich in lichens (Dahlberg & Bültmann, Chapter 10). Marine benthic invertebrates show highest species richness in the Barents/Kara Sea area, although some of those latter patterns partly may result from more intensive sampling in these areas (Josefson & Mokievsky, Chapter 8).

Although the relationship between diversity and productivity remains unclear (e.g. Currie *et al.* 2004), zones of high productivity often support higher diversity of species. Deltas and estuaries of large Arctic rivers are among such areas of high local productivity due to riverine nutrient inputs, mixing zones and upwellings from deep marine waters. These areas contain high fish biodiversity, consisting of mixtures of wholly freshwater species inside the deltas, diadromous species moving between fresh and marine waters, and nearshore marine species tolerant of waters of widely varying salinities (Christiansen & Reist, Chapter 6).

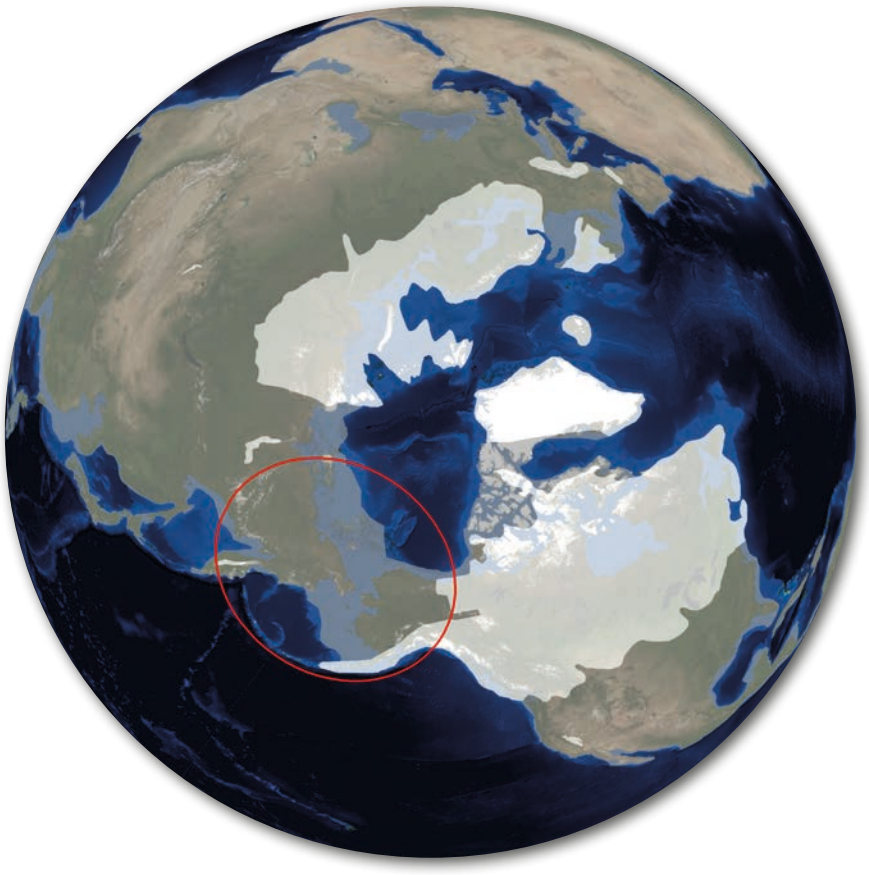


Figure 2. Beringia and other glacial refugia in the Arctic: distribution of ice cover (white shading) and ice-free areas in the northern hemisphere during the last glacial maximum 18,000 years ago (from Ray & Adams 2001). Beringia is enclosed within the red oval.

2.1. Terrestrial ecosystems

The terrestrial Arctic makes up about 5% of the Earth terrestrial surface. Most of it is within relatively short distance from icy coasts that make up one fifth of the total coastline of the world. Compared with most other biomes on Earth, the terrestrial Arctic is generally low in species diversity, which is explained by a number of properties, such as its relatively young age, low solar energy input, extreme climatic variability and decreasing biome area with increasing latitude (Payer *et al.*, Chapter 2). The high Arctic has particularly low vascular plant diversity compared with lower latitudes in the Arctic (Daniëls *et al.*, Chapter 9). But at a small scale, species diversity can be very high. In sample-plots of 25 square meters, for example, almost 100 species of vascular plants, bryophytes and lichens can grow together (Vonlanthen *et al.* 2008) with an unknown number of other fungi, algae and microbes, which is as high as in the richest grasslands of temperate and subtropical regions (Daniëls *et al.*, Chapter 9, Dahlberg & Bültmann, Chapter 10). Together with the absence of woody

plants and sedges (*Carex* spp.), this makes this marginal northern rim of the Arctic a unique ecosystem of the world (e.g. Matveyeva 1998, Vonlanthen *et al.* 2008, Ims & Ehrich, Chapter 12).

Terrestrial Arctic ecosystems are characterized by a short productive summer season, but also by large regional differences including markedly steep environmental gradients. For example on the Taimyr Peninsula in Siberia only 500 km separate the relatively lush sub-Arctic and the high Arctic 'desert' (CAVM Team 2003, Callaghan 2005). The defining features of the terrestrial Arctic are cool summers (see Box 1) and short growing seasons resulting in low primary productivity and reduced biomass in comparison with southerly latitudes. Adaptations include slow growth and long life cycles in plants and fungi, small fungal sporocarps and small average body sizes in invertebrates (Callaghan 2005, Dahlberg & Bültmann, Chapter 10). Another prominent feature of much of the Arctic is extreme seasonality with ground-level differences of up to about 80 °C between winter minimum and summer maximum temperatures and with strong spatial north-south and coast-inland gradients. Arctic organisms are well adapted to this seasonality either by their ability to migrate during winter, or through characteristics making them suited to the cold and snow (Callaghan *et al.* 2004a). These include short extremities, winter whiteness, insulation through fur, feathers and fat, freeze tolerance, endogenous antifreeze compounds, hibernation and the ability to survive desiccation and oxygen deficiency, together with behavior exploiting the insulative properties of snow. Similarly, sessile organisms such as plants have developed a variety of individual strategies to economize or reduce loss in biomass and to persist through adverse conditions, such as asexual reproduction, small and compact growth, furry or wax-like coatings, positive photosynthesis balance at low temperature and survival at extremely low temperatures and levels of water content during winter dormancy.

The main feature of the terrestrial Arctic is tundra; the land without trees. In the low Arctic, vegetation of scrubs and herbs may be knee-high, while in the high Arctic it only reaches the ankle. Photo: Jeff Wilson/naturepl.com

Arctic terrestrial biodiversity has had to adapt to the high variability of the Arctic climate both in the form of inter-annual variability (including extreme events) and more regular (short or long-term) climatic fluctuations (see Walsh *et al.* 2011). This variability can drive, and may regionally synchronize, fluctuations in wildlife populations (e.g. Vibe 1967, Krupnik 1993, Hansen *et al.* 2013). Inter-annual variability in weather includes extraordinarily severe winters, highly varying amounts of snow, spells of winter rain and thaw (ice crust formation on land; see Rennert *et al.* 2009), variable timing in spring snow melt and sea ice break up, and poor summer weather including periods of strong winds and snowfall. There is increasing evidence that such events occur in cyclical patterns governed by geophysical phenomena such as the Arctic, North Atlantic and Pacific Decadal Oscillations (see Hurrell *et al.* 2003). Moreover, the internally driven (endogenous) multi-annual, high-amplitude cycles in animal and plant biomass driven by trophic interaction in tundra food webs, contribute to the temporal variability of biodiversity (Ims & Fuglei 2005, Ims & Ehrich, Chapter 12). There is rarely a 'normal' year in the Arctic.

2.2. Freshwater ecosystems

The Arctic landscape is characterized by a wide range of types and sizes of freshwater systems including

Arctic landscapes are young landscapes sculpted by repeated glaciations, strong water flow each year at snow melt, and a large variety of frost actions resulting in all kinds of wetlands and patterned ground. Aerial view in May of Mackenzie River and associated delta lakes in the sub-Arctic of Northwest Territories, Canada. Photo: Lance Lesack.

flowing systems (rivers and streams) and many types of standing water systems (lakes, ponds) (ACIA 2005, Wrona *et al.* 2006, Vincent *et al.* 2008). High seasonality and in many cases ephemerality characterize all systems (Pielou 1994). A unique combination of climatic, geological and biophysical features, related cold-regions processes and the interactions among them produce a diverse range of environmental conditions that shape Arctic freshwater ecosystems and distinguish them from those found at lower latitudes.

Although freshwater ecosystems are abundant in the Arctic, they do not generally support the levels of biodiversity found in more southerly regions. The regional numbers of freshwater species typically decrease sharply poleward, although the differences among regions in the Arctic can be considerable. Fish species diversity is generally low at both regional and local scales in high latitudes, although considerable diversity of the fishes exists below the species level (Reist *et al.* 2006). Although Arctic freshwater systems gener-

ally display less biological diversity than temperate or tropical systems, they contain a diversity of organisms that display specialized adaptation strategies to cope with the extreme environmental conditions they face. Examples of adaptations include life-history strategies incorporating diapause and resting stages, unique physiological mechanisms to store energy (i.e. lipids) and nutrients, an ability to grow and reproduce quickly under short growing seasons, and extended life spans relative to more temperate species (Wrona *et al.* 2005).

2.3. Marine ecosystems

Arctic marine ecosystems differ from other marine ecosystems on the planet. Dominated by large areas of seasonally-formed sea ice over extensive shelves and a large central area of perennial (multi-year) pack ice – at least until recent times – the Arctic Ocean is characterized by seasonal extremes in solar irradiance, ice cover and associated atmospheric exchanges, temperature and, on the shelves, riverine inflow. The seasonality in environmental conditions and the physiography of the Arctic Ocean, together with its connection to the Atlantic and Pacific Oceans through the 'Arctic gateways', are key elements structuring its diversity of species and ecosystems.

The Arctic Ocean is stratified because the large freshwater inflow from rivers and seasonal sea-ice melt makes the upper layer of the ocean less salty than other oceans (Fig. 3). The surface stratification is important in that it can limit nutrient supply from nutrient-rich deep waters to the upper water column, where primary production takes place when there is sufficient light in spring/summer. During winter, the absence of light limits photosynthetically driven primary production, which will resume upon the return of the sun, and is, therefore, dependent on latitude. When sufficient light

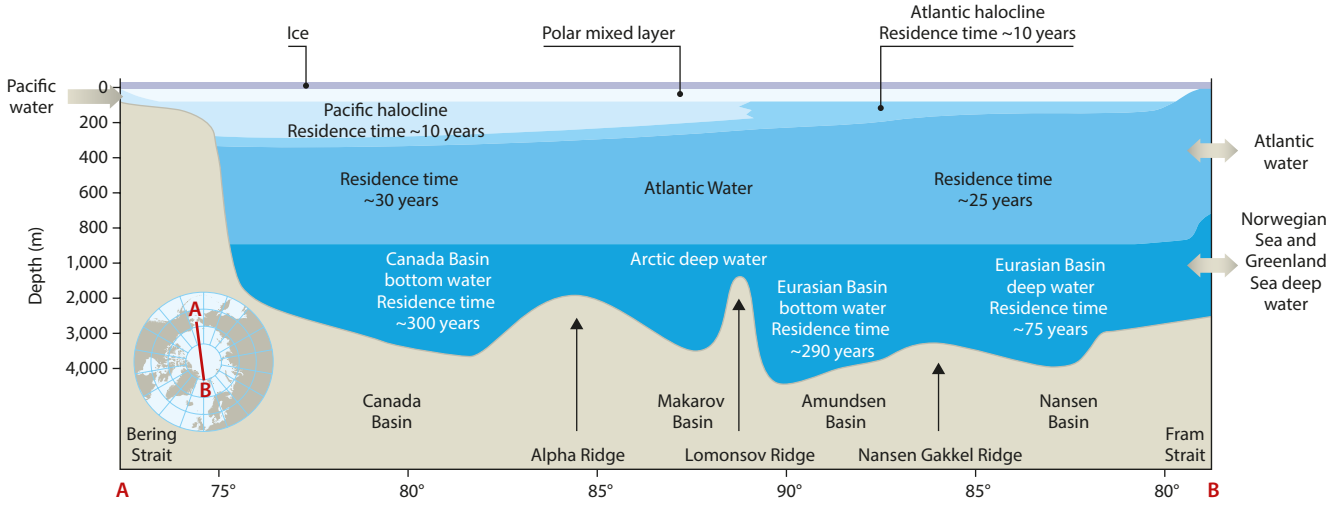
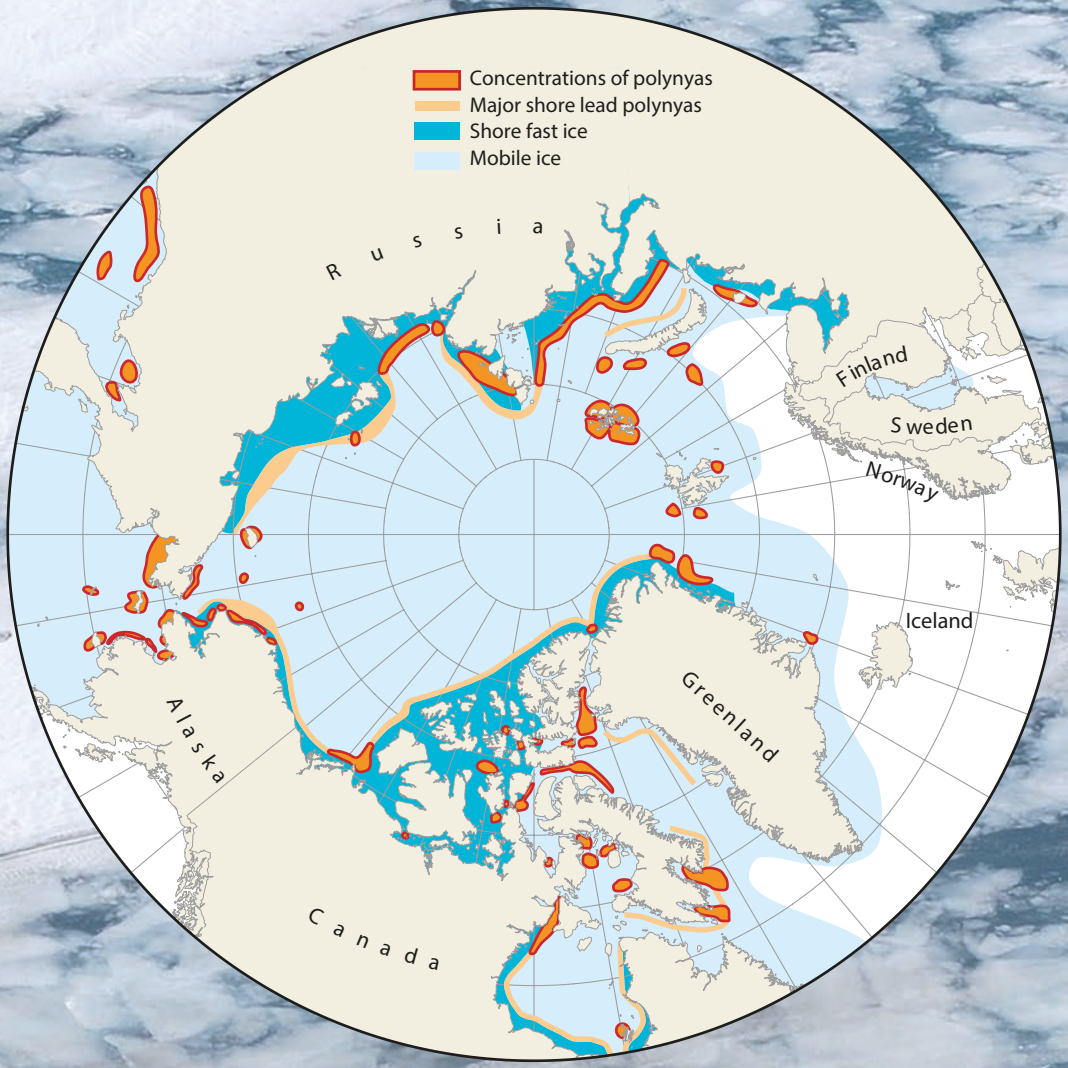


Figure 3. Schematics of different water masses in the Arctic Ocean, emphasizing vertical stratification (from AMAP 1998).

Figure 4. Circumpolar map of known polynyas. Note that some polynyas no longer exist in the form known from their recent history (from Barber & Masson 2007).
Photo: yui/shutterstock.com



is available in or under the ice, or at ice edges and in open water areas (e.g. in polynyas and ice-free waters in the Barents Sea), short and highly productive phytoplankton or ice algal blooms develop, delivering of energy and materials to zooplankton and other trophic levels that also display a high seasonality in feeding, reproduction and migration patterns.

In the marine Arctic, the central Arctic basins are typically (in the presence of multi-year ice) regions of low productivity. However, some of the most productive marine ecosystems on Earth are found in the outer Arctic seas (e.g. Barents, Chukchi and Bering Seas) and in polynyas, i.e. recurrent areas of open water amid sea ice (Fig. 4). Many species of invertebrates, fish, seabirds and marine mammals occur in large aggregations at such particularly productive sites. Interestingly, Arctic sea ice can host productive microbial communities, and the deep waters of the Arctic Ocean also have unique hot vent communities adapted to very high temperatures, highlighting the range of extremes found in Arctic marine ecosystems.

2.4. Arctic species and foodwebs

On a global scale, Arctic terrestrial ecosystems are relatively young, having developed mainly during the last three million years (Payer *et al.*, Chapter 2, Ims & Ehrich, Chapter 12). The early Quaternary Arctic flora included species that evolved from high-latitude forest vegetation by adapting to colder conditions, plus others that immigrated from alpine habitats in temperate regions of Asia and North America. During the Quaternary Period, Arctic ecosystems have been profoundly molded by climatic history, including more than 20 cycles of glacial advance and retreat, along with associated changes in sea-ice cover. In many areas, these broad-scale changes displaced, then readmitted, biological communities. Consequently, many Arctic species are well adapted to climate variability and extremes, but poorly adapted for secondary ecological stressors such as increased competition, parasites and diseases (Callaghan *et al.* 2004a).

Many Arctic animal, fungal and plant species are widely distributed within the circumpolar region, with a significant proportion having circumpolar distributions. Endemic species, for which ranges are restricted to a limited geographic region such as the Arctic or parts of the Arctic, are found in many groups of Arctic animals, plants and fungi. However, because of the shifting conditions, local-scale adaptation and speciation is rare outside Beringia, leading to low numbers of local endemics. Among invertebrates, endemic species range from single cell testate amoebae to the higher arthropods such as spiders, mites, springtails and beetles (Hodkinson, Chapter 7). Among marine invertebrates, the moss animals (bryozoans), being sessile and generally characterized by restricted dispersal ability, show a relatively high degree of endemism (Josefson & Mokievsky, Chapter 8). Some helminth parasites also have restricted geographic distributions coinciding with their avian, mammalian and piscine hosts (Hoberg & Kutz, Chapter 15). Among vascular plants, endemic species include more than one hundred narrow-range species especially in Beringia and even some planktonic cold-adapted algae (Daniëls *et al.*, Chapter 9). Among fungi, there are many endemic or restricted range lichens, especially from Svalbard, Greenland, Novaya Zemlya, eastern Chukotka and Ellesmere Island. Most of these are rock-dwelling microlichens confined to the high Arctic (Dahlberg & Bültmann, Chapter 10). Among terrestrial insects, several beetle species are endemic to the Beringia region of NE Siberia. Several species of char *Salvelinus* spp., several whitefishes *Core-*

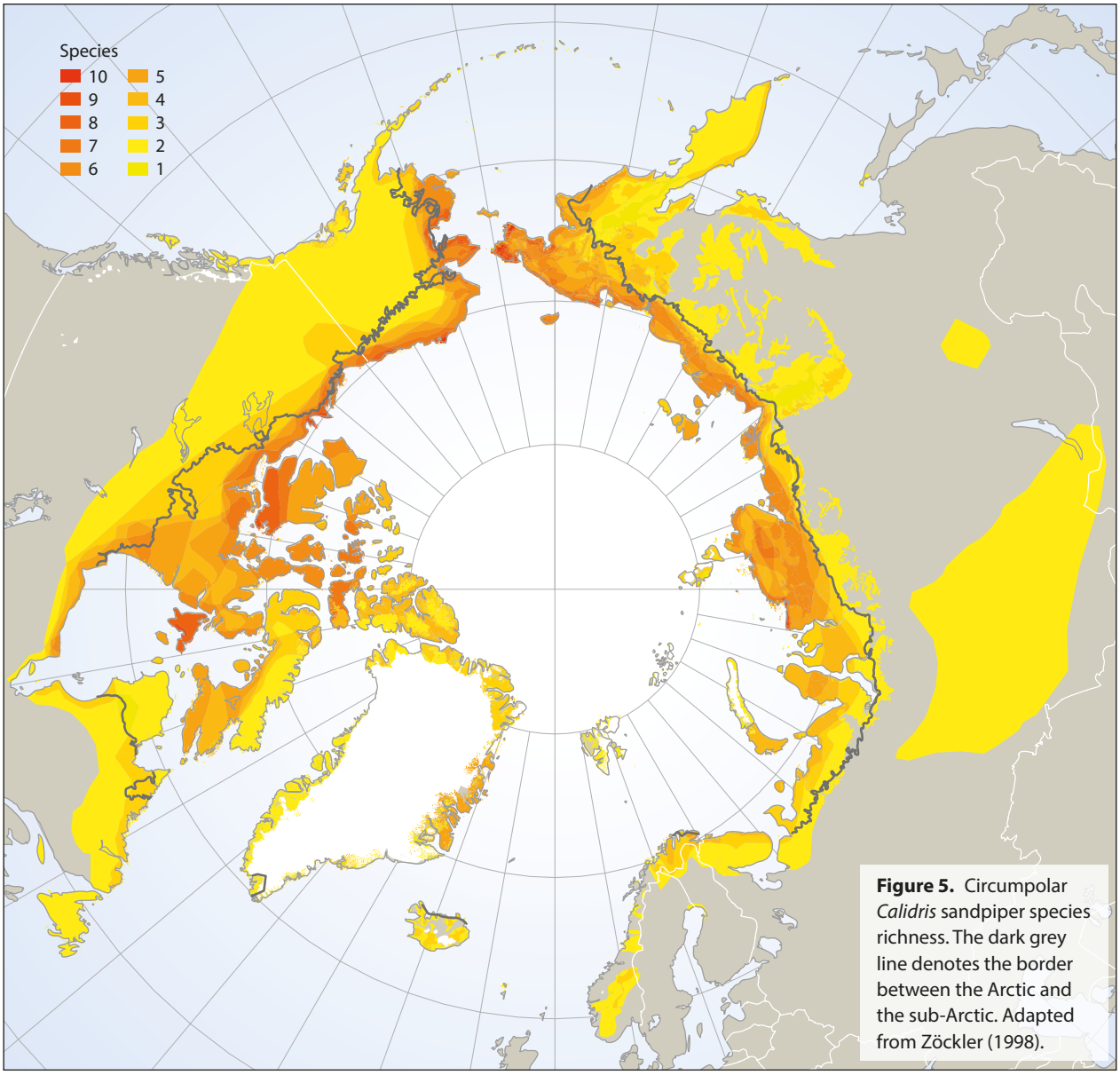


Figure 5. Circumpolar *Calidris* sandpiper species richness. The dark grey line denotes the border between the Arctic and the sub-Arctic. Adapted from Zöckler (1998).

gonus spp. and a few other freshwater and marine fishes are endemic or near endemic to the Arctic (Christiansen & Reist, Chapter 6). In birds, the loons/divers Gaviidae and the auks Alcidae are mainly found in the Arctic and sub-Arctic, while the eiders *Somateria* spp. and *Polysticta*, gulls (Laridae) and *Calidris* sandpipers reach their highest diversity there (Fig. 5; Ganter & Gaston, Chapter 4). Also among mammals, a number of highly adapted species are found almost exclusively in the Arctic (Reid *et al.*, Chapter 3).

Among flying birds, few of the Arctic species can be classified as restricted range species, i.e. species with a total historical breeding range of less than 50,000 km^2 (BirdLife International 2012). However, among other groups, several species exhibit more limited distributions. Some Arctic endemics are confined to one or a few locations, such as longfin char *Salvethymus svetovidovi* and small-mouthed char *Salvelinus elgyticus*, which are found only in Lake El'gygytgyn, a three million-year-old meteorite crater lake in central Chukotka (Christiansen & Reist, Chapter 6). Mammals with restricted ranges include some species of shrews and lemmings, such as the Pribilof Island shrew *Sorex pribilofensis* and the Wrangel Island brown lemming *Lemmus portenkoi*, which inhabit islands that were once part of a broader land mass but became isolated by rising sea levels after the last ice age.

Therophytes (annual plant species) are rare in the Arctic because of short growing seasons, marked interannual variability and nutrient-poor soils. Conversely, polyploidy[2] is common across the Arctic vascular plant flora, in particular in the northern and longer-glaciated North Atlantic areas of the Arctic (e.g. Brochmann *et al.* 2004, Solstadt 2009). The evolutionary success of polyploids in the Arctic may be based on their fixed heterozygous genomes, which may buffer against interbreeding and genetic drift through periods of dramatic climate change. Moreover the ecological amplitude of polypoids is broad and thus they have a greater ability to cope with a changing climate and adapt to more diverse ecological niches than a diploid could (Brochmann *et al.* 2004, Daniëls *et al.*, Chapter 9). Among birds, plumage polymorphism is widespread (e.g. skuas/jaegers *Stercorariidae*, northern fulmar *Fulmar glacialis*, snow geese *Chen* spp., Iceland gull *Larus glaucoides*, nestling murres *Uria* spp.), perhaps as a result of population differentiation and introgression during the Pleistocene glacial and interglacial periods (see also Box 17.10 in Cook, Chapter 17).

In response to extreme seasonality, many Arctic species are migratory. This involves a high proportion of bird species and several marine mammals that migrate out of the Arctic entirely, whereas others such as reindeer/caribou migrate long distances within the Arctic or to adjacent sub-Arctic areas. Migratory birds, in particular, visit the Arctic to breed or feed intensively during the summer burst of productivity, both on land and in the sea. Many of them spend more than half the year outside the Arctic, where they may be found in practically every other part of the world, except inland Antarctica (Ganter & Gaston, Chapter 4).

A special kind of migration is shown by diadromous[3] fish, which either spend each summer in the sea to fatten up, or live there for most of their lives before going up rivers to reproduce in fresh water (Christiansen & Reist, Chapter 6).

Arctic ecosystems have generally been considered to possess shorter food chains with fewer trophic levels

2 More than two sets of chromosomes occurring in an organism.

3 Fish migrating between fresh and marine waters.

than other biomes (Callaghan 2005). However, this concept is increasingly challenged (see e.g. Hodkinson, Chapter 7 and Michel, Chapter 14), and Arctic marine ecosystems are found to be as diverse as more southern marine ecosystems (Smetacek & Nicol 2005, Josefson & Mokievsky, Chapter 8). However, the numerical dominance of relatively few key species in Arctic food webs, together with highly variable climatic conditions, makes them prone to strong food web interactions (for instance leading to community-wide cycles) and environmentally driven fluctuations with cascading effects through entire ecosystems (Post *et al.* 2009, Gilg *et al.* 2012, Hansen *et al.* 2013). Consequently, Arctic ecosystems are unstable in terms of species composition and abundance, but nevertheless have shown substantial resilience to natural variability in the Holocene, largely because of the wide distributions and mobility of their constituent organisms. This mobility, which enables much of the fauna and flora to move and seek new habitat elsewhere in response to unfavorable circumstances, is often an essential part of their adaptation to locally and regionally variable conditions. Mobility can be active, in which animals seek out new habitat, or passive, involving non-directed dispersal of animals, fungi and plants by wind, surface melt-water and streams, and local ocean currents or by phoretic dispersal on the bodies of vertebrates or larger flying insects. When planning for Arctic conservation, it is essential to consider the vast spatial scales over which many organisms operate as well as the existing barriers to mobility that influence the current distribution of some species (e.g. marine barriers to movements of some terrestrial mammals such as the Arctic ground squirrel *Spermophilus parryii*).

Each spring, millions of birds migrate to the Arctic from almost all parts of the world to take advantage of the bounty of plant and invertebrate production in the short Arctic summer. Red knots, dunlins, grey plovers and bar-tailed godwits staging in the European Wadden Sea before taking off to the Siberian tundra in late May. Photo: Jan van de Kam.

3. HUMAN USE OF WILDLIFE THROUGH TIME

» *This is what I want to pass on to my descendants: good food from the land, caribou and fish. The land makes you live well and be healthy.*

(Rosie Paulla, Canada 1976).

» *The reason I exist today as an Inuk is because of my ancestors that really tried and survived on wildlife and whales… When I go whale hunting … there are a lot of things that go through my mind, not about the world today, but about the world where we were before, where my ancestors were coming from. Yeah, you can almost hear echoes from the past when you are whaling.*

(Johnny Mike, Pangnirtung, March 1995).

From the first arrival of humans in the Arctic to the modern day, the use of wildlife has been an essential contributor to individual and community well-being. Patterns and purposes of use have varied by time and place, with differing implications for biodiversity. The harvest of wildlife remains both a vital connection between humans and biodiversity and a source of impacts to at least some wildlife populations, whereas today other stressors pose a greater threat to Arctic biodiversity. This section provides a brief outline of such uses and impacts, from prehistory until today, by indigenous peoples and more recent arrivals.

Resources from marine mammals have been pivotal to Inuit and other Arctic cultures for millennia. Meat and blubber were and are used for food for humans and dogs, blubber for light and heating as well, and skin and bones for clothing and tools. Seal meat remains a most appreciated food item. Photo: Carsten Egevang/ARC-PIC.com

People in the Arctic have harvested wild species for millennia with wild mammals, birds, fish and plants providing nutritional as well as cultural sustenance (Huntington *et al.*, Chapter 18). Arctic cultures have been more dependent on hunting than people in almost any other part of the world because of the limited availability of edible wild plants to complement hunted species. Some species, such as bears and whales, have great symbolic importance in Arctic cultures, and harvest of wildlife is deeply rooted in the self-perception of Arctic peoples. Although traditional foods typically account for a smaller portion of indigenous diets today (Hansen *et al.* 2008, Vaktskjold *et al.* 2009, Wheeler *et al.* 2010; see also Huet *et al.* 2012), biodiversity and the natural environment remain integral to well-being of Arctic peoples, providing not only food but the everyday context and basis for social identity, cultural survival and spiritual life (Huntington *et al.*, Chapter 18).

Indigenous cultures and technologies allowed people to thrive in the Arctic and to cope with a high degree of natural environmental variability. However, the Arctic has fewer resources and fewer alternatives in times of scarcity than the sub-Arctic and boreal zones, creating a higher degree of risk from changes in weather patterns or wildlife populations. The archeological record indicates, as one result, the repeated disappearance of whole cultures such as in Greenland and the Canadian Arctic since the Arctic was first inhabited (Born & Böcher 2001). Scarcity and even famine remained a part of life in much of the Arctic even into the modern era.

Climate change and human hunting probably worked together to force major changes in Arctic biodiversity in the late Quaternary (Lorenzen *et al.* 2011). Still, for several millennia human population density was so low in most parts of the Arctic[4], and the means of transport and hunting so limited in range, that significant human impacts on animal populations were probably limited to a number of long-lived and slow-reproducing species together with easily accessible colonies of breeding seabirds and marine mammals (see e.g. Krupnik 1993 and Freese 2000). It is also likely that hunting had marked impacts on the behavior of several species, which became wary of human presence, while most remained relatively little affected.

Arctic cultures often view human-environment interactions in terms of the relationship between individual humans and animals. For example, hunters may be admonished to treat harvested animals well, by using them fully, storing them properly and respecting their spirit. While such practices no doubt contribute to the well-being of Arctic societies and may have helped sustain animal populations, they should not be interpreted solely in light of modern conservation principles based on scientific understanding of population dynamics, reproduction rates and habitat needs (see e.g. Berkes 1999). Instead, such practices must be understood as part of the cultures and knowledge systems in which they were practiced, and can be incorporated into today's conservation efforts.

The perception of pre-modern sustainability of Arctic peoples' harvest of mammals, birds and fish varies considerably. Scholarly reviews are given, for example, by Berkes (1999) and Krupnik (1993) representing slightly differing 'anthropological' and 'natural sci-

4 With the possible exception of reindeer herding areas in northern Eurasia, which to a large extent relied on boreal resources, the most densely populated Arctic areas were probably the highly productive coasts around the Bering and Davis Straits (SW Greenland) populated by Inuit and Yup'ik (see AMSA 2009).

Fish has been an important resource for all Arctic people through millennia. Arctic char. Photo: Carsten Egevang/ARC-PIC.com

ence' views, respectively. There are well documented examples of measures such as rotational harvest to avoid overexploitation in the North, but most of these are from the sub-Arctic and boreal regions (Berkes 1999, Mustonen & Mustonen 2011, Christiansen & Reist, Chapter 6), where more alternative resources were available. As expressed by Krupnik (1993) "In contrast [to the Arctic], an overkill hunting strategy appears to have no parallel among the hunters and fishers of the northern forests or the temperate coastal zone, because the resources of the river valleys and maritime ecosystems are far less marked by instability and unpredictability." Similarly, people in the sub-Arctic Faroe Islands and Iceland practiced strong regulation of the take of birds and eggs in seabird colonies to avoid depletion of this very important resource (see e.g. Nørrevang 1986 and Olsen & Nørrevang 2005).

Indeed, people living in the Arctic often harvested more than they consumed, and for good reasons (Krupnik 1993). The living conditions in the Arctic – i.e. among people without access to alternative boreal resources – have always been unpredictable enough that it was a necessary strategy to use any opportunity to secure as much food and other materials as possible, as a reserve against

future scarcity (see also Meltofte 2001). Animals were harvested in accordance with need, considering both immediate use as well as longer-term insurance against scarcity. In addition, if important local resources were depleted, there was room in most parts of the Arctic to move elsewhere.[5]

The migration of people from the south, particularly from the 17th century onwards, increased the pressure on several wildlife populations considerably. Several populations of marine mammals suffered sharp population declines due to commercial whaling and other new forms of exploitation. During the whaling era, two whale populations – the Atlantic gray whale *Eschrichtius robustus* and the Northeast Atlantic right whale *Eubalaena glacialis* – were driven to extinction (Krupnik 1993, Nowak 1999, Reid *et al.*, Chapter 3). A few species that were already reduced in population or distribution by local hunting were driven extinct by newcomers. The Steller's sea cow *Hydrodamalis gigas* was driven extinct within a decade of the arrival of southern expeditions and whalers (Doming 1978, Turvey & Risley 2006). The great auk *Pinguinus impennis* in the North Atlantic met a similar fate during the 19th century (Nettleship & Evans 1985, Meldgaard 1988). Later, commercially exploited fish stocks came under pressure until recently when more effective management measures were put in place in most places, although by-catch and the allocation of harvest remain problematic for some stocks, especially for some indigenous fishers (FAO 2005, Christiansen & Reist, Chapter 6, Michel, Chapter 14, Huntington, Chapter 18; also see Section 5.1.2 for a summary of impacts and trends of harvest on biodiversity).

For the many Arctic species such as birds and whales that migrate to southern wintering areas, hunting and habitat degradation outside the Arctic have added to the pressure, which in some cases is more severe than in the Arctic. Dire examples of this are the likely extermination of the New World Eskimo curlew *Numenius borealis* by hunting and habitat change primarily in the late 19th and early 20th century (Ganter & Gaston, Chapter 4) and the highly endangered spoon-billed sandpiper *Eurynorhynchus pygmeus* of easternmost Siberia that appears to be at the brink of extinction due to habitat loss and harvest on its wintering grounds in Southeast Asia (Zöckler *et al.* 2010).

While Arctic biodiversity for thousands of years has formed the basis for human cultures in almost all parts of the Arctic, today the harvest of Arctic living resources cannot provide sufficient incomes to support a modern lifestyle across entire communities or regions. Thus, access to additional income from mineral resource exploitation or subsidies from southern societies (transfer payments) are necessary to maintain living standards considered basic in the 21st century (Duhaime 2004), though these economic changes have repercussions for biodiversity and human use thereof. Accordingly, in large parts of the Arctic the importance of Arctic biodiversity to human societies will increasingly emphasize cultural and ethical values including activities such as increasing tourism (see e.g. Hvid 2007 and Huntington, Chapter 18). Yet, harvest of wildlife has importance in securing people against the fluctuation and instability of the monetary economy, such as happened after the end of the Soviet Union (Duhaime 2004).

5 Famine is not considered here, since it most often was the result of unfavorable sea ice or other climatic conditions in certain years or periods reducing the availability of game (see e.g. Vibe 1967, Krupnik 1993).

Arctic and sub-Arctic fisheries are among the richest on Earth, like here in W Greenland. Photo: Anders Skov Hansen/ARC-PIC.com


FURUNO

Mass captures of up to 3,000 flightless geese in one go and up to 26,000 flightless ducks in three days took place in northern Eurasia well up into the 20th century, probably contributing to the critically low population sizes in several goose populations in the middle of the century (from Storå 1968).

Marine fisheries form an important exception to this trend, in that some of the richest fisheries on Earth are found in the North, particularly along the sub-Arctic fringes. These commercial fisheries harvest millions of tonnes annually, including more than 10% of global marine fish catches by weight and 5.3% of crustacean catches, for an economic value in billions of US dollars (Christiansen & Reist, Chapter 6, Michel, Chapter 14, Huntington, Chapter 18). By contrast, harvest of Arctic species other than fishes and shellfish – even though an important part of the seasonal activities and nutrition of many humans in the Arctic – is an important source of income for a dwindling number of people (Huntington *et al.*, Chapter 18).

The rapid growth of human population in most other parts of the world was primarily due to the development of agriculture, followed more recently by the industrial revolution and modern health practices. Thanks to these innovations, southern societies have increased population densities by several orders of magnitude and at the same time – in most parts of the world – raised

living standards to hitherto unknown levels. This was not possible in the Arctic as the 'carrying capacity' of Arctic biodiversity could not support dense human populations. Instead, recent Arctic population growth has resulted from increasing integration with southern economies and societies including the introduction of modern medicine and technology (such as rifles) together with the prevention of widespread starvation and death in periods of poor hunting. For example, the population of Greenland has grown by a factor of 10 since contact with Europe was established almost 300 years ago (Born & Böcher 2001, Danmarkshistorien.dk 2012). Within this general trend, there have been local and regional population decreases and other impacts resulting from impacts of commercial exploitation, environmental variability and economic downturns. However, the separation of human population levels from local carrying capacity and the advent of commercial hunting practices that reward higher harvests led to severe overexploitation of several animal populations such as walrus and a number of seabird species in W Greenland (Merkel 2004a, Witting & Born 2005, Reid *et al.* Chapter 3, Ganter & Gaston Chapter 4).

Human interactions with animals are not limited to hunting and fishing. In some cases, humans are the prey species, as is the case with biting flies and especially mosquitoes. Arctic ecosystems provide ideal aquatic breeding habitats for these insects. While the diversity of mosquito species is generally low, individual species often attain such high summer densities as to make life intolerable for humans and many other vertebrate species. The depredations of mosquitoes alter patterns of behavior in both humans and other vertebrates, including caribou/reindeer. A consequence of increasing abundance of mosquitoes is seen in the explosive emergence of infections of filarioid nematodes that over the past decade have driven mass mortality among reindeer in sub-Arctic Finland and represent direct threats to food security (Hoberg & Kutz, Chapter 15). It is predicted that such ephemeral events linked to patterns of high temperature and humidity may become increasingly common, due to accelerated warming at high latitudes. Currently, no major pathogens are transmitted by Arctic mosquitoes, but as climate warms there is potential for the spread of several insect-borne diseases of humans and other vertebrates into the Arctic. The effects of future warming on biting insects are highly uncertain, however, as they depend on interactions between insect life cycles and temperature, precipitation patterns and tundra hydrology.

Reindeer herding in Eurasia is one of the most extensive forms of human interactions with tundra ecosystems. Both herding practice (range use and migration pattern) and deer abundance (herd size) matter in terms of grazing impacts. Substantial increases of herd sizes both in northern Fennoscandia and on the Yamal Peninsula are associated with large impacts on vegetation, even to the extent that semi-domestic reindeer may counteract the processes of climate-induced encroachment of tall shrubs in tundra (Ims & Ehrich, Chapter 12).

Human-wildlife interactions also include activities such as birdwatching and tourism. These are increasing in the Arctic, especially through more voyages by cruise ships (AMSA 2009). Tourism can increase awareness of Arctic biodiversity and support for its conservation, but if not carefully managed can also lead to disturbance of animals, especially at areas of high aggregations such as bird colonies or marine mammal haul outs, which offer excellent wildlife viewing opportunities and thus attract visitors. The presence of tourists may also interfere with traditional hunting, fishing and herding activities, since these activities to some extent compete for the same locations or resources.

4. STATUS AND TRENDS IN ARCTIC BIODIVERSITY

An accurate accounting of the status and trends of the species of Arctic flora and fauna is impossible except for relatively few well-known vertebrates (see Box 5 on the Arctic Species Trend Index). For many species or species groups, we have data on distribution and sometimes also density, but lack the record through time to assess trends. In addition, many short-term trends reflect cyclical patterns rather than long-term increases or declines. Among the best known of these cyclical patterns are those of Arctic lemmings and lemming-dependent predators with their characteristic 3-5 year cycles (Reid *et al.*, Chapter 3, Ims & Ehrich, Chapter 12). Caribou populations may also fluctuate over the course of decades, making it difficult to distinguish natural variability from new impacts such as industrialization or climate change. For some species, monitoring is facilitated by formation of temporary aggregations associated with seasonal habitat preferences or predator-avoidance behaviors. Examples include

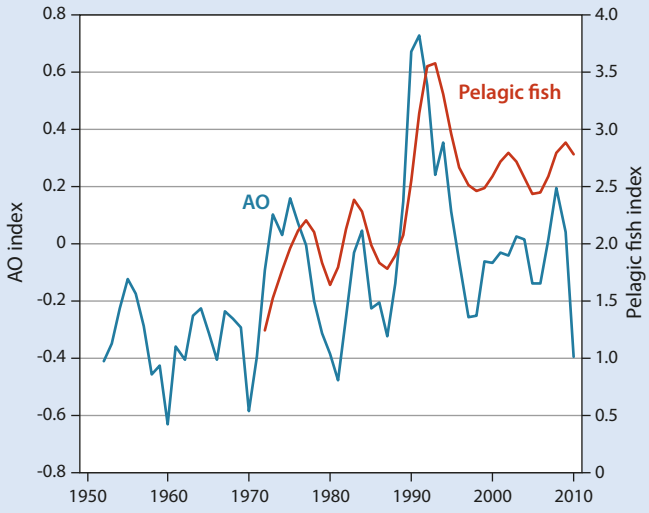
Incubating red knot after a snowfall at Cape Sterlegova, Taimyr, Siberia, 27 June 1991. This shorebird represents the most numerically dominating and species rich group of birds on the tundra and the harsh conditions that these hardy birds experience in the high Arctic. Photo: Jan van de Kam.

Box 5.
The Arctic Species Trend Index

Mike Gill, Circumpolar Biodiversity Monitoring Program, Environment Canada

Evaluating trends in species abundance reveals much about broad-scale patterns of biodiversity change. The Arctic Species Trend Index (ASTI), developed for this purpose, uses population trend data from 890 populations of 323 vertebrate species (37% of known Arctic vertebrate species) using 1970 as the baseline year. It is the Arctic component of a global index of vertebrate species trends, the Living Planet Index (LPI). The ASTI data set can be used to dig deeper and look at patterns in species trends as well as to look at how these trends are related to other changes in Arctic ecosystems (e.g. pelagic fish and the Arctic Oscillation (see below)).

Recent analysis has yielded the following Key Findings:



1. The Arctic Species Trend Index: 2011 update

1.1. Average abundance of Arctic vertebrates increased from 1970 until 1990 then remained fairly stable through 2007, as measured by the ASTI 2011.

1.2. When species abundance is grouped by broad ecozones, a different picture emerges, with the abundance of low Arctic species increasing in the first two decades much more than high Arctic and sub-Arctic species. The low Arctic index has stabilized since the mid-1990s whilst the high Arctic index appears to be recovering in recent years and the sub-Arctic index has been declining since a peak in the mid-1980s.

1.3. The trend for Arctic marine species is similar to that of the overall ASTI, while the trend for terrestrial species shows a quite different pattern: a steady decline after the early 1990s to a level below the 1970 baseline by 2005.

Box 5 Figure 1. Comparison of the three year running average for the CBMP pelagic Arctic fish index and the Arctic Oscillation (AO). Oscillation data from: esri.noaa.gov/psd/data/correlation/ao.data

2. Tracking trends in Arctic marine vertebrates

2.1. The trend for marine fish is very similar to the trend for all marine species, increasing from 1970 to about 1990 and then levelling off. This indicates that the ASTI is strongly influenced by fish trends. Overall, marine mammals also increased, while marine birds showed less change.

2.2. The three ocean regions, Pacific, Atlantic and Arctic, differed significantly in average population trends with an overall decline in abundance in the Atlantic, a small average increase in the Arctic and a dramatic increase in the Pacific. These differences seem to be largely driven by variation in fish population abundance – there were no significant regional differences for birds or mammals.

2.3. Pelagic fish abundance appears to cycle on a time frame of about 10 years. These cycles showed a strong association with a large-scale climate oscillation. See Box 5 Fig. 1.

2.4. The ASTI data set contains population trends for nine sea-ice-associated species. There were mixed trends among the 36 populations with just over half showing an overall decline.

2.5. The Bering Sea and Aleutian Island (BSAI) region of the Pacific Ocean is well studied, providing an opportunity to examine trends in more detail. Since 1970, BSAI marine fish and mammals showed overall increases, while marine birds declined. However, since the late 1980s, marine mammal abundance has declined while marine fish abundance has largely stabilized.

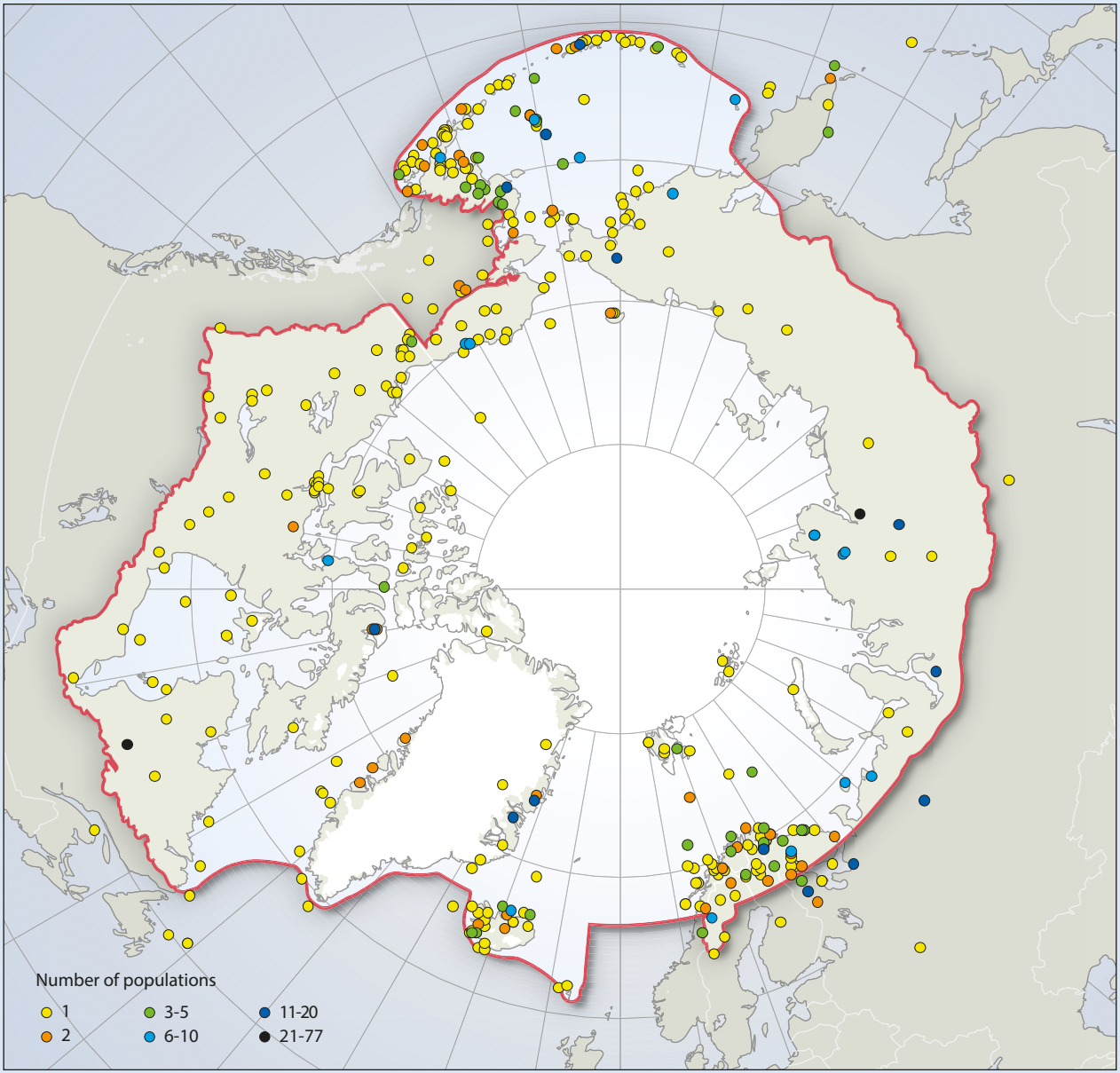
3. Tracking trends through space and time

3.1. Spatial analysis of the full ASTI data set (1951 to 2010) started with an evaluation of vertebrate population trend data from around the Arctic. The maps produced from this analysis provide information useful for identifying gaps and setting priorities for biodiversity monitoring programs.

3.2. Mapping trends in vertebrate populations provides information on patterns of biodiversity change over space and time, especially when examined at regional scales.

3.3. Understanding of the causes of Arctic vertebrate population change can be improved by expanding the spatial analysis of ASTI data to include spatial data on variables that represent drivers of biodiversity change.

(Box 5. continued)



Looking at spatial patterns in Arctic biodiversity trends, the ASTI can be used to assess not only areas of potential conservation concern around the Arctic but also to assess our current and historical monitoring coverage. With over 366 sites with trend information in the ASTI, the locations of these sites was not evenly spread across the Arctic region with concentrations of monitoring efforts found in the Bering Sea, northern Scandinavia and Iceland with more sparse monitoring efforts in northern Canada, northern Russia and northern Greenland (see Box 1.4 Fig. 2). This pattern largely reflects the reality of remote areas and limited human populations associated with areas of limited monitoring coverage. When investigating areas showing concentrated declines, the Labrador Sea, Queen Elizabeth Islands and NE Siberia were three areas where broad scale declines have been occurring. And finally, when investigating the percent of the 366 locations with increasing or stable populations by decade, we see a continual decline in the percentage of stable or increasing populations from the 1950s to the 2000s. Analyzing the main purpose of the monitoring programs that provided this data, it appears that a bias towards increasingly monitoring species of conservation concern (e.g. declining species) cannot explain this trend.

Box 5 Figure 2. Distribution of population time series data across the political cooperation area of CAFF (red line).

caribou and beluga calving grounds, seal pupping areas, and goose and seabird colonies. In addition, migratory birds that breed in a dispersed fashion may aggregate on migration or during winter at southern staging and wintering areas, enabling satisfactory monitoring outside the Arctic (e.g. shorebirds and some raptors). Consequently, some of the species for which trends are best known are highly migratory and highly social, at least during some part of the year. Solitary or highly dispersed species are much harder to monitor and feature disproportionately among species for which information is lacking. This section presents a summary of current understanding by taxonomic[6], ecosystem and functional group in accordance with the chapters in the assessment.

Approximately 67 terrestrial and 35 marine **mammal species** are found in the Arctic, of which 19 terrestrial and 11 marine species are more or less confined to this biome (Reid *et al.*, Chapter 3). This represents about 2% of the world's estimated number of mammal species. Arctic mammals are unevenly distributed, with more species and generally higher abundances in the low Arctic than in nearby high Arctic areas (Fig. 6). Regions that remained largely unglaciated (e.g. Beringia) during the last ice age now have the greatest diversity of terrestrial species (Fig. 6). Among marine mammals, species richness is highest in the Pacific and Atlantic sectors of the low Arctic in the vicinity of the Arctic gateways, which provide corridors for seasonal migrations from temperate seas. There are several examples of population and range changes in Arctic mammals during historical times, in which direct actions by humans have had large effects on a number of

6 Taxonomy is the science of identifying and naming species and other systematic groups of organisms, and arranging them into a classification system.

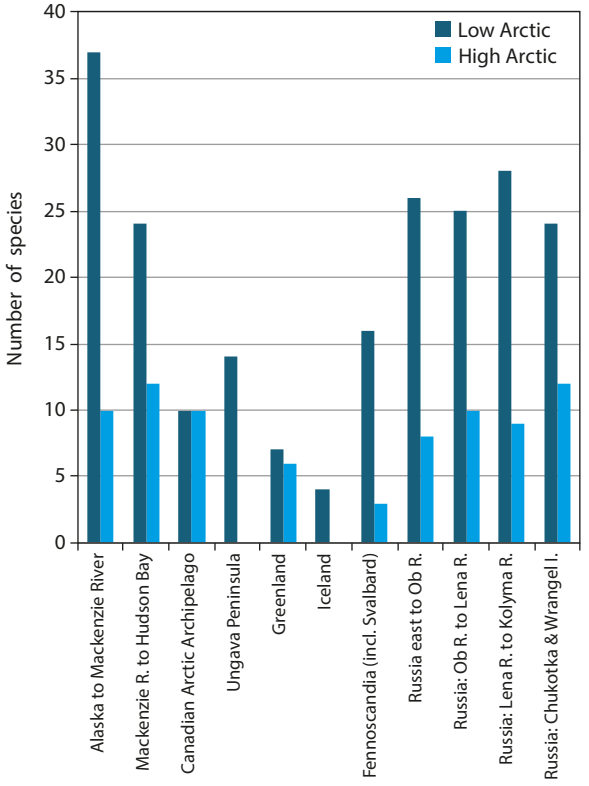


Figure 6. Number of terrestrial mammal species occupying low and high Arctic zones in each of the circumpolar Arctic regions.

species. Overharvest has caused extinction of one species, Steller's sea cow, as well as regional extirpations of carnivores such as the gray wolf *Canis lupus*. Excessive commercial harvest extirpated the Atlantic gray whale and NE Atlantic northern right whale. In some areas, subsistence overharvest reduced populations of walrus and beluga *Delphinapterus leucas* to low levels, but the introduction of quotas has allowed recovery in some populations. Humans have moved muskoxen around the Arctic, reestablishing historically extirpated populations such as those in Arctic Alaska and NE Siberia. The decreasing extent and duration of sea-ice cover due to climate change has resulted in decreased survival and body condition in some polar bear populations. Heavy and more frequent icing events following freezing rain and winter thaws have driven declines in some populations of muskoxen and caribou. Proliferation of shrubs in the low Arctic is allowing Eurasian elk *Alces alces*, moose *Alces americanus* and snowshoe hares *Lepus americanus* to spread further into the low Arctic. The amplitude and frequency of lemming cycles have changed in some Arctic regions, likely due to changes in timing and quality of snow accumulation in a warmer climate. The northwards expansion of the red fox *Vulpes vulpes* at the expense of the Arctic fox has been attributed to a warming climate, but recent evidence suggests that food supplementation by humans is an additional causal factor. Recently, several wild reindeer/caribou populations have shown pronounced population decreases, probably related to natural fluctuations, climate-induced crashes and overharvest, while other populations are increasing. Among terrestrial mammals only the Pribilof Island shrew *Sorex pribilofensis* is considered endangered according to IUCN criteria.

Seabirds are prominent members of Arctic marine ecosystems. Photo: Ole J. Liodden, thick-billed murres.

Two hundred **bird species**, about 2% of the global total, occur regularly in the Arctic (Ganter & Gaston, Chapter 4). The majority of these are waterfowl, shorebirds and seabirds, with relatively few songbird species. The Bering Strait region is the richest in species, and for several shorebird species it also supports the highest population densities. Most species spend only a few summer months in the Arctic while dispersing to virtually all parts of the globe during the northern winter. Population trends among Arctic birds are best known for geese and seabirds. Most Arctic-breeding goose populations have increased markedly in the last 30-50 years, many of them recovering from low populations in the mid-20th century. Goose populations breeding in the eastern Russian Arctic and wintering in East Asia (mainly China) are an exception; they have undergone steep declines in the late 20th century. Similarly, eight Arctic-breeding shorebird species migrating through East Asia to winter in Australia have suffered severe declines over the last 25 years or so. However, nearly all shorebird populations in the West Palearctic appear to be stable or increasing, while about a third of the Nearctic-breeding shorebird populations may be decreasing. Several Arctic seabirds appear to have declined in recent decades (e.g. thick-billed murre *Uria lomvia* and the ivory gull), as have several populations of sea ducks. Population sizes and trends of many migratory Arctic birds are influenced by overharvest, disturbance and habitat loss outside the Arctic, with the probable extinction of the Eskimo curlew, mainly due to hunting on its migration areas, as a grave example. Likewise, there is evidence that the critically endangered spoon-billed sandpiper faces extinction due to habitat loss and harvest on its wintering areas

in Southeast Asia, while disturbance and mortality on migration and wintering areas probably contribute to the threatened status of the lesser white-fronted goose *Anser erythropus*, red-breasted goose *Branta ruficollis*, bristle-thighed curlew *Numenius tahitiensis* and Siberian crane *Leucogeranus leucogeranus*.

Due to physiological constraints in these cold-blooded animals, **amphibians** and **reptiles** are few in the Arctic and only found along the southern periphery (Kuzmin & Tessler, Chapter 5). Only five primarily boreal and temperate amphibians – four in the Palearctic and one in the Nearctic – together with a single Palearctic lizard range into the low Arctic with all of them considered stable. However, population and distribution data are lacking from most of their Arctic ranges.

Approximately 250 marine and 127 diadromous and freshwater **fish species** inhabit Arctic seas and freshwaters (Christiansen & Reist, Chapter 6). Altogether, the 378 fish species within the Arctic correspond to 1.3% of the global total. If the adjacent sub-Arctic seas are included, i.e. the Norwegian, Barents and Bering Seas, the number of marine fish species rises to nearly 640. By far the highest marine diversity is found in the 'Arctic gateways' i.e. the sub-Arctic seas connecting the Arctic Ocean with the Atlantic and the Pacific Oceans. Only 63 marine fish species are considered genuinely Arctic specialists, and none is regarded as endangered. However, due to lack of data, 95% of the Arctic marine fish species have not been evaluated for threat status according to IUCN criteria. High local diversities of fishes also occur in the mouths of the large Arctic rivers where freshwater forms intermingle with diadromous forms and nearshore marine species. Local fisheries of mostly freshwater and anadromous[7] fishes along the Arctic coasts and during autumn migrations upstream into rivers have been ongoing for centuries. Local harvests are often quite high with fish primarily used as food for people and dogs; limited commercial fisheries exist in some areas, although landings are small in comparison to marine fisheries. Several freshwater and diadromous species are listed as 'at some form of risk' according to national conservation definitions which parallel IUCN criteria; in most cases these are taxa with limited distributions in sensitive habitats subject to anthropogenic stressors. There are no clear cases of extinction of freshwater or diadromous fish species, although local populations have been extirpated in some areas. Such populations are often unique forms, but are not described as separate species. For marine fishes, landings from commercial fisheries can be high, amounting for example to an excess of two million tonnes from a single stock of Atlantic herring *Clupea harengus* in the NE Atlantic. Whereas herring and other pelagic fish stocks show negative or highly variable trends, the overall trend for marine groundfishes, and codfishes in particular, appears strong and positive. In 2012, the total allowable catch (TAC) for Alaska pollock *Gadus chalcogrammus* in the Bering Sea was about 1.2 million tonnes, whereas the 2013-TAC for Atlantic cod *Gadus morhua* in the Barents Sea makes history with one million tonnes – the latter quota being shared between Norway and Russia.

A few amphibians and reptiles extend their distribution into the Arctic, such as this moor frog of Eurasia. Photo: Konstantin Mikhailov/naturepl.com

7 Anadromy is a particular form of diadromy in which summer sea-feeding species return to fresh water to reproduce and/or overwinter.

There are upwards of 4,750 species of **terrestrial and freshwater invertebrates** living in the Arctic representing 27 classes of animals spread across at least 16 phyla (Hodkinson, Chapter 7). One class, the Micrognathozoa is known only from Greenland and the sub-Antarctic Crozet Island. The most speciose groups are testate amoebae, rotifers, water bears, water fleas and copepods, ostracods, enchytraeid worms, eelworms, spiders, springtails, mites and insects. Among insects, the true flies (Diptera) are the dominant group. In several groups, many species remain to be described. Representation of the known world fauna in the Arctic differs greatly among groups. Soil-dwelling, soil-surface-living or aquatic taxa such as testate amoebae and springtails often represent significant proportions of the described world species (7-18%). By contrast, the taxon with a high proportion of free flying and plant-feeding species, the insects, is far less strongly represented (0.3%). Arctic endemism is similarly highly variable across taxa. It is high in enchytraeid worms (19%), mesostigmatid mites (31%) and calanoid copepods (28%), but low in stoneflies (0%), cyclopoid copepods (0%), testate amoebae (3%) and Collembola (3%). Some globally rare Arctic endemic species, such as the Svalbard aphids *Sitobion calvulus* and *Acyrthosiphon svalbardicum* and several elements of the Beringian beetle fauna, have highly restricted distributions and appear particularly susceptible to disturbance and climate change. Population densities of some individual invertebrate species such as nematode worms, springtails and mites can reach tens of thousands to millions per square meter. Life cycles are highly variable within and among groups. Some aphids produce 2-3 generations per year; other species, such as some springtails, mites, craneflies and moths, have free-running life cycles lasting from three to eight years. The precise life-history and general biology of most Arctic invertebrate species is unknown. Herbivorous species are relatively few, but invertebrates play essential roles in several ecosystem processes, especially organic matter decomposition and nutrient recycling. They are crucial for the pollination of many Arctic plants and serve as the major food resource for many breeding birds and freshwater fish species, such as Arctic char *Salvelinus alpinus*. There is a lack of good quantitative data sets that demonstrate long-term trends in Arctic invertebrate populations and community composition. Nevertheless, a growing body of casual observational evidence among indigenous peoples and scientists suggests that invertebrate communities are changing. Some larger species, notably beetle, are now being observed at sites where they were previously unknown, and in some places the seasonal patterns of occurrence and abundance of biting flies is changing.

Excluding microbes, about 5,000 species of **marine invertebrates** in 17 phyla are found in the Arctic (Josefson & Mokievsky, Chapter 8). These organisms are associated with sea-ice, pelagic or benthic realms, with the benthic realm being clearly dominant (about 90% of described species found there). However, since several areas, in particular the East Siberian Sea, the Canadian Arctic and deep sea areas of the Central Arctic Basin and at the Arctic-Atlantic frontier, are undersampled, this figure is likely to increase substantially as more studies are made. In contrast to the terrestrial biomes, the marine invertebrate fauna is not impoverished compared with more southern biomes, but is intermediate in species richness. Marine arthropods, by far the most species-rich group in the marine Arctic and accounting for 37% of all marine invertebrate species in the Arctic Ocean, show high species richness in the Arctic compared with some adjacent non-Arctic areas. However, our current knowledge indicates that the Arctic Ocean is largely a sea with species originating from outside the Arctic, and there are few endemic Arctic species. One reason for this may be the low

The mirid bug *Chlamydatus pullus* feeding in a flower head of the dandelion *Taraxacum croceum* in the preserved herb field of Østerlien near Arctic Station at Godhavn/Qeqertarsuaq on Disko Island, W Greenland. Photo: Jens J. Böcher.

Purple saxifrage is a very common plant in poorly vegetated areas all over the high Arctic. It even grows on Kaffeklubben Island in N Greenland, at 83°40′ N, the most northerly plant locality in the world. It is one of the first plants to flower in spring and serves as the territorial flower of Nunavut in Canada. Photo: Erik Thomsen, Zackenberg 2003.

degree of isolation of the Arctic Ocean from adjacent oceans since the Pliocene. Although data are limited, a few studies suggest that boreal species are increasing in Arctic waters – including some invasive alien species such as red king crab *Paralithodes camtschaticus* in the Barents Sea – with negative effects on native species.

Among **plants** (Daniëls *et al.*, Chapter 9), about 2,220 vascular species (including subspecies, apomictic aggregates[8] and collective species) are found in the Arctic, less than 1% of the world total. No fewer than 106 species (about 5% of the Arctic vascular plant flora) are endemic to the Arctic. Almost all are forbs and grasses with high ploidy[9] levels. Distribution patterns and ecological features of the native Arctic vascular plants are considered still intact, and no native species are known to have gone extinct due to human activities. No such information is available for bryophytes (mosses and liverworts) and algae. An estimated 900 species of bryophytes have been recorded in the Arctic, which is about 6% of the world's total. They occur in almost all vegetation types and locally dominate mires, fens and snow beds. Together with lichens, they contribute strongly to the high species diversity of high Arctic ecosystems in particular. Endemism is not well developed among bryophytes. A conservative estimate of 4,000 algae species are found in circumpolar regions, including both freshwater and marine algae (micro- and macroalgae such as kelp), which represents about 10% of world's recognized species. However, only about 10% of the estimated global total of algae has been described.

Fungi, including both 'true' fungi (i.e. non-lichenized fungi, here called fungi) and lichenized fungi (lichens), are one of the most species rich groups of organisms in the Arctic (Dahlberg & Bültmann, Chapter 10). The known number of fungal species in the Arctic is about 4,300, of which 2,030 are macrofungi with apparent sporocarps and 1,750 are lichens. This corresponds to about 4% of the presently known number of fungi species in the world, but 10% of the global total for the lichens alone. However, due to their largely cryptic nature, fungi – especially microfungi – have been insufficiently studied, and the total fungal-species richness in the Arctic may exceed 13,000. Fungi are pivotal in Arctic terrestrial food-webs, since vascular plants largely rely on mycorrhizal[10] and decomposing fungi to drive nutrient and energy cycling, and lichens such as reindeer lichens, i.e. *Cladonia* (subg. *Cladina*) and *Stereocaulon* spp., are important primary producers. Different fungal species contributes differently to these processes. The ongoing greening of the Arctic driven by climate change will alter fungal diversity and fungal ecosystem services such as plant's uptake of nutrients, decomposition and long-term carbon sequestration in soil. Most species appear to be present throughout the Arctic and also occur in alpine habitats outside the Arctic. Few fungi are endemic to the Arctic. Of lichens,

8 Group of genetically closely related microspecies originating by asexual reproduction through seeds.

9 Variations in chromosome number involving more than the diploid number of complete chromosome sets.

10 Mycorrhiza is a widespread symbiotic relationship between fungi and roots of most Arctic plants in which the fungus obtains its sugars from the plant, while the plant benefits from the efficient uptake of mineral nutrients and water by the fungal hyphae.

The golden colored blackening waxcap *Hygrocybe conica* var. *aurantiolutea* is a colorful member of waxcaps that grows in grasslands in the low and sub-Arctic zones. At appropriate climatic conditions, the cryptically growing long-lived mycelia produce sporocarps in August-September. Waxcaps are sensitive to nitrogen, and their occurrence is strongly reduced in temperate and boreal zones due to anthropogenic deposition of nitrogen and fertilization. Photo: Flemming Rune, Tasiusaq at Qassiarsuk in South Greenland, 1987.

143 species have been found only in the Arctic, but it is likely that the majority will prove to be synonyms of other species or be found outside the Arctic. Arctic fungi have not been evaluated for threat status, but no species are considered endangered. In contrast, up to 296 lichens are possibly endangered, i.e. very rare in the Arctic and either endemic (126 species) or also rare outside the Arctic (170 species). However all rare taxa require an evaluation of their taxonomic status. No data on trends exist.

Microbes, defined here as bacteria, archaea and single celled eukarya (protists), are ubiquitous and diverse members of all biological communities with c. one million cells per milliliter of seawater and most freshwaters and contributing to the complexity of microbial food webs with a multitude of trophic interactions (Lovejoy, Chapter 11). The historic dichotomy of autotrophic 'algae' and heterotrophic 'protozoa' is not borne out in modern classification systems, and many photosynthetic microalgae (Daniels *et al.*, Chapter 9) are also heterotrophic. This mixotrophic life style is particularly common in Arctic marine and freshwaters enabling photosynthetic organisms to maintain active populations over the winter and under ice when sunlight is limited. Indeed, microbial community interactions and dominant species largely determine the efficacy of the biological carbon pump, where carbon dioxide is drawn down from the atmosphere and sequestered in the deep ocean. However, there is a lack of long-term comprehensive baseline data on microbial biodiversity in terrestrial, freshwater and marine systems, which largely impedes understanding ecosystem structure and resilience[11] over both local and regional scales. Because of

11 Resilience is the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same structure, function and identity.

their small size and often large populations, microbes in principle may have global distributions as they are transported by moving masses of air and water. Since for the most part they cannot be identified morphologically, sound historical records are lacking, and new tools are being used to taxonomically identify these small species from DNA and RNA collected from the environment. In the Arctic, where terrestrial, freshwater and marine heterotrophs[12] and microalgae are particularly poorly known, this approach has been used to identify likely Arctic endemics among mixotrophic microalgae and heterotrophic single-celled grazers.

For **terrestrial ecosystems** the expected effects of global warming are increasingly being seen in empirical observations (Ims & Ehrich, Chapter 12). June snow cover has decreased by 17.8% per decade since satellite records began in 1979 (Fig. 7), i.e. more than the concomitant reduction in Arctic summer sea ice. Vegetation seasonality in the Arctic region has had a 7° latitudinal shift equator ward during the last 30 years, and plant flowering has advanced up to 20 days during one decade in some areas. As a result, primary productivity and vascular plant biomass ('greening of the tundra') have increased rapidly – in particular in terms of increased growth and expansion of tall shrubs. Other plants belonging to the lowest vegetation stratum, i.e. cryptogams such as mosses and lichens, have been found to be declining in abundance. Altogether, these structural changes alter the function of the ecosystem in terms of reduced albedo, increased soil temperature, higher ecosystem respiration and increased release of trace gases. The extent of greening (both earlier onset in the season and increased plant biomass) as assessed by remote sensing is, however, regionally highly heterogeneous, which to some extent can be due to spatial variation in the rate of climate change, but also a host of other factors including anthropogenic stressors. Changing abundances of keystone herbivores, such as lemmings, reindeer/caribou, geese and insects, sometimes accentuate the greening of the tundra, and sometimes counteract it. Consequences of regional collapse

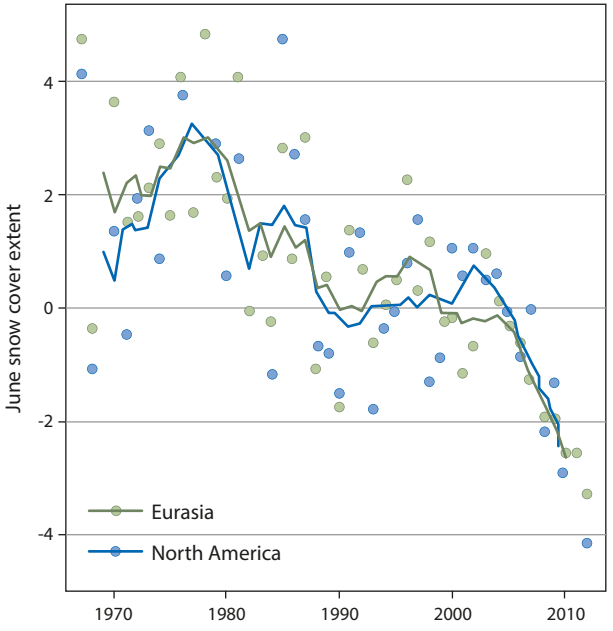


Figure 7. Trends in terrestrial June snow cover 1967-2012 based on averages for the North American and Eurasian continents, virtually all of it in the Arctic. Values are standardized anomalies with respect to the 1988-2007 mean. Solid lines are five-year running means (adapted from Derksen & Brown 2012). The combined influence of the timing of snow melt and the length of the growing season is of major importance for the functioning and feedback dynamics of Arctic Ecosystems.

12 A heterotroph is an organism that relies on other organisms for food.

of lemming cycles, human-induced overabundance of ungulates and geese, and new phenology-driven trophic matches and mismatches are also beginning to be seen as cascading impacts in terrestrial food webs with negative consequences for endemic Arctic species and positive effects for expanding boreal species. Among such impacts are reproductive failures in caribou (phenological mismatch with food plants) and in lemming predators and their alternative prey (resulting from collapse of cycles), as well as the spread of new insect pest species and plant pathogens north to the forest-tundra transition zone.

Arctic **freshwater ecosystems** are important trans-ecosystem integrators (i.e. they link terrestrial, freshwater and oceanic environments) of multiple environmental and anthropogenic drivers and stressors (Wrona & Reist, Chapter 13). Hence, freshwater ecosystems and their related structural and functional biodiversity serve as important ecological transition zones within and between ecosystems since they concentrate key processes and drivers. Freshwater ecosystems are undergoing rapid environmental change in response to the influence of both environmental and anthropogenic drivers. Primary drivers affecting the distribution, abundance, quality and hence diversity of freshwater ecosystems and associated habitats include climate variability and change, landscape-level changes to cryospheric components (i.e. permafrost degradation, alterations in snow and ice regimes) and changes to ultraviolet (UV) radiation. Directly and indirectly, these drivers and interactions among them are being increasingly shown to affect the types, number and distribution of freshwater ecosystems in the Arctic region and, correspondingly, associated biological and functional diversity. Observed changes in freshwater geochemistry including enhanced nutrient additions (eutrophication) arising from the release of stored nutrients from thawing permafrost and deepening of the active layer, increases in the length of the open water season related to diminishing ice cover duration, warmer winter and spring water temperatures, and enhanced UV radiation regimes have been shown to affect the resource availability, productivity and trophic interactions and dynamics of freshwater organisms. For example, changes in ice regimes, increased terrestrial productivity combined with permafrost degradation of tundra and associated slumping into water bodies (both of which are effects of climate change) may increase freshwater habitat suitability, food availability and use by migratory waterfowl and aquatic mammals, thereby increasing the 'natural eutrophication' of Arctic lake, pond and wetland ecosystems. Moreover, other secondary environmental and anthropogenic drivers that are gaining circumpolar importance in affecting Arctic freshwater ecosystem quantity and quality include increasing acidification and pollution from deposition of industrial and other human activities (wastewater, release of stored contaminants, long-range transport and biomagnification of pollutants), landscape disturbance from human development (dams, diversions, mining, oil and gas activities, together with development of linear corridors like roads, trails and cut lines, and population increase) and exploitation of freshwater systems (fisheries, water withdrawals).

The Arctic is richer in wetlands than most other biomes on Earth. Photo: Patrick J. Endres/AlaskaPhotoGraphics.com

The marine Arctic spans a wide range of environmental conditions including extremes in temperature, salinity, light conditions and the presence (or absence) of sea ice, leading to diverse Arctic **marine ecosystems** (Michel, Chapter 14). Approximately half of

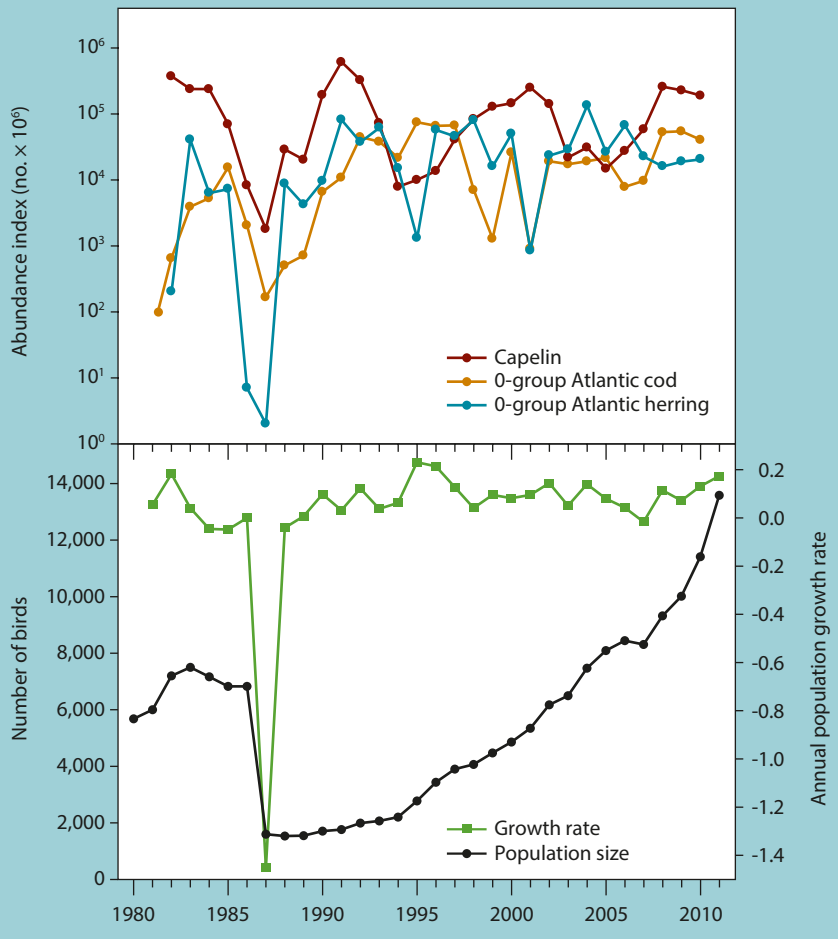


Figure 8. In 1987, the breeding population of common murre *Uria aalge* in the Barents Sea collapsed as a result of concomitantly low populations of their preferred prey, 0-group Atlantic cod *Gadus morhua*, capelin *Mallotus villosus* and 0-group Atlantic herring *Clupea harengus*. These low fish population levels were probably caused by a combination of climate variability, ocean current variability and overharvest with different weight of these causes between populations. Since such a situation of concomitantly low populations has not occurred since then (upper panel), the annual common murre population growth on Hornøya in NE Norway has remained high, and the murre population on this island is now higher than before the collapse (from Erikstad *et al.* 2013).

the Arctic Ocean area overlays shelf areas, i.e. areas with water depths < 200 m. Consequently, the Arctic Ocean has the most extensive shelf areas of the world oceans, accounting for nearly 30% of the global shelf area. The Arctic marine ecosystems are experiencing rapid changes in their chemical, physical and biological characteristics together with unprecedented socio-economic pressures. Changes in the distribution and abundance of key species and cascading effects on species interactions, structure and functionality of marine food webs are already being observed. Range extensions are taking place throughout the Arctic, with a northward

Protostrongylus stilesi, a lung nematode typical in Dall's sheep *Ovis dalli* from the Brooks Range and Alaska Range of the western North American Arctic, and in muskoxen in the Brooks Range and Arctic Coastal Plain of Alaska and Yukon Territories, Canada. Shown is the tail end of an adult male with characteristic copulatory structures which are important in diagnosis of these miniscule parasites. Photo: E.P. Hoberg.

expansion of sub-Arctic species and a narrowing of Arctic habitats. Range expansions associated with shifts in the distribution of Pacific and Atlantic water masses are already influencing the distributions of invertebrate and fish species and that of parasites, particularly among seabirds (Hoberg & Kutz, Chapter 15). Changes in water mass distribution also have downstream impacts on sub-Arctic marine systems through trans-Arctic transport of marine species (Michel, Chapter 14). The rapid decline in summer sea ice extent, with an overall average sea ice loss of 39% in September 2010-2012 compared with the 1979-2000 average and occurring faster than predicted by climate models, if maintained, is predicted to lead to a largely summer ice-free Arctic Ocean within the next 30-40 years. The impacts of the ongoing changes in sea ice are seen at all ecosystem levels, from the composition of protist communities to the distribution and abundance of top predators such as killer whales *Orcinus orca* and polar bears. Unique Arctic ecosystems, such as multi-year ice and millennia-old ice shelves are currently in rapid decline. Marine resource exploitation is also changing. In addition to a renewed interest in hydrocarbon exploitation, some fisheries have shifted. For example, landings in W Greenland have shifted, as in other areas of the North Atlantic, from a strong dominance of Atlantic cod to northern shrimp *Pandalus borealis* (Christiansen & Reist, Chapter 6, Michel, Chapter 14). Another example is the significant population changes in fish and seabirds that happened in the Barents Sea in the late 1980s (Fig. 8).

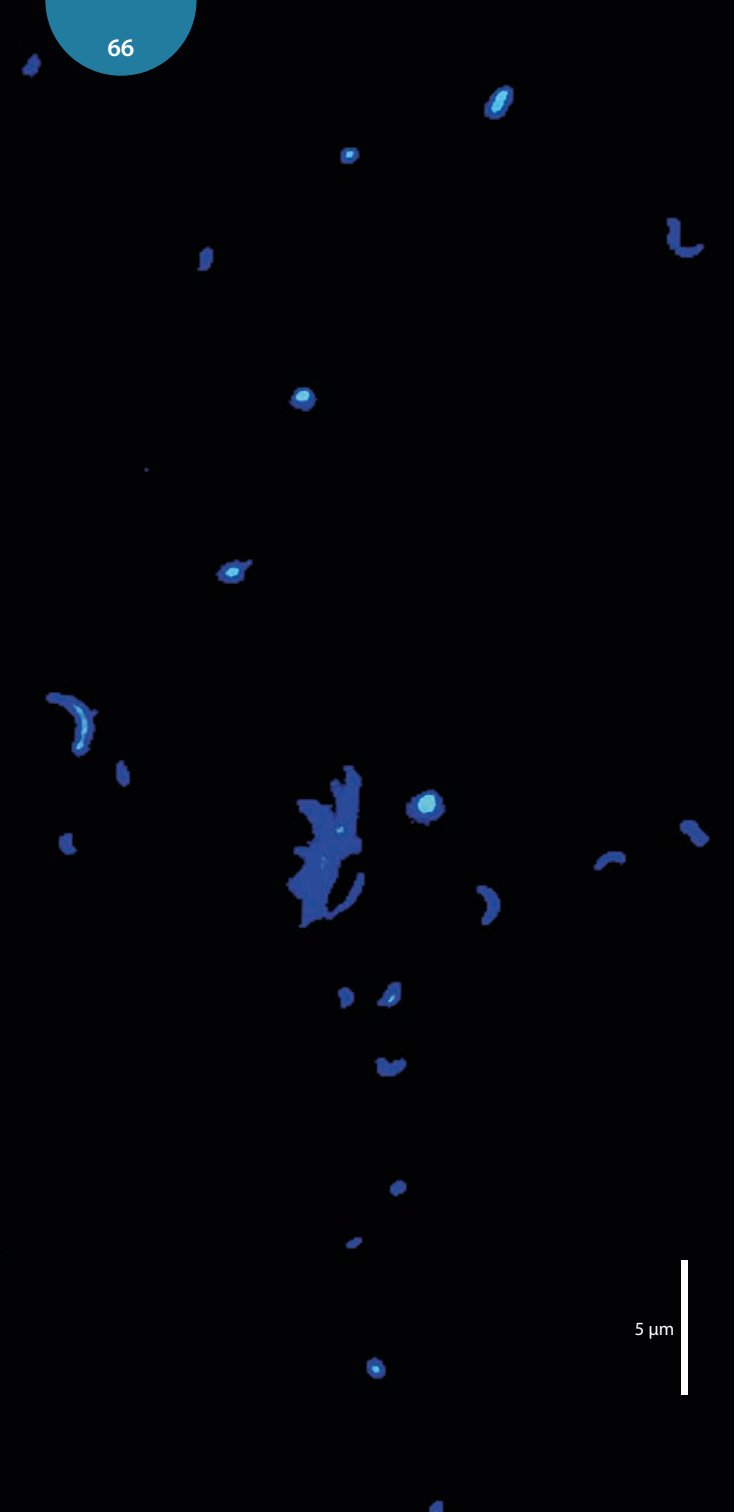
Parasites represent in excess of 40-50% of the organisms on Earth, are integral components of all ecosystems, and have considerable involvement in at least 75% of trophic links within food webs (Hoberg & Kutz, Chapter 15). Recognition of this complex web of interactions serves to establish the remarkable signifi-

cance of parasites in ecological structure and biodiversity. Macroparasites (worms and arthropods) and microparasites (viruses, bacteria and protozoans) have at least one life stage that must live on or in another species, or host. Parasites are taxonomically complex and diverse, even in high latitude systems characterized by relatively simple assemblages, and are considerably more species rich than the vertebrate hosts in which they occur. Based on global estimates, there are between 75,000 and 300,000 species of helminths (worms) that infect terrestrial and aquatic vertebrates. In the Arctic, diversity for helminths in marine fishes (c. 3,780 species), freshwater fishes (720), birds (1,700) and mammals (900) is estimated near 7,100 species, but this value is conservative. As a generality, species richness for parasites declines on a gradient from south to north in terrestrial, freshwater and marine systems reflecting an interaction of historical processes and current ecological conditions. However, even for the best known host species, there is a general lack of long-term and comprehensive baselines for parasite biodiversity in the Arctic, and considerable cryptic diversity represented by currently undescribed species remains to be documented. Paradoxically, the presence of diverse assemblages of parasites is indicative of a healthy ecosystem because their presence denotes stability and the maintenance of connections among fishes, birds or mammals within and across complex food webs. Parasites are particularly sensitive to ecological conditions, environmental perturbation, migration pathways and habitat use because transmission is most often directly linked to food habits and foraging behavior for hosts.

Many human-introduced alien species are found in the sub-Arctic and will probably be able to spread northwards in a warming climate putting indigenous species under pressure. One such species is Nootka lupin spreading extensively in Iceland and also found in S Greenland. Photo: Sigurður H. Magnússon.

Relatively few **invasive species**, i.e. human-introduced alien species that are likely to cause economic or environmental harm or harm to human health, are currently known in the Arctic (Lassuy & Lewis, Chapter 16). However, ecosystem altering invasive plants are known to have invaded the low Arctic in Alaska; over a dozen terrestrial invasive plant species are already known from the Canadian low and high Arctic, and 15% of the flora from the high Arctic archipelago of Svalbard was reported to be alien. Nootka lupin *Lupinus nootkatensis* has now invaded disturbed sites and sub-Arctic heathland vegetation in almost all of Iceland and even occurs in SW Greenland but without spreading into the tundra vegetation so far. The status of aquatic invasive species in the Arctic and sub-Arctic is less well known, but benthic communities in northern Norway and the Kola Peninsula are already likely facing significant disturbance from the introduced red king crab.

Genetic perspectives are keys to understanding population fluctuations, identifying and characterizing endemic species, tracking the invasion of species, recognizing emerging pathogens, revealing the status of threatened species, and demonstrating adaptations that allow species to thrive in the Arctic environment (Cook, Chapter 17). To mitigate the impact of climate-induced perturbations, an essential first step is to develop an understanding of how high latitude species and ecosystems were influenced by past episodes of dynamic environmental change. A history of ecological perturbation and faunal interchange in both terrestrial and aquatic environments driven by cyclical changes in climate is a general theme for high latitude biota. Reconstruction of past Arctic climates and biomes has



been accomplished over different time scales using the fossil and sub-fossil remains of organisms such as diatoms, dinoflagellate cysts, beetles, chironomid midge larvae, ostracods and testate amoebae (Hodkinson, Chapter 7), in addition to the pollen record. Molecular genetics provides another powerful window into past change in Arctic populations. Integrated genetic studies have indicated the importance of mechanisms for episodes of geographic expansion (or retraction), genetic introgression, altered levels of sympatry and parasite host colonization in establishing broader patterns of biodiversity (Hoberg & Kutz, Chapter 15). Understanding that Arctic systems have evolved in this crucible of dynamic change provides an analog for identifying the possible outcomes of accelerated global warming and environmental change. DNA-based views, especially when integrated with ecological niche or other modeling approaches, provide a basis for exploring how biomes and individual species will respond in the future and thus are a key component of an advanced early-warning system for natural systems in the Arctic. Yet, because Arctic environments are remote and difficult to access and few specimens are available, there is limited information about geographic structure or the genetic basis for adaptation for most species. A number of Arctic species are now experiencing a reduction in their distributions, abundance and ability to exchange individuals among populations that will ultimately reduce population variability. These factors will hamper

Microorganisms play a significant functional role in all Arctic ecosystems. Here is an epifluorescene micrograph from a northern Baffin Bay water sample. Bacteria and the nucleus of single celled eukaryotic plankton appear in blue. The smaller points are bacteria and the larger are Eukarya. Photo: Connie Lovejoy.

or dampen the capacity for adaptation under changing conditions and perhaps the potential to maintain resilience under exposure to novel pathogens and parasites.

When considering biodiversity, it is essential to recognize and understand the **functional significance** of the various species and species groups within Arctic ecosystems. By functional significance we mean the precise quantifiable role of each group of organisms in driving the essential ecosystem processes, such as primary production, decomposition and nutrient cycling that sustain life in the Arctic. This is particularly important for the less charismatic and often microscopic groups of organisms, including some plants, many invertebrates, many fungi, phytoplankton and bacteria, which are of overriding ecological significance in terms of energy flow through ecosystems yet frequently receive less attention and recognition than their ecological importance warrants. An example is the functionally highly important decomposer microorganisms that are responsible for the greater majority of soil respiration during the decomposition process (Heal *et al.* 1981). The chemical breakdown of cellulose and lignin, the major components of soil leaf litter, is almost exclusively the preserve of these microorganisms, together with a strictly limited number of soil invertebrate species. Soil invertebrates, however, accelerate the decomposition process by reducing litter particle size and by feeding on and thus stripping out senescent microfloral colonies, thereby re-stimulating their activity. Microorganisms are the groups primarily responsible for the release of the major greenhouse gasses carbon dioxide and methane from tundra soils and are of paramount importance in contributing to change within the Arctic climate system. The actual composition of biodiversity in terms of its more cryptic components may determine whether the Arctic will become a source or a sink for greenhouse gases in a warming climate, and whether the Arctic amplification will become stronger or weaker.

Provisioning and cultural services are two of the ecosystem services provided by Arctic biodiversity, along with regulating and supporting services (which were not addressed in the ABA due to lack of information) (Huntington, Chapter 18). These services change over time for various reasons, but on the whole are relatively strong, with few signs of serious declines. There have been major changes in at least some aspects of reindeer herding, but these are predominantly the result of societal changes such as the break-up of the Soviet Union and its support system for remote herders. In some North American migratory caribou, rapid recent declines have forced heavy reductions in subsistence harvest. Commercial fisheries remain major economic activities in the Barents and Bering Seas and in Greenland and Icelandic waters, even if some areas have seen major shifts, such as the cod-to-shrimp transition in SW Greenland (Christiansen & Reist, Chapter 6). Traditional hunting, fishing and gathering remain essential contributors to diet and to overall well-being in many Arctic communities, although such foods provide smaller proportions of daily energy intake than in the past. Sport fishing and hunting are increasing as the Arctic becomes a more popular destination for tourists, with the potential for additional stress on mammal, bird and fish populations. Perhaps as an indication of the increasing global scarcity of wild places and species, Arctic wildlife and wilderness are increasingly valued by people around the world simply for existing as they are (Huntington, Chapter 18). In other words, these services remain strong in the Arctic.

Trends in **disturbance, feedbacks and conservation** are not as positive in outlook (Huntington, Chapter 19). Increasing industrial activity is leading to

Use in modern media is of decisive importance to the survival of indigenous languages. Photo: Magnus Elander.

disturbance in more and more areas, especially through construction of new roads. Modern construction, extraction and transportation techniques, however, offer the potential for developments to have less impact than they used to, but the overall trend is towards a greater human footprint in the Arctic. Feedbacks within the climate system tend to exacerbate greenhouse gas induced warming in the Arctic (see Section 5.2.1). Terrestrial protected areas are a major contributor to Arctic conservation, but marine protected areas are nearly nonexistent. Protective measures for species are increasing, which may indicate greater commitment to this conservation method, but could also indicate that more species are in need of protection. On a more positive note, the involvement of local communities in monitoring and conservation activities appears to be increasing.

The Convention on Biological Diversity (CBD) recognizes that **linguistic diversity** is a useful indicator of the retention and use of traditional knowledge, including knowledge of biodiversity. Twenty-one northern languages have become extinct since the 1800s, and 10 of these extinctions have taken place after 1990, indicating an increasing rate of language extinction (Barry *et al.*, Chapter 20). Thirthy languages classified as critically endangered are in dire need of attention before they, too, are lost forever. Over 70% of the indigenous languages of the North are spoken only in single countries, and so are particularly exposed to the policies of a single government, which may also allow more responsive conservation of these languages as no cross border efforts are required. The remaining languages are spread across a number of jurisdictions and are therefore subject to differing approaches when it comes to addressing their revitalization. Language revitalization is possible, and there are multiple examples to illustrate it. However, the investment of time and resources needed to make revitalization a reality is a matter that needs to be addressed sooner rather than later. Many northern indigenous groups have already begun working on language revitalization, viewing it as an important component of their identity. In this context, the CBD provides an opportunity for indigenous peoples of the North to maintain their subsistence and traditional lifestyles. It expands the role and scope of conservation measures and allows a deeper understanding of relevance of indigenous cultures, practices and

languages in the context of biodiversity conservation. Article 8j of the Convention has enabled local communities to become actors in biodiversity discussions in the North and helps to contribute to the preservation of 'knowledge and practices' of indigenous peoples, including their languages.

Considering all aspects of biodiversity, **the most prominent climate related changes in Arctic biodiversity** are northward (and upward on mountain slopes) range shifts observed by both scientists and Arctic residents in mammals, birds, amphibians, fish, terrestrial and marine invertebrates, parasites, plants and marine plankton (including new pest and invasive species) (Reid *et al.*, Chapter 3, Ganter & Gaston, Chapter 4, Kuzmin & Tessler, Chapter 5, Christiansen & Reist, Chapter 6, Hodkinson, Chapter 7, Josefson & Mokievsky, Chapter 8, Daniëls *et al.*, Chapter 9, Lovejoy, Chapter 11, Ims & Ehrich, Chapter 12, Wrona & Reist, Chapter 13, Michel, Chapter 14, Hoberg & Kutz, Chapter 15, Lassuy & Lewis, Chapter 16). Decreasing extent and duration of annual sea-ice cover are impacting marine species, including some polar bear and walrus populations, and heavy and more frequent icing events have caused declines in some populations of muskoxen and caribou (Reid *et al.*, Chapter 3). Lemming cycles have changed in some Arctic regions likely due to changes in timing and quality of snow accumulation, with consequent impacts to lemming predators and alternative prey (Reid *et al.*, Chapter 3, Ims & Ehrich, Chapter 12). Earlier snowmelt is stimulating advanced plant and arthropod phenology in some areas resulting in potential timing mismatch with caribou and bird migrations and reproductive cycles (Reid *et al.*, Chapter 3, Ganter & Gaston, Chapter 4, Hodkinson, Chapter 7). Rapidly increasing primary productivity, vascular plant biomass and shrub extension has resulted in 'greening of the tundra' and a transformation of some low Arctic to sub-Arctic conditions, while cryptogams have been found to be declining in abundance. These vegetation changes involve higher ecosystem respiration and increased release of trace gases (Ims & Ehrich, Chapter 12). Floristic changes have also been observed in moist to wet sites such as snow beds, mires, fens and shallow ponds, likely resulting from habitat warming and/or drying of the substrate associated with climatic warming and earlier snow melt (Daniëls *et al.*, Chapter 9). Climate-related shifts in range and seasonal movement patterns have altered predator-prey relationships, resulting e.g. in changes in diet of seabirds (Ganter & Gaston, Chapter 4). Similarly, distributions and rates of infection by such diverse pathogens as lungworm (in caribou/reindeer and muskoxen), helminths, protozoans (in salmon) and avian cholera have changed under a regime of contemporary warming and increasingly benign environments (Hoberg & Kutz, Chapter 15). Marine Arctic ecosystems are also experiencing dramatic climate-related changes that impact their chemical, physical and biological characteristics. Changes in the distribution and abundance of key species and cascading effects on the species interactions, structure and functionality of marine food webs are already being observed (Josefson & Mokievsky, Chapter 8, Michel, Chapter 14, Hoberg & Kutz, Chapter 15). The impacts of rapidly declining summer sea ice cover are seen at all ecosystem levels, from the composition of protist communities to the distribution and abundance of top predators. Unique Arctic ecosystems, such as multi-year ice and millennia-old ice shelves, are currently in rapid decline (Michel, Chapter 14). Further, apparent expansion of parasites in alcid seabirds from the Bering Sea through the Arctic Basin has coincided with the development of new oceanic current patterns linked to climate warming (Hoberg & Kutz, Chapter 15).

5. STRESSORS AND THEIR ALLEVIATION

As a contribution to halting the loss of biodiversity, the Arctic Council initiated the Arctic Biodiversity Assessment and asked for scientific advice on what could be done to alleviate stressors that put Arctic biodiversity under pressure. Detailed advice is given in the individual chapters, and in this section we the lead authors of the scientific chapters of the ABA present an overview of stressors on Arctic biodiversity together with possible actions to enhance biodiversity conservation. Our aim is to suggest appropriate, scientifically based actions, which should be seen as facilitative and not prescriptive.

Arctic biodiversity is at risk from climate change and other human-caused stressors, and these pressures need to be addressed by prompt and concerted action at the local, national, circumpolar and global levels. Within the Arctic, stressors that directly affect habitats and populations include human infrastructure, unsustainable harvests, disturbance and pollution. Stressors coming from outside the Arctic include climate change, pollutants, invasive species, expansion of boreal species into the Arctic, and threats to migratory species in staging and wintering areas.

Arctic biodiversity is under pressure from a variety of stressors originating from within the Arctic as well as from abroad. Some can be solved at national level, while others require international cooperation. Photo: Susan Morse.

Arctic ecosystems are resilient to considerable climatic variability and change (Payer *et al.*, Chapter 2). However, continued warming is likely to be too rapid and intense for many species and processes to adapt or adjust *in situ*. Global warming is already causing local changes in Arctic climate regimes corresponding to biome shifts (see Section 4). Much depends on whether Arctic species and biological communities can shift distributions along with changing climate regimes, or persist in refugial regions where change is less rapid or extreme. Moreover, climate-related alterations to many cryospheric components (e.g. glaciers, ice sheets, permafrost and sea ice) are likely to produce new biophysical states that will not easily return to previous conditions within the timescale of centuries or even millennia (AMAP 2011a), creating repeatedly novel living conditions for most species and biological communities whose demographics and interactions operate in annual to decadal timescales. This not only involves temperature, wind and precipitation changes, but perhaps of equal importance the increasingly pronounced interannual variability and interactive feedbacks of climate change that are ongoing and expected. All of these will influence biodiversity across many interacting scales.

Many Arctic ecosystems bear signs of human activity from decades ago, indicating slow regeneration. This is because the growing season is very short, and the input of solar energy is low, meaning that Arctic habitats and many populations are particularly slow in regenerating from physical or other changes (Freese 2000). Since the true Arctic species are adapted to demanding Arctic conditions, but not to competition from 'southern' species, they could be more vulnerable to competition from southern intruders benefiting from climate change (Callaghan *et al.* 2004b). Arctic ecosystems also consist of relatively few species with even fewer keystone species in the food chains, which implies that population changes in just one keystone species may have strong cascading effects in the entire ecosystem (Gilg *et al.* 2012). Yet, the recovery of some bird, mammal and fish species from overharvest demonstrates the potential for effective conservation action.

Stressors affecting Arctic biodiversity originate from a multitude of sources, some of which are indigenous to the Arctic, while others originate fully or partially outside the Arctic. Section 5.1 discusses 'internal' stressors and related suggestions for actions, highlighting the stressors Arctic nations are responsible for. The second section (5.2) deals with 'external' stressors, which require cooperation from countries where they originate. In this and the next section the focus is on anthropogenic stressors (i.e. factors created by or induced by humans), which human societies can do something about.[13]

5.1. Stressors originating from within the Arctic

In much of the world, nature conservation is now a question of protecting what little is left or of trying to restore what has been damaged. In this respect, the Arctic offers a rare opportunity to put sustainable development into practice and to apply solid conservation measures not as an afterthought, but as a priority (CAFF 2002).

5.1.1. Direct human impacts on habitats

Many Arctic regions have seen little or no locally-driven, human-induced habitat change compared with other parts of the world (MEA 2005). In particular,

13 In this report, we do not take a position with regard to efforts to establish an international treaty for the protection of the Arctic (see Nowlan 2001 and Ebinger & Zambetakis 2009).

there is very little agriculture and animal husbandry – with the important exception of reindeer husbandry – and no forestry, factors that are the main drivers of wild species population decreases in many parts of the world (MEA 2005). Furthermore, in large parts of the Russian north, marked human population declines took place following the breakdown of the Soviet Union in 1991 (Bogoyavlenskiy & Siggner 2004), temporarily reducing the direct impact from human activities.

Many Arctic species have wide distributions with most habitats still intact, and relatively few have restricted ranges. This means that many species may be relatively resilient to some habitat loss from conversion, degradation and infrastructure. However, most Arctic species respond to habitat patchiness and seasonality with significant selection for certain localized habitats during certain times of the year or across years. Large bodied species may be most at risk because they tend to have smaller population sizes and larger ranges intersecting more potential human activities at the landscape scale.

Heavy grazing and trampling by domesticated reindeer may be the most widespread direct human-induced pressure on terrestrial Arctic habitats, especially in Eurasia, but its causes are often a combination of regulatory, economic and ecological factors (Ims & Ehrich, Chapter 12). Such human-induced impacts by one species may propagate to other species through food web interactions. Hence, overabundant semi-domestic reindeer in northernmost Fennoscandia (see Section 3) appear to have resulted in range expansions and increased abundance of boreal generalist predators and scavengers such as the red fox, with detrimental effects on the Arctic fox (Ims & Ehrich, Chapter 12).

Oil, gas and mineral extraction and transport are important stressors in parts of the Arctic and are expected to increase in the near future. However, on land this activity is largely limited to geographically small areas with oil and gas pipelines and access roads to mines and wells having the greatest geographical extent in most of the Arctic. Furthermore, onshore accidental oil releases will usually cover a much smaller geographical area than releases at sea and are therefore easier to address. In contrast, oil spills in the marine environment are not easily managed and pose a serious threat to marine ecosystems and particularly to seabirds and marine mammals (AMAP 2009b; see Section 5.1.4).

Dams, impoundments, diversions and water withdrawals produce physical and geochemical (e.g. enhanced mercury mobilization) impacts affecting freshwater systems and their surrounding and downstream environments including wetlands, deltas, estuaries and nearshore marine habitats. Ecological issues surrounding the development of hydroelectric facilities (in particular in the Canadian and Russian Arctic regions) and other reservoirs are projected to increase, resulting in implications for local and regional freshwater biodiversity (Prowse *et al.* 2011a, Wrona & Reist, Chapter 13). Similarly, from a terrestrial landscape perspective, crossings of linear corridors (roads, trails, cutlines, railways, pipelines) over rivers and creeks can have impacts on water quality. Equally important are seismic exploration lines in winter, which compress vegetation and may form drainage channels and alter landscapes. These can be many thousands of kilometers in length in a single year in some areas.

Off-road driving with tracked vehicles poses a problem in parts of the Arctic, and especially in Russia. Tracks form drainage channels that may erode into gullies draining wetlands and changing vegetation (see Kevan *et al.* 1995 and Forbes 1998). Under some conditions, severe impacts to tundra vegetation can persist for dec-

ades following disturbance by tracked vehicles (Jorgenson *et al.* 2010).

Although more common in the boreal forest, wildfires have scorched thousands of square kilometers of low and sub-Arctic tundra in particularly warm and dry summers (see e.g. Krupnik 1993, ACIA 2005). However, the extent to which such fires are natural phenomena or are ignited by humans is unknown. Fire has been largely absent from most of the tundra biome since the early Holocene epoch (Higuera *et al.* 2008), but its frequency and extent are increasing, probably in response to global warming (Hu *et al.* 2010) with a positive feedback effect (Mack *et al.* 2011).

In some areas, fishing practices such as bottom trawling may pose serious threats to benthic communities and remain an important stressor that needs to be studied and monitored (Christiansen & Reist, Chapter 6, Josefson & Mokievsky, Chapter 8, Michel, Chapter 14). Conventional bottom trawl fisheries for groundfishes are highly efficient, but can be damaging to the environment, as they can perturb and change the composition of benthic communities (Tillin *et al.* 2006, Thurstan *et al.* 2010). Restrictive measures have been put in place in some areas to address this (Michel, Chapter 14).

Tourism concentrated on particular sites may have impacts on habitat through wear on sensitive vegetation or erosion of unconsolidated substrates. However, this pressure is still negligible in most places (e.g. Daniëls & de Molenaar 2011) and is relatively easy to regulate if unacceptable levels arise. Furthermore, tourists fascinated by the Arctic and its wildlife can be strong advocates of conservation needs for Arctic nature and environment and thereby enhance motivation for conservation (Prokosch 2003). (See also Sections 5.1.3 and 5.2.3.)

Managing and understanding the impact of human activities on biodiversity and ecosystems is increasingly important as direct impacts on Arctic habitats will increase significantly in the future (Nellemann *et al.* 2001). Future management will require modeled projection of possible impacts, empirical monitoring of potential trouble-spots and consultation with a wide-ranging team of knowledge holders from scientific disciplines as well as indigenous and local knowledge.

Possible conservation actions

- To succeed, biodiversity conservation needs to be a cornerstone of natural resource management and land and marine planning throughout the Arctic for the benefit of Arctic residents and biodiversity in general. To achieve this, a diversity of legal, regulatory and best management practice tools could be employed at diverse scales. Possible detrimental cascading effects on nearby endemic Arctic biodiversity and unique Arctic habitats are important considerations in land and marine planning and monitoring.

- Comprehensive national approaches to protected area planning and establishment are effective biodiversity conservation mechanisms. Eco-regional representation, connectivity, critical areas for various life stages, biodiversity hotspot analyses and maintenance of the most productive and/or resilient areas are important approaches to consider.[14] This work could build on work already done, such as AMSA IIC (AMSA 2009) and RACER (Christie & Sommerkorn 2011).

- Given the scale of changes forecast for the Arctic that will often result in substantial habitat displacements (c.f. Section 5.2.1), it is important that protected areas are: (1) large enough to safeguard critical habitat for target populations, (2) strategically selected (i.e. forming ecological networks of sites) and (3) actively managed in coordination with other approaches that support the overall resilience of regional ecosystems and species (see also Section 19.4.1.3 in Huntington, Chapter 19).

- To secure species representation, protection of areas with many *unique* species should be given high priority, so that a total Arctic network is based on the 'complementary species richness' method and covers as much of the entire biodiversity as possible (Vane-Wright *et al.* 1991, Myers *et al.* 2000).

Arctic habitats are among the least physically disturbed on Earth, and huge tracts of almost pristine tundra, mountain, freshwater and marine habitats still exist. W Spitsbergen, Svalbard with little auk colonies. Photo: Wild Arctic Pictures/shutterstock.com

14 Targets for area coverage were agreed upon internationally at the 10th meeting of the CBD parties in Nagoya, Japan, in October 2010, i.e. the Aichi goals of protection of > 17% and > 10% for land and sea territory, respectively. In 2009, 11% of the Arctic as defined by CAFF (i.e. includes large tracts of sub-Arctic and boreal forest together with much of the Greenland ice shelf) had some form of protection. More than 40% of Arctic protected areas have a coastal component, but for the majority of these areas it is not possible at present to determine the extent to which they incorporate or extend into the adjacent marine environment (Barry & McLennan 2010).

- Productive and varied areas deserve high priority in protected area planning and management. Especially in the high Arctic, such areas often constitute 'oases' that may function as source habitats for surrounding areas (Hodkinson, Chapter 7, Daniëls *et al.*, Chapter 9, Michel, Chapter 14). Such hotspot areas are found in terrestrial, marine and freshwater biomes, and include biologically important polynyas, persistent areas of perennial sea ice, large river deltas, unique lake systems, hot springs and cold seeps, and seasonally important areas for reproduction, molt and fattening of many birds, fishes and mammals (Reid *et al.*, Chapter 3, Ganter & Gaston, Chapter 4, Wrona & Reist, Chapter 13). The same priority applies to important areas for endangered species and particularly sensitive or vulnerable populations (see also Section 5.1.2).

- The design and implementation of mechanisms to ensure the maintenance of ecosystem structure, functions and processes and the representativeness of marine habitats and refugia with low human impact should be considered. A circumpolar Marine Protected Area (MPA) network could be an important part of such an effort. As many important areas cross jurisdictional boundaries, cooperation is essential. Such a network could include the establishment of an effective management system of deep-sea areas and large estuaries, which contain a relatively high proportion of endemic invertebrate species as well as several members of the species-rich fish families (Christiansen & Reist, Chapter 6, Josefson & Mokievsky, Chapter 8).

- Arctic fish species are largely bottom-living (Karamushko 2012), and since Arctic groundfish fisheries are expected to increase in the coming years, the development and deployment of fishing practices that minimize by-catch and seabed destruction are critical.

- Since protected areas are of little conservation value if their legal protections are moderated when economic or other conflicting interests appear (see section on protected area failure in Sutherland *et al.* 2011), the status of protected areas needs to be maintained and enforced.

- When unavoidable alteration of high priority areas takes place, these impacts could be mitigated by improved protection of other important habitat. However, true compensatory measures in the form of 're-wilding', which are used in other parts of the world, are of little relevance in the Arctic where there is almost no modified habitat to return to a more natural state. Areas already impacted by bottom trawling and heavy grazing and trampling by reindeer are exceptions to this, as there is room for recovery of affected areas by reducing the impacts and allowing for re-generation.

- Mitigation and restoration of disturbed or damaged habitat needs to be incorporated into development projects at the planning stage. This should include consideration of the full cost of restoration and remediation activities.

See further discussion in Sections 5.1.2, 5.1.3 and 5.2.1.

5.1.2. Harvest of mammals, birds and fish

According to Article 2 of The Convention on Biological Diversity *"Sustainable use" means the use of components of biological diversity in a way and at a rate that does not lead to the long-term decline of biological diversity, thereby maintaining its potential to meet the needs and aspirations of present and future generations.*

The harvest of mammals, birds and fish has formed the basis of Arctic societies since humans first arrived in the Arctic (see Section 3). Key species such as ringed seal *Pusa hispida* and fishes were able to sustain local human populations for millennia, although periods of famine and population declines show that the Arctic environment lay on the margins of human habitability. Today, harvest of living resources remains vital to the cultures of Arctic peoples, and contributes important protein and other nutrients for many Arctic residents (Huntington, Chapter 18).

During the last few hundred years, harvest of wildlife in the Arctic changed from a small-scale practice by scattered human populations to the use of modern hunting and catching technologies, more efficient means of transport such as snowmobiles, all-terrain vehicles, power boats and ocean going vessels, and increased accessibility through more extensive road systems. In combination with population growth and commercial markets in some regions for wildlife products, this increased the pressure on several wildlife populations (Huntington, Chapter 18).

Even though historically overharvest was one of the most common pressures on Arctic wildlife, it is also the most manageable (Klein 2005). In most areas, hunting and fishing are regulated, at least for species of conservation concern. Indeed, the pressure from overharvest has been largely removed as a major conservation concern for most species due to improved management and conservation actions. The switch from dog teams to snowmobiles has contributed to reducing harvests in many areas, and changing tastes and the increased availability of agricultural foods have also led in some places to lower harvests (Huntington, Chapter 18; see also Michel, Chapter 14).

In the Russian Arctic, where marked human population declines took place after the break down of the Soviet Union, a major shift has happened in the harvest of wildlife. The reduced population has lowered hunting pressure on wildlife in general, but has increased local dependence on harvest of local wildlife as a result of decreasing subsidies (Duhaime 2004, Wheeler *et al.* 2010). Since regulation and law enforcement decreased at the same time, the result has been that hunting, egg collection and fishing pressure on some populations have increased, while other populations have benefited from reduced harvest (K.B. Klokov & E.E. Syroechkovskiy in litt.).

In many regions of the Eurasian Arctic, the adoption of reindeer herding by indigenous hunting cultures led to the extirpation or marked reduction of wild reindeer and drastic reductions of wolves, lynx *Lynx lynx*, wolverines *Gulo gulo* and other potential predators of reindeer (Nuttall 2005).

> *I could say for sure that there are much more bowhead whales now than there used to be when we were children. Where today you now could see a single whale, 2, 3 or 4 whales in one group. While in the olden days we used to only observe single bowhead whales and never more than one…*
>
> (Elijah Panipakoocho, Nunavut, Canda; Hay *et al.* 2000).

Some populations (for example some whales, muskox and common eider *Somateria mollissima*; Fig. 9) have recovered or are recovering from overharvest following conservation and management measures that have been put in place over the past few decades (Reid *et al.*, Chapter 3, Ganter & Gaston, Chapter 4). Similarly, sound regulation of bowhead whale hunting in the Bering-Chukchi-Beaufort region has helped populations

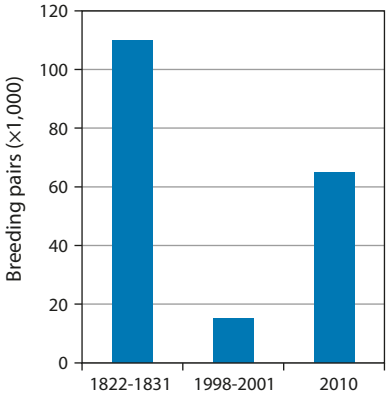


Figure 9. Common eider *Somateria mollissima* population depletion and recovery in W Greenland from the early 19th century to the present (estimates by F. Merkel in litt. based on data from Müller 1906 (down collection), Merkel 2002, 2004a, Christensen & Falk 2001 and annual growth rates from 2001 to 2007 in NW Greenland from Merkel 2010). The depletion was probably mainly caused by overharvest (hunting and egg collection), while the recovery was the result of tightened legislation and cooperation with local hunters since 2001 (Gilliland *et al.* 2009, Merkel 2010).

Species protection has focused on preventing overharvest, which has historically been the largest threat to Arctic biodiversity. Seabirds are an example of biodiversity that is susceptible to such overharvest, and this has caused population declines in some parts of their range. In these areas, careful regulation of harvest is necessary as part of a conservation and restoration strategy. Photo: Knud Falk, Kippaku, NW Greenland.

increase from previously depleted levels (see Box 14.6 in Michel, Chapter 14). Others are not recovering or are only slowly recovering (several sub- and low Arctic carnivore populations, some polar bear populations and some reindeer/caribou populations together with W Greenland walrus, harbor seal *Phoca vitulina* and thick-billed murre; the three latter being red-listed in Greenland; Boertmann 2007, Rosing-Asvid 2010, Reid *et al.*, Chapter 3, Ganter & Gaston, Chapter 4).

In addition, overharvest has not only caused depletion of some target populations, but in some cases it has had cascading ecosystem effects. For example, the elimination of large whales by commercial whaling may have been followed by increasing populations of smaller marine mammals together with some seabirds (Springer *et al.* 2003). Another example is the depletion of large populations of predatory fish (Smetacek & Nicol 2005) that may have resulted in reduced genetic variability (Cook, Chapter 17). Generally, however, the impact of historical harvest of marine mammals, fish and seabirds on current Arctic marine ecosystem structure is not well documented, but the removal of such a large biomass of targeted species would have affected the flow of energy and trophic interactions that shaped the Arctic marine food web that existed previously (Michel, Chapter 14).

In several species of seabirds and small cetaceans, by-catch in fishing nets and on hooks is related to overharvest in that it results in additional mortality on top of other harvests. However, by-catch in gill-nets in the Arctic seems to have diminished in recent decades, at least in the Atlantic sector, due to reduced use of gill nets in the high seas of Greenland and Norway (Bakken & Falk 1998). However, it still is of major concern in coastal fisheries, e.g. in W Greenland and the NW Pacific (Chardine *et al.* 2000, Merkel 2004b, 2011).

» *There has been improvement on the salmon stock. It was in the 1970s that the Norwegians prohibited this trawl-like sea fishing. Already in the next year we had small salmon swimming upstream. Nowadays the sea is being fished out of shrimp that is leaving the salmon with only little shrimp to feed on. This has caused the color of salmon to fade. It is not as red as Atlantic salmon from the Arctic Sea used to be. And the flesh or meat, that used to be much thicker in the past. Back then a salted salmon fillet was like a wood board. This is also due to overcatching shrimp.*

(Late salmon fisherman Jouni Tapiola from Kaava, Finland; Helander *et al.* 2004).

Fisheries conservation and management measures put in place over the last few decades have resulted in large Arctic commercial fisheries which from a global perspective are relatively well managed, although there have been management failures, and high harvest pressure continues on some fish stocks (Christiansen & Reist, Chapter 6, Huntington, Chapter 18). Arctic countries are at the forefront of development of sustainable fisheries. Examples of improvements include national and sub-national regulations, restrictions and large-scale management planning processes and international cooperation (Huntington, Chapter 18, see especially Box 18.3). The need for using a precautionary approach for fisheries and resources management is reinforced by the paucity of baseline data and long-term monitoring in the Arctic compared with other marine ecosystems, combined with rapid climate-associated changes (Michel, Chapter 14). In US waters of the Arctic, for example, commercial fishing has recently been prohibited as per the Arctic Fisheries Management Plan until more information is available to support sustainable management of potentially harvestable species (NPFMC 2009).

Accurate statistics on by-catch are crucial in upcoming Arctic fisheries and call for adaptable management policies to meet conservation aims. No single harvesting practice is foolproof (Pitcher & Lam 2010). Catch Quota Management (CQM; Danish Ministry of Food, Agriculture and Fisheries 2012), a new policy that is currently being tested in North Sea fisheries, may provide urgently needed by-catch data, which is a first step to better controlling the impacts of by-catch.

While harvest can be a major force influencing ecosystem structure and function by altering community composition and species interactions, it also interacts with other stressors and influences as well. For example, while trends in some areas may imply 'fishing down' of the ecosystem, the shift in community structure and landing composition also coincides with a rapid change in climatic and oceanographic conditions, and other stressors. Nevertheless, the contribution of climate change and direct human intervention will have profound impact on marine ecosystems (Christiansen & Reist, Chapter 6, Michel, Chapter 14).

Harvest of animals inside the Arctic is not the only source of harvest stress, as migratory species are also harvested outside the Arctic (see Section 5.2.4).

Possible conservation actions

› To maximize the adaptive capacity of harvested populations of mammals and birds, with respect to harvest, climate change and genetic viability, populations should be allowed to achieve and maintain healthy population levels that meet sustainable harvest management goals. This step includes allowing depleted populations to recover (see text above for examples). Maintaining viable populations can be achieved by, for example, regulation of the take itself,

harvest methods and the establishment of protected zones e.g. for reproduction, molting and feeding.

- The principles of ecosystem-based management (EBM) distribute risk such that ecosystem sustainability is enhanced and ecosystems do not disproportionately suffer the impacts of tradeoffs resulting from management decisions concerning utilization of Arctic resources. This approach would help support the resilience and sustainability of ecosystems in the face of harvests and the many other uses of and impacts to Arctic resources and areas.

- Ongoing improvements in data gathering and analytical techniques for estimating sustained yield are needed. Ideally, such information would include an ability to differentiate populations and stocks, repeated estimations of stock or population abundance, and accurate and complete harvest or catch data including individuals not retrieved. The same applies to by-catch of mammals and birds – and non-targeted fish species – in fishing gear.

- Continued and increased international cooperation on the gathering and assessment of data on population structure, harvest monitoring and harvest methods and regulations is needed, so as to improve the planning and management of harvests. Existing examples include the International Agreement on the Conservation of Polar Bears and cooperation through the North Atlantic Marine Mammal Commission. Many other species and inter-jurisdictional issues require such attention (see also Section 5.2.4).

- Improved means of accessing and exchanging information between hunters, fishermen, scientists and management authorities is of paramount importance. This can involve implementing community monitoring programs, public education, information campaigns on sustainability, involvement in public debates, and more.[15]

5.1.3. Displacement of animals from important habitats

The effects of disturbance on displacing mammals and birds from important habitats are closely related to shyness of the individual species (Madsen & Fox 1995, Laursen *et al.* 2005). This shyness has both an inherited (genetically fixed) and an acquired element. Both are related to the level of population pressure created by such disturbance through death and injury over the course of generations. Usually, the more a population of mammals or birds has been subject to hunting, the shyer it is, and potentially the more effect further disturbance (e.g. in the form of human presence) can have on the population. The exceptions to this are species that rely on cryptic behavior, such as ptarmigan.

Most mammal and bird species in the Antarctic are indifferent towards humans when on land, where there are no mammalian predators (see Box 4). Similarly, in the Arctic much wildlife is relatively indifferent to human presence, so that they can be approached by humans to within 10-20 m – similar to the escape distance from foxes and other mammalian predators. This is not the case for hunted populations, which often have flight distances of several hundred meters, at least during the time of the year when they are hunted. Conversely, birds and mammals can sometimes reduce

15 The appropriateness of co-management systems is outside the scope of this report to make recommendations on. However, much experience exists in Arctic countries on how to handle this, if such methods are desired (see Huntington, Chapter 19).

their flight distances surprisingly quickly when protected from hunting (e.g. mallards *Anas platyrhynchos* and other waterfowl in 'city parks' such as in larger cities in Greenland – a situation that was unthinkable until few decades ago; H. Meltofte, pers. obs.).

Few studies have documented the effects of disturbance at the population level (see Madsen & Fox 1995), probably because they are hard to disentangle from other effects of human presence such as direct mortality or habitat disturbance. Large aggregations of breeding, molting and wintering waterbirds, marine mammals at haul outs and calving caribou may be most sensitive to disturbance, with heavy and continued disturbance having an effect similar to habitat loss, since the birds or mammals are prevented from utilizing important habitat. Such behavioral changes may lead to reduced foraging time, increased energy expenditure and poorer physiological condition leading to reduced fecundity and increased mortality. Disturbance may also have indirect effects such as increased predation, when birds leave their nests due to human disturbance and predators can move in easily to take eggs or chicks. This effect is especially severe in dense bird colonies. In some cases it may be hard to separate the effect of disturbance from the direct effect of the take of individuals from the population. For example, when walruses no longer haul out on land in W Greenland (Born *et al.* 1994), it is hard to know whether this is an effect of continued shooting at haul out sites or the extermination of the local animals, but most likely it is a combination of these pressures.

The potential disturbance due to human presence is closely related to the level of hunting that the populations in question are subject to. For instance, tourists may approach incubating black-legged kittiwakes *Rissa tridactyla* and thick-billed murres to within a few meters in Svalbard, while these and other harvested species may flush at distances of several hundred meters in areas where they are hunted such as in Greenland (Merkel *et al.* 2009, pers. com., Egevang 2011, H. Meltofte, pers. obs.). The balance between hunting-induced shyness and the interests of non-hunters, including tourists, in being able to enjoy wildlife will ultimately depend on the priorities of the individual jurisdictions responsible for hunting and recreational activities.

Other potentially harmful disturbances are ship traffic, seismic operations and aircraft, which may have the same effect as direct human disturbance. Low-flying aircraft – especially helicopters – may displace birds and mammals from key habitats and can even cause destruction of eggs and young on bird cliffs (Mosbech & Glahder 1991, Chardine & Mendenhall 1998, Overrein 2002, Moore *et al.* 2012). The properties of sound in water are of particular concern, since increasing ship traffic may hamper the ability of whales to communicate over large distances (Southhall *et al.* 2007).

Indeed, disturbance will inevitably increase in the future, and it remains a challenge to avoid harmful disturbance to sensitive species such as whales and other marine mammals or particularly sensitive areas such as molting areas for waterfowl and breeding areas for seabirds.

The rapidly diminishing Arctic sea ice cover including the decline in multi-year ice will open up large sea territories for economic development such as exploitation of natural resources that were previously physically or economically unfeasible. This also involves new shipping routes and increased tourism (AMSA 2009).

Possible conservation actions

- The effects of human disturbance on population size and fecundity is largely unknown. As human activities increase, the impact of this as a stressor needs to be better understood and monitored.

- Human disturbances should to be kept at a level that does not significantly alter animals' patterns of utilizing existing food resources, natural behaviors and ability to breed, molt and rest. One of the tools for achieving this is the establishment of reserves and other low-disturbance areas as refugia especially for hunted populations (see e.g. Madsen & Fox 1995). Other tools include seasonal restrictions, speed limits, reducing or minimizing travel in key areas during sensitive periods[16], height restrictions for aircraft and minimizing noise in marine ecosystems including stand-off distances and a ramp-up period at the start of seismic activities.

- For species coming under severe pressure from climate change, alternative habitat should be or safeguarded such as safe coastal haul out sites for walrus, in areas where ice haul out sites are no longer suitable due to loss of ice or distance from feeding areas.

In general, the more a population of mammals or birds has been subject to hunting, the shyer it is, and potentially the more effect further disturbance (e.g. in the form of human presence) can have on the population. Photo: Jenny E. Ross/Lifeonthinice.org

16 Of particular concern is some parts of the tundra during sensitive time periods, including spring calving (caribou and muskoxen), den selection (foxes), nest initiation (e.g. geese, owls and raptors) and molting (geese and other waterfowl).

5.1.4. Pollutants originating in the Arctic

People living in the Arctic probably consume, individually, as many goods and as much energy as people from the industrialized world (e.g. Grønlands Statistik 2011), thus likely contributing as much to global pollution on a per capita basis as humans elsewhere. However, there is relatively little industrial production in the Arctic, and human density is very low. Total emissions of toxic contaminants are thus minimal in the Arctic when compared with more southern latitudes. Pollution within the Arctic is both direct via local releases (e.g. carbon dioxide and black carbon from energy production and combustion of waste often on open dumps, ozone depleting substances from refrigerators etc.) and indirect via the consumption of imported goods whose manufacture and transport contribute to global pollution – which then may disperse to the Arctic. Reducing local pollution will benefit biodiversity around Arctic communities and will contribute to global pollution-reduction efforts. In addition, larger sources such as mining, oil and gas activities, and legacy sites such as military bases are substantial sources of pollution within the Arctic (e.g. AMAP 1998, 2004, 2009b).

Oil, gas and other mineral extraction and use is probably the single most important human-induced contributor to pollution, both locally in the form of release of toxic compounds and accidents (AMAP 2009b) and globally in the form of greenhouse gases, black carbon and mercury emitted when fossil fuels are combusted. This is particularly relevant for the Arctic, since the region potentially holds one fifth of the world's yet undiscovered resources (Fig. 10; USGS 2011, Michel, Chapter 14). Oil spilled both on land and at sea decomposes more slowly in the cold Arctic environment than at warmer latitudes, and hence remains bio-active for a longer time (AMAP 2007). Furthermore, response capabilities in the Arctic are typically far below what they are in other oil-producing regions (AMAP 2007). A risk assessment by two major insurance and risk analyses companies, Lloyd's and Chatham House (2012) concluded that "while particular risk events – such as an oil spill – are not necessarily more likely in the Arctic than in other extreme environments, the potential environmental consequences, difficulty and cost of clean-up may be significantly greater, with implications for governments, businesses and the insurance industry."

Accidental release of oil into the Arctic marine environment threatens all trophic levels (see Michel, Chapter 14). Most obvious to the public are effects on birds and mammals, especially compromising their feathers and fur, resulting in hypothermia and potential mortality. In addition, metabolic effects are documented for invertebrates, birds and mammals. Furthermore, Arctic seabirds and marine mammals are particularly susceptible to oil spills should one occur where and when they congregate in large numbers to nest, rear young and molt each year (Reid *et al.*, Chapter 3, Ganter & Gaston, Chapter 4).

According to the Arctic Oil and Gas 2007 overview report from Arctic Council (AMAP 2007) "There are no effective means of containing and cleaning up oil spills in broken sea ice." The same conclusion was reached by the US National Research Council (2003): "No current cleanup methods remove more than a small fraction of oil spilled in marine waters, especially in the presence of broken ice." However, recent experiments under optimal conditions have been able to achieve 'in situ burning' of significant shares of oil in waters covered with 70% drift ice (Sørstrøm *et al.* 2010).

Oil spill accidents of cargo, military and cruise vessels (Fig. 11) pose a serious local threat particularly in

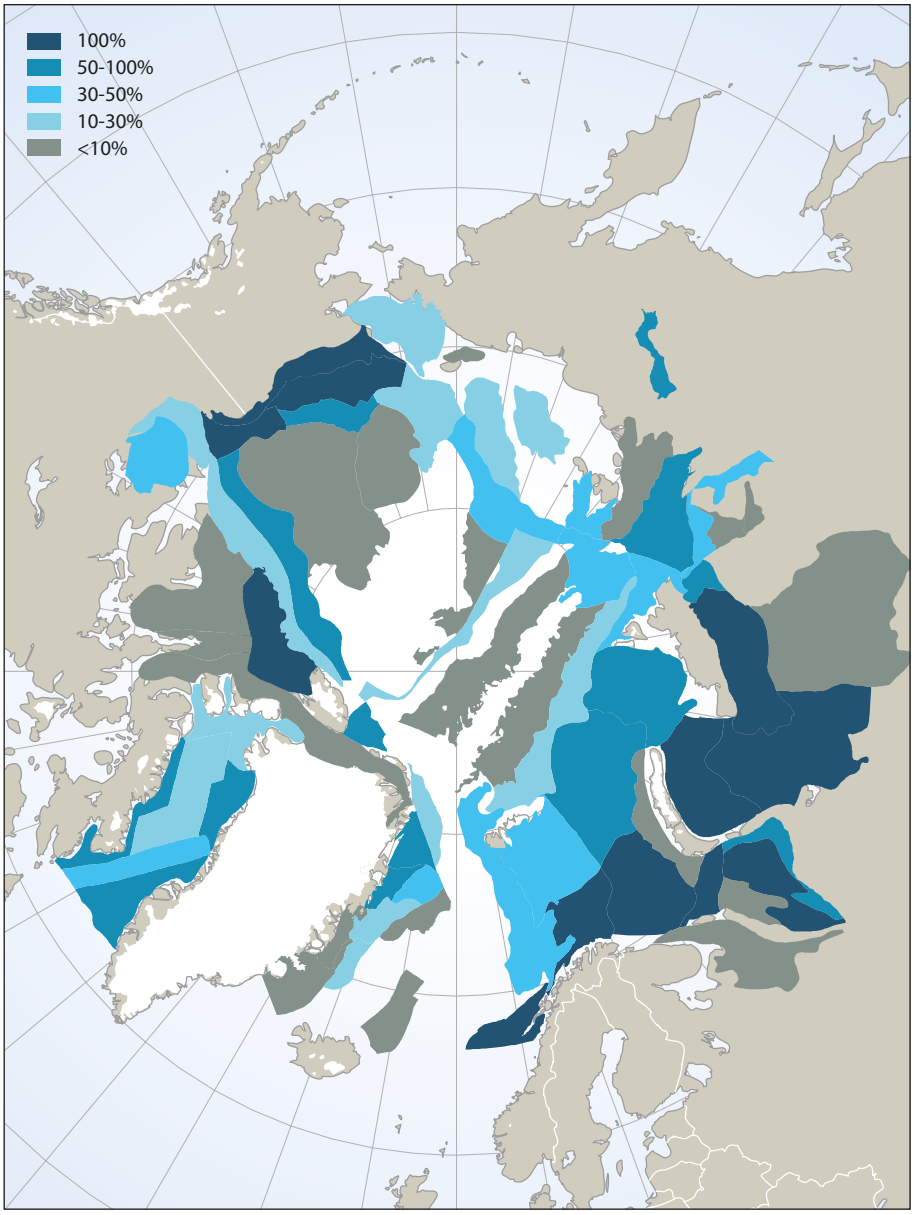


Figure 10. Circumpolar distribution and probability of potential petroleum reserves (from US Geological Survey 2011).

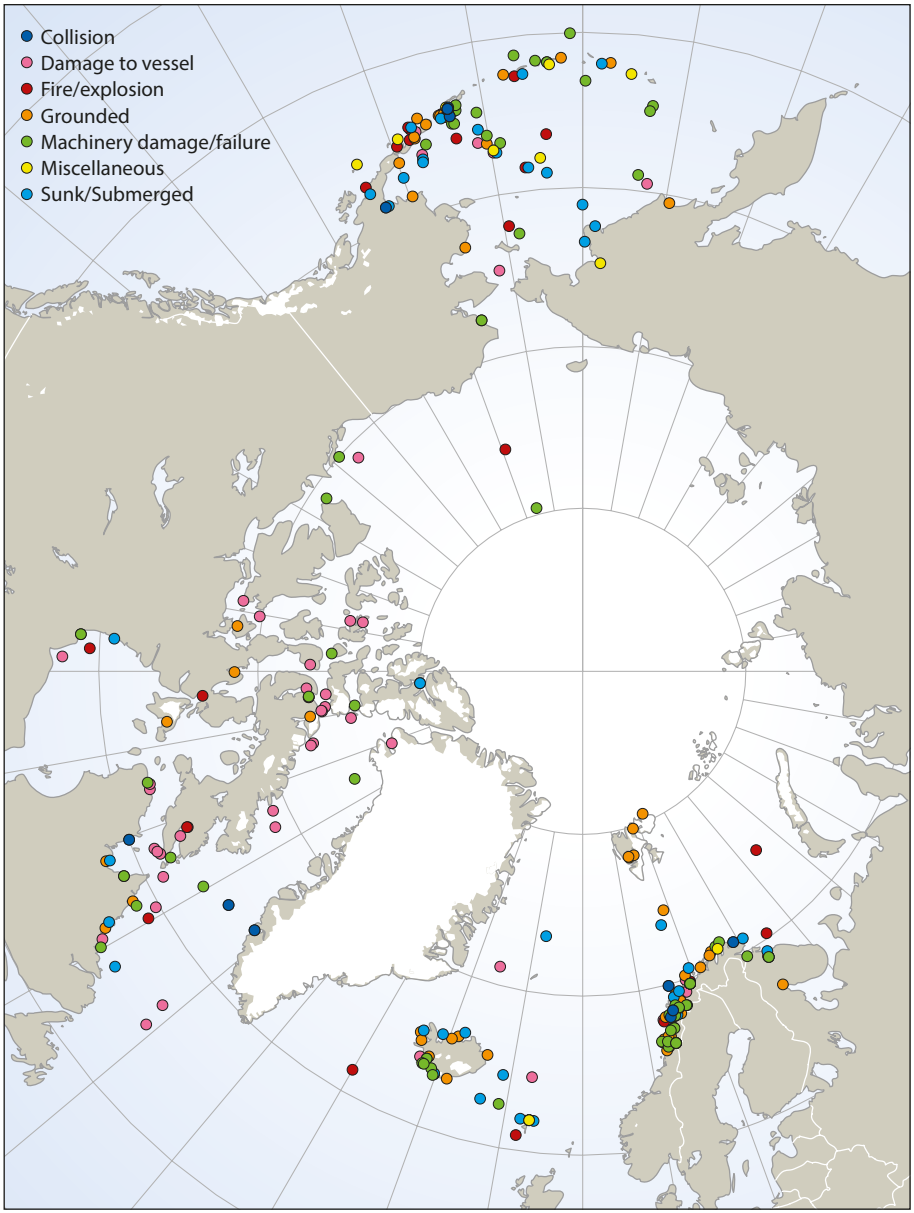


Figure 11. Locations of sub-Arctic and Arctic shipping accidents and incident causes, 1995-2004 (from AMSA 2009).

areas with seabird colonies and similar concentrations outside the breeding season (staging, molting and wintering congregations in particularly important areas; AMSA 2009). Yet, the magnitude of spills from ships – even with oil tankers – is significantly smaller than the potential magnitude of a spill from an oil blowout from an under-sea well. The Deepwater Horizon accident in the Gulf of Mexico released on the order of twenty times as much oil as at the Exxon Valdez spill in Prince William Sound, Alaska (c. 790,000 m^3 vs. c. 37,000 m^3; AMAP 2009b, Graham *et al.* 2011). Although spills on land are generally more readily contained, they are still a serious threat to tundra, lake and river systems.

Legacy contaminants (e.g. PCBs in Svalbard) and radioactivity from legacy military activity can potentially have an impact on biodiversity (e.g. AMAP 1998, Bustnes *et al.* 2010). Open rubbish dumps may have a negative impact on wildlife population dynamics through an increase in predators and parasites and the spread of contaminants (e.g. from industrial wastes) and pathogens (see e.g. Pamperin *et al.* 2006, Weiser & Powell 2011, Stirling & Derocher 2012).

Possible conservation actions

- A major oil spill in ice filled Arctic waters would be detrimental to biodiversity and very difficult to clean up, particularly under problematic weather, light and ice conditions. However, if oil development is undertaken, a precautionary approach adhering to regulations and guidelines specific to the Arctic and based on the best available science would reduce risks, including that development activities in the most sensitive areas are avoided.[17]

- Research efforts into understanding the consequences of oil spills in sea-ice environments remain essential to ensure advances in knowledge and development of improved technologies specific to oil and gas development in the Arctic.[18]

- Some tools that may help to reduce other pollution originating from within the Arctic are: (1) for ship operations in the Arctic, a mandatory polar code encompassing vessel construction, maintenance and operations (e.g. routes, speeds) would help minimize the risks, (2) best management practices for local waste management are desirable throughout the Arctic, (3) minimizing black carbon emissions would reduce the impact of this important driver of climate change, and (4) ongoing clean-up of legacy contaminated sites from military activity and historic mining and oil and gas exploration will continue to reduce contaminant inputs to the environment.

See further discussion in Sections 5.2.1 and 5.2.2.

17 See AMAP 2007 for management recommendations.

18 The work of EPPR significantly advanced this issue in its 2011 report *Behavior of oil and gas and other hazardous and noxious substances spilled in Arctic waters* and its other work on pollution prevention. Similar work by others continues to advance the science of oil and gas development in ice-filled waters, including a Norwegian project led by SINTEF (www.sintef.no/jip-oil-in-ice) and Canadian work done by Environmental Studies Research Fund (www.esrfunds.org/) and the Program on Energy Research and Development (www.nrcan.gc.ca/energy/science/programs-funding/1603). As well, new research is proceeding on the potential for microbes to degrade oil in ice-filled environments.

5.2. Stressors originating from outside the Arctic

5.2.1. Climate change

Since 1980, the rate of increase of atmospheric temperatures in the Arctic has been twice that of the rest of the planet (McBean 2005, IPCC 2007a, AMAP 2009a, AMAP 2011a), and projections show that the Arctic will experience the largest future temperature changes on the planet (Overland *et al.* 2011). This is the result of 'polar amplification' caused by a combination of feedback mechanisms such as snow and ice melt leading to lowered albedo (which leads to further snow and ice melt and so on) and increased heat transport from lower latitudes (Graversen *et al.* 2008, Screen & Simmonds 2010, AMAP 2011a).

In addition to the well-known effect of greenhouse gases on global warming (IPCC 2007a), incomplete combustion of fossil fuels and biomass by human action or in forest fires releases black carbon which, when deposited on ice and snow, increases melt by reducing albedo. Hence, black carbon adds to the positive feedback of snow and ice melt (AMAP 2011c, UNEP *et al.* 2011; see also Section 5.1.4) and may – together with a decline in reflective sulphate aerosols – have played a significant role in the warming of the Arctic in recent decades (Lenton 2012).

Arctic species are well adapted to harsh conditions, but often struggle to compete with species moving in from the south as a result of climate warming. Photo: Kent Olsen.

» *Long ago [it] used to be [a] long spring. Used to stay out there [at his hunting camp] for months. In the springtime (...) we do fishing first. After that, hunt geese; then go fishing again after that. Now we don't even go fishing after goose hunting because it melts too fast.*

(Geddes Wolki, Western Canadian Arctic; Nichols *et al.* 2004).

Full implementation of the measures recommended by UNEP *et al.* (2011) for reducing warming globally is estimated to be able to reduce warming in the Arctic in the next 30 years by about two-thirds compared with projections.

Increased vegetation growth following global warming is another potential feedback mechanism operating through a reduction of the albedo and hence, leading to further warming (McBean 2005, Ims & Ehrich, Chapter 12). Finally, massive amounts of peat-based carbon and gas hydrate deposits, bound in permafrost both on land and in marine shelf areas, may be released at accelerated rates. This process will release both carbon dioxide and the much more potent greenhouse gas, methane (Zimov *et al.* 2006, Shakhova & Semiletov 2007, AMAP 2009a, Lenton 2012; see also Huntington, Chapter 19). However, the extent to which this will be counterbalanced by enhanced carbon uptake by increased vegetation growth on the tundra is uncertain (Callaghan 2005, AMAP 2009a, 2011a). Contributing to this uncertainty is the possibility that increased plant growth and compositional shifts in vegetation communities induce net loss of carbon to the atmosphere via mycorrhiza activity that increases the rate of decomposition of soil organic matter.

The ten year period 2001-2010 had the highest global mean temperature recorded for a 10-year period since records began in 1850 (WMO 2012), and there are

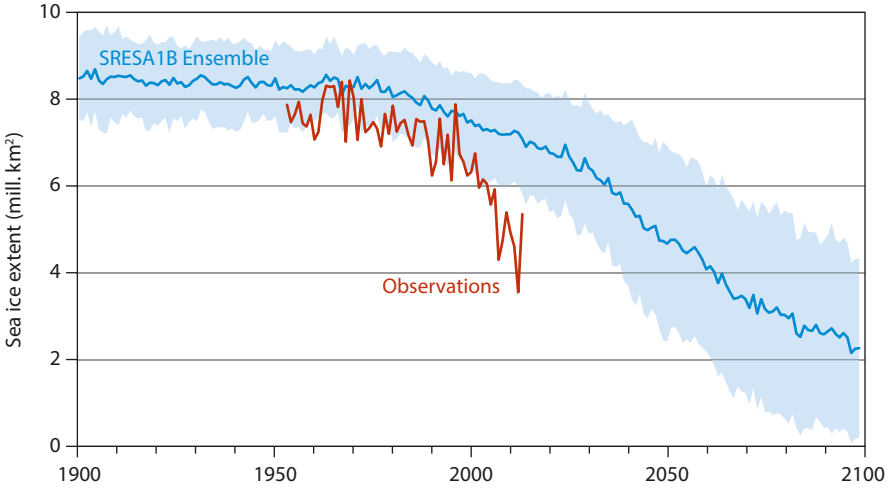


Figure 12. The loss in summer extent of Arctic Ocean sea ice has occurred much faster than the initial projections had anticipated, so that the total ice cover at the summer minimum reached an all time low in September 2012 with only half the extend as compared with the 1979-2000 average (modified from Stroeve *et al.* 2007; see also photo on page 4). Similarly, the loss in monthly averaged Arctic Ocean ice volume for August 2013 was 76% lower than the maximum in 1979 (Polar Science Center 2013).

indications that summer temperatures in the Arctic during recent decades have been warmer than at any time in the past 2000 years (Walsh *et al.* 2011). Within this century, temperatures in the Arctic are projected to continue to increase at a greater rate than the global average, with the most pronounced increase in autumn and winter and an annual increase of between 2.8 and 7.8 °C (Kattsov & Källén 2005, Dahl-Jensen *et al.* 2011, Overland *et al.* 2011). June snow cover in the northern hemisphere (almost entirely within the Arctic) has already decreased by more than 45% since records began in 1979 (see Fig. 7). Similarly, Arctic summer sea ice cover – and particularly the amount of multi-year ice. – is decreasing at an accelerating rate, so that total ice cover at the summer minimum reached an all time low in September 2012 with only half the extend as compared with the 1979-2000 average (Fig. 12). Current projections suggest that the Arctic Ocean will become largely ice-free in summer within the next 30-40 years (Meier *et al.* 2011). Similarly, negative mass balance of Arctic ice caps and glaciers are projected to contribute to an expected global sea level rise of 0.7-1.6 m at the end of the 21st century (Grinsted *et al.* 2010, Dahl-Jensen *et al.* 2011).

The impacts of climate change include a long list of changes in the physical environment, which will have profound effects on Arctic biodiversity. The conditions will vary spatially, but aside from temperature increases, the most pronounced changes are likely to include (cf. Callaghan 2005, Kattsov & Källén 2005, AMAP 2011a):

- increased precipitation with more winter snow
- increased frequency of winter thaw-freeze events including rain-on-snow resulting in ice crust formation
- earlier and more variable snow melt
- earlier drying of ponds
- disappearance of perennial snow beds
- increased periods of summer drought but with more severe rains

Climate change is already causing earlier snow melt, which initially may benefit many Arctic organisms. But in the longer term it will make it possible for more competitive southern species to 'take over' what are currently Arctic habitats. Photo: Erik Thomsen.

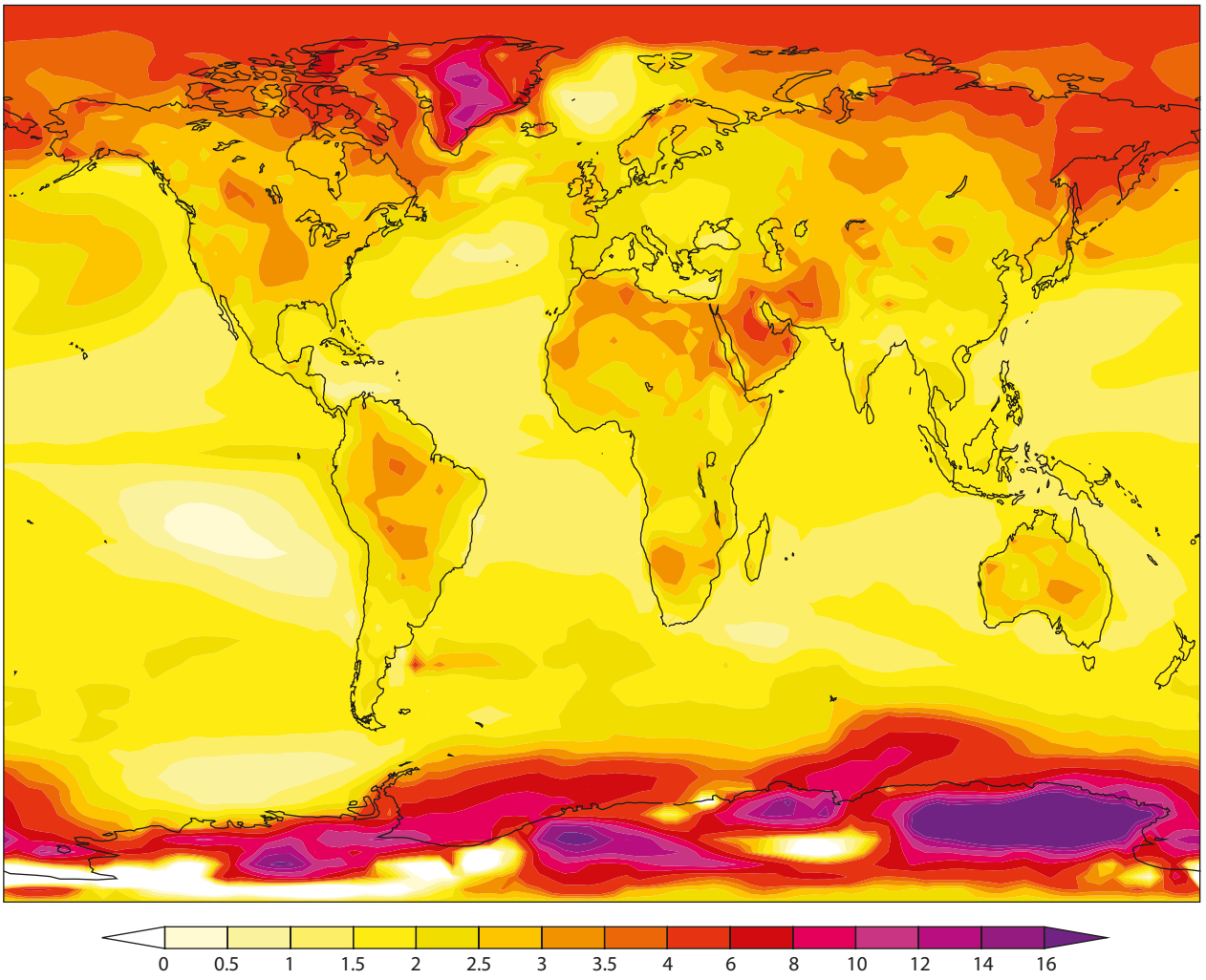


Figure 13. Temperature response (°C) to an increase of CO_2 from 280 to 400 p.p.m. calculated as 'Earth System Sensitivity' resulting in significantly larger sensitivity than in 'traditional' models. From Lunt *et al.* 2010 and Richardson *et al.* 2011. Reprinted with permission from Nature Publishing Group.

- thawing permafrost and thermokarst development with drainage of peatlands and ponds or establishment of new ponds
- increased freshwater discharge into the Arctic Ocean
- disappearance of coastal ice shelves
- flooding of low coasts
- coastal erosion
- later onset of autumn snow
- more frequent and severe extreme events (icing, erosion, storms, flooding, fire)
- accelerating loss of sea ice cover, especially multi-year ice, and
- ocean acidification.

The extent to which these effects are expected to develop varies between projections, but the overall direction is clear, and several of them are already evident now (AMAP 2011a).

In addition to linear changes comes the risk of reaching tipping points, where a system (geophysical or ecosystem) moves from one state to another from which it is hard to change back across a certain threshold (ARCUS 2009, Rockström *et al.* 2009, Barnosky *et al.* 2012). Here, "we may already be at (or very close to) a tipping point for some large-scale systems in the Arctic" such as the Greenland Ice Sheet (Richardson *et al.* 2011, Lenton 2012). That the risk of reaching such tipping points is higher than was anticipated earlier is due to the fact that recent trends in a number of climate related elements have been more pronounced than the IPCC projections (e.g. AMAP 2011a); i.e. the 'Earth System' may be more sensitive to carbon dioxide forcing than previously thought (Fig. 13; Lunt *et al.* 2010, Richardson *et al.* 2011).

The most profound effect will be the loss of ice on land (permafrost), in freshwater and in the ocean (AMAP 2011a, Prowse *et al.* 2011b). This is expected to have major and often non-linear effects on Arctic biodiversity because of complex feedbacks and interactions between freeze-up and melt cycles and species assemblages (Callaghan 2005; see also Walther 2010). These feedbacks are anticipated to accelerate changes in the physical environment and in biodiversity (AMAP 2011a). The direct effects of higher temperatures, and in some cases higher precipitation, may at first involve increased plant growth and abundance and possibly increasing populations of some animals, but in the longer term the effects are likely to include the disappearance of large tracts of what we recognize today as Arctic ecosystems and populations and hence surpass the effects of all other stressors taken together (Callaghan 2005, Meltofte *et al.* 2007).

» *You got an example of that [ice crust] now with the caribou coming around here, a lot of people wondering why they didn't stay around right. They want them to stay around and they're in the woods. Why are they down there? Because the hills are all iced up. They're pure ice in places and they can't get their food so, they're not going to stick around where they can't dig now. They know more than we do. And they know what's coming, they can, I don't know how they know, but they know that it's going to be icy, they move on.*

(Ron Webb, Anaktalâk Bay, Labrador; Davies 2007).

A meta-analysis of data from the last 40 years has shown that a wide range of species' distributions has moved away from the Equator by a median speed of 16.9 km per decade and uphill by a median speed of 11.0 m per decade, and that these range changes tracked temperature trends (Chen *et al.* 2011). Similar northward range extensions have been recorded in sub-Arctic and Arctic species, where also a marked 'greening' has taken place

in large regions since relevant satellite pictures became available in 1982 (Jia *et al.* 2007; see Section 4 for a range of observed climate-related changes together with references to relevant chapters). It is possible that about half the present tundra may be replaced by the end of the 21st century by shrubs and trees from the south (Callaghan 2005, Kaplan 2005, SNAP 2012, Pearson *et al.* 2013) – provided that the spread of woody vegetation is not counterbalanced by drought (Callaghan *et al.* 2011a), outbreaks of insect pests or intense herbivory (Ims & Ehrich, Chapter 12). Similar changes are taking place in the marine environment including changes in the timing and duration of land fast ice and a reduction of little-studied biota associated with coastal ice shelves, which imply the loss of a globally unique ecosystem (Michel, Chapter 14). Furthermore, the retreat of summer sea ice from continental shelf seas altogether means the loss of an entire type of marine polar ecosystem at a global scale. With these impacts occurring already, the reduction of human-induced climate change is the most urgent action in securing Arctic biodiversity for the future or, as concluded by AMAP (2011a; summary report): "Combating human-induced climate change is an urgent common challenge for the international community, requiring immediate global action and international commitment."

Because of the rapidity of change, the dominant response of many Arctic species to climate change is more likely to be by phenotypic[19] adaptation rather than genotypic[20] adaptation (Callaghan 2005, Gilg *et al.* 2012). This may involve northward displacement of whole habitats resulting in a reduction in the area occupied by Arctic ecosystems – particularly those characteristic of the high Arctic – because of the reduction in the available surface area when moving north towards the pole. In terrestrial species and ecosystems this loss of surface area ultimately stops at the northern shores of continents and islands, so that sub-Arctic and boreal species expanding from the south squeeze Arctic habitats – and particularly high Arctic habitats – up against the Arctic Ocean (Callaghan 2005, Kaplan 2005, Meltofte *et al.* 2007, Hof *et al.* 2012, Hope *et al.* 2013). Considering the fact that during the last 0.8-1.0 million years, glacial stages *sensu lato* accounted for > 85% of the time with much more extensive steppe-tundra habitats than in interglacial periods like the present, the whole Arctic biome can already now be considered to be a refugium for Arctic biodiversity (Ims & Ehrich, Chapter 12).

> *We never saw them before. This is what we have observed. New plants have arrived here and on tundra. Rivers and lakes are filled with small-flowered a kind of duckweed* [Lemnaceae]*, and the lake started to bloom. Life of the fish is more difficult and likewise peoples fishing opportunities as lakes grow closed up with the new plants…*
>
> (Larisa Avyedeva, Saami, from Luujavre, Russia, on new species of plants which have arrived to the territories of the Kola Saami 2001-2004; Cherenkov *et al.* 2004).

Arctic biodiversity has been exposed to strong selection pressures in the harsh and highly fluctuating Arctic environment over periods of up to three million years with repeated glaciations interrupted by relatively short interglacial periods. Photo: Jenny E. Ross/ Lifeonthinice.org

19 The composite of an organism's observable characteristics or traits such as morphology, development, biochemical or physiological properties, phenology and behaviour.

20 The genetic makeup of a cell, an organism or an individual.

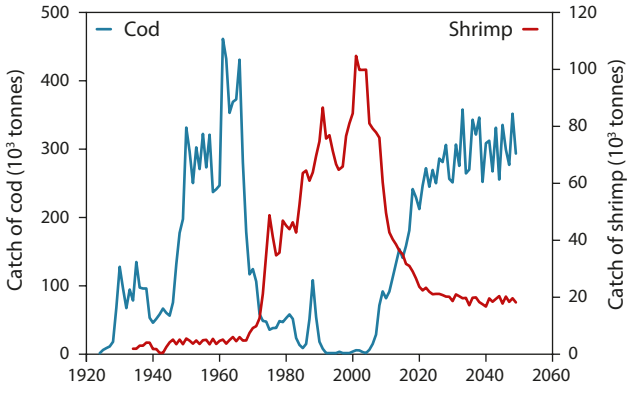


Figure 14. Following socioeconomic transitions and climatic fluctuations, fisheries in W Greenland have shown a dramatic shift from harvest founded on Atlantic cod *Gadus morhua* (~ 1920-1970) to the present-day harvest of northern shrimp *Pandalus borealis*. This harvest is projected to switch again in coming years as a consequence of ocean warming (ACIA online; see Christiansen & Reist, Chapter 6).

Unlike many lower latitudes, where dispersal and colonization can, in theory at least, result in a rearrangement of ecosystems without necessarily involving species loss, global warming at high latitudes if allowed to proceed unchecked is certain in the long run to cause the extinction of many specialized high Arctic organisms together with small island endemics (Cook, Chapter 17). However, in absolute numbers, relatively few Arctic species may be subject to extinction in the 21st century. A number of true Arctic vertebrates and sea-ice-associated biota are likely to be most at risk (Callaghan 2005, Smetacek & Nicol 2005, Michel, Chapter 14; yet, see Section 5.2.2 for the potential effects of ocean acidification). Moreover, a substantial proportion of land area currently classified as high Arctic consists of islands well isolated from continental land masses (e.g. Svalbard, Franz Josef Land, the Canadian Arctic Archipelago). Future changes in these island ecosystems will be strongly affected by their isolation. Simple expansion of existing low Arctic ecosystems will be inhibited by water/ice barriers, and become increasingly so as the open-water season lengthens. Highly mobile species such as birds and some insects may expand their ranges to these islands as the climate moderates, while terrestrial mammals, non-flying invertebrates and plants with animal-dispersed seeds may take much longer to reach them. The protection of high Arctic biota, especially animals such as lemmings, Arctic hare *Lepus arcticus* and muskoxen, is likely to be easier in such refugia, the more so because their maritime climates are likely to remain cooler than those of continental regions (Gaston *et al.* 2012).

Nevertheless, predictions of such changes are fraught with large uncertainties. Current ecological projection models are often mechanistically naïve in the sense that differential dispersal capacities and interspecific interactions are not taken into account (cf. Guisan & Thullier 2005, van der Putten *et al.* 2010). Thus, novel types of habitats and ecosystems may emerge under rapid climate change. Moreover, within the range of projections from Global Circulation Models there are outcomes that represent 'novel climates' with no analogues (Williams *et al.* 2007), which naturally limit inferences about how biota are likely to respond.

In the marine environment, the northward expansion of sub-Arctic species (see example in Fig. 14) takes place via dispersion and transport of planktonic larvae or adult animals. In addition, increasing temperatures and the opening of migration corridors as the ice retreats favor range extension of marine species such as the killer whale, with expected impacts on marine food

webs (Michel, Chapter 14). In addition, global warming will increase the potential for exchange of species and populations between the Pacific and the Atlantic sectors (Cook, Chapter 17). The same applies to alien invasive species (Lassuy & Lewis, Chapter 16).

The strong selection pressures inherent in the harsh and highly fluctuating Arctic environment, applied to organisms over periods of up to two million years, should ensure that those that persist display high fitness and resilience to climatic variability and change (see Beaumont *et al.* 2011 and Walsh *et al.* 2011). This does not mean, however, that climate variability and shifts will have little effect. A few degrees increase in mean winter temperature will result in more frequent and much more pronounced freeze-thaw events including winter rains resulting in ice crust formation (Rennert *et al.* 2009), which may pose severe problems or even extinction of several species and corresponding change in ecosystem structure (see example in Fig. 15). Similarly, a few degrees of temperature increase will result in extensive sea ice reductions, particularly of multi-year ice, as is already taking place (Smetacek & Nicol 2005). As a result, the global polar bear population has been predicted to decrease by about 30% during the next 45 years (Amstrup *et al.* 2008, Stirling & Derocher 2012), and the range of polar bears is forecast to contract significantly, particularly in the southern parts of their distribution (Durner *et al.* 2009).

Furthermore, Arctic communities are not entirely composed of common and widespread species. Some invertebrate and lichen species, for example, are either widespread but uncommon elements of a particular community type or have a highly restricted distribution. We do not yet fully understand the ecology of rarity, the functional importance of these rarer species in ecosystem processes or their role in community resilience. The capacity for rapid adaptation by organisms to a changing Arctic environment will differ markedly between groups. For example, bacteria, microalgae and some smaller invertebrates are likely to adapt more rapidly *in situ* to change than birds or mammals, which are more likely to have to move to new areas in search of favorable conditions.

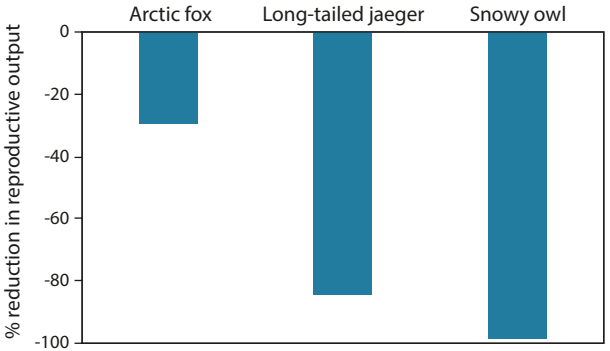


Figure 15. In recent decades, a fading out or collapse of lemming population cycles has been reported from several Arctic regions and has been attributed to increased frequency of melting-freezing events leading to ground ice-crust formation (Ims & Ehrich, Chapter 12). The impact of such a collapse of the lemming cycle on the reproductive performance of three Arctic predator species with different degrees of specialization to lemming prey were documented at Trail Island, NE Greenland. Comparing two periods with presence (1998-2000) and absence (2000-2011) of regular peak years, Snowy owl fledgling production declined by 98% after the collapse of the collared lemming *Dicrostonyx groenlandicus* cycle, and no lemming nests with signs of predation from stoat *Mustela erminea* have been found since then. Data were derived from Schmidt *et al.* (2012).

In ungulates, increasing temperature has already been shown to strongly influence development rates, popula-

tion amplification, distributions and emergence of disease attributable to some helminth parasites. Temperature changes can facilitate expansion of parasite and host assemblages from the south, leading to a range of interactions with northern endemic faunas, including changing patterns of exposure for zoonotic parasites transmitted from animals to people (Hoberg & Kutz, Chapter 15).

To human societies in the Arctic, climate change and its impacts on biodiversity are now and will increasingly be a challenge (Hovelsrud *et al.* 2011). Some may see the multitude of changes as beneficial, such as less inclement winters, longer summers, easier boat traffic (including marine hunting and fishing, where this primarily takes place from boats; e.g. Hvid 2007 and Michel, Chapter 14), better possibilities for agriculture and aquaculture, together with improved access to mineral resources. Also, increased marine productivity and new fish and other wildlife species may become available for harvest and improve economic opportunities (MacNeil *et al.* 2010). However, to what extent these advantages will be outweighed by the negative impacts such as decreasing biological resources currently harvested, is uncertain and furthermore much dependent on individual situations and preferences including the sense of 'Arctic identity'. Successful adaptation will demand considerable adjustment to new pressures as well as the ability to make use of new opportunities (see e.g. Nuttall 2005). The conservation interest lies in keeping the change from all stressors as much as possible within the scope of adaptation and adjustment (i.e. resilience) for all socio-ecosystem com-

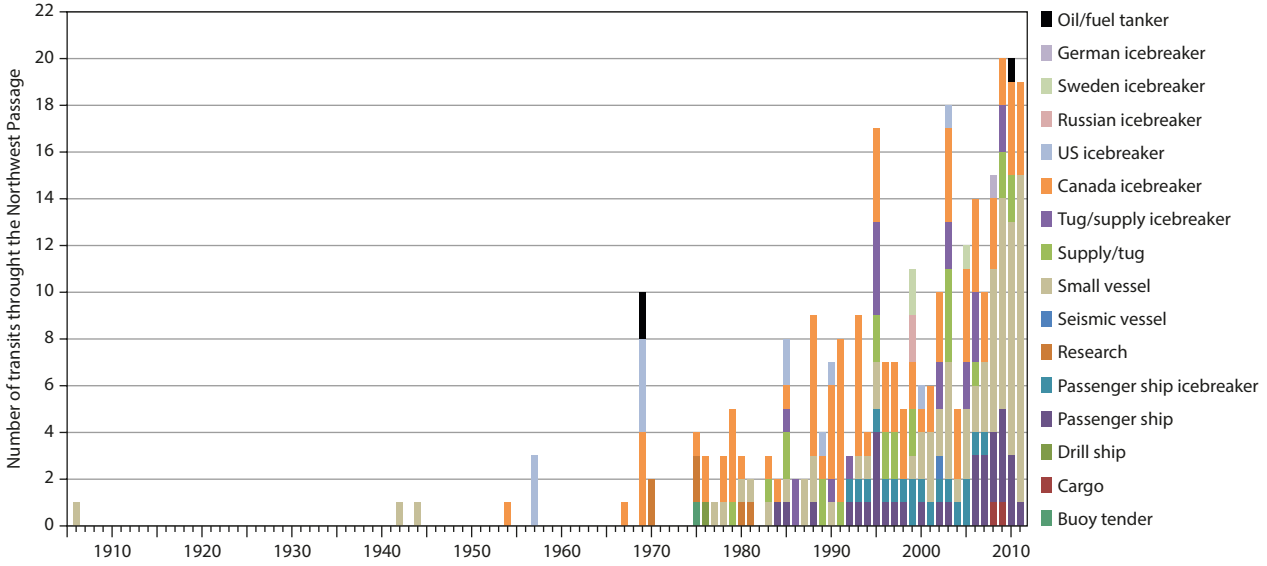


Figure 16. Ship transits of the Northwest Passage 1906-2011. From the NWT State of the Environment report (ENR 2011) with data from NORDREG updated to 2012.

ponents, including humans, so that massive disruption of ecosystems does not result.

When considering impacts of climate change on Arctic ecosystems, interactions between climate change and other stressors must be taken into consideration. Offshore oil and gas exploration, increasing terrestrial and marine traffic (Fig. 16), fishing activity, and heavy metal and organic contaminants are all stressors that may be exacerbated by ongoing climate change (Callaghan 2005, Callaghan *et al.* 2011b, Wrona & Reist, Chapter 13, Michel, Chapter 14). Furthermore, warmer climates may enable – in addition to 'naturally expanding' boreal species – the expansion of a number of invasive species into the present Arctic (Lassuy & Lewis, Chapter 16; see also Section 5.2.3).

Climate change will also alter productivities of Arctic aquatic ecosystems (Wrona & Reist, Chapter 13, Michel, Chapter 14). Most Arctic salmonids (e.g. chars, whitefishes), important mainstays of coastal and subsistence fisheries, are represented by polymorphic forms and also exhibit variable life histories (Christiansen & Reist, Chapter 6). Stressors (e.g. climate change, river damming) will result in changes in the relative proportions of these variant forms with possible negative consequences for fisheries. An example is the present dominance of anadromy in the mid-latitudes of the range of Arctic char (i.e. 50-70 °N in North America), relative to non-migratory counterparts present in the same lakes, where sea-run fish are preferred in fisheries due to greater size/weight, larger abundances and lower parasite loads. Anadromy in fishes is believed to result from greater productivity in the sea relative to freshwater systems (Gross 1987); this is especially relevant in the Arctic where the differential is substantial. Climate-change driven increases in productivity from present levels are likely to be higher in fresh waters than in the adjacent marine waters. Accordingly, benefits from migrating to the sea (e.g. enhanced growth) will be lower relative to costs (e.g. migration, predation), thus, decreased anadromy may ensue with follow-on consequences to fish quality and quantity (Reist *et al.* 2006). Limited evidence accrued to date suggests that some char populations are already exhibiting a lower proportion of anadromy (Finstad & Hein 2012).

The huge variation between the effects that climate change has on different species and even on the same species in different parts of the Arctic may cause significant shifts in 'match' to occur between species assemblages and food webs such as simultaneity in plant flowering and emergence of insect pollinators (Gilg *et al.* 2012). This may result in improved 'matches' in some inter-species relations (Vatka 2011, Ims & Ehrich, Chapter 12), but it is more likely that such changes will result in trophic mismatches, leading to reduced reproductive success in many Arctic species (Ganter & Gaston, Chapter 4, Michel, Chapter 14; see also Miller-Rushing *et al.* 2010 for discussion) as hypothesized for Greenland caribou (Post *et al.* 2009).

Climate change is also predicted to have a significant impact on levels of contaminants and their effects on wildlife. Contaminants may become more mobile in the Arctic environment with climate change. For example, mercury is expected to increase in the Mackenzie River with increased discharge rates (Leitch *et al.* 2007) and with increases in primary productivity associated with warmer temperatures and less ice cover (Carrie *et al.* 2010). Similarly, climate change is expected to release contaminants accumulated in ice sheets, glaciers and permafrost that are now melting and thawing (Callaghan *et al.* 2011b, Kallenborn *et al.* 2011, UNEP/AMAP 2011).

Possible conservation actions

- Sufficient efforts to reduce global greenhouse gas emissions, and thereby human-induced climate change, are needed if the threat of climate change is to be addressed. Continued warming is overwhelmingly the most serious predicted threat to Arctic biodiversity, as it will fundamentally alter Arctic biodiversity at the habitat, species and ecosystem level. In fact, the global goal that world leaders have set for climate change mitigation, i.e. 2 °C (UNFCCC 2010), may not be adequate to protect Arctic biodiversity since the Arctic is warming twice as fast as the global average. Mechanisms to address climate change are presented by IPCC (2007b), UNEP *et al.* (2011) and elsewhere, recognizing that urgent and far-reaching global actions are required to address this problem that has worldwide causes and world-

With the acidification expected in Arctic waters, populations of a key Arctic pelagic mollusc – such as the pteropod *Limacina helicina* – can be severely threatened due to hampering of the calcification processes. The Greenlandic name, Tulukkaasaq (the one that looks like a raven) refers to the winged 'flight' of this abundant small black sea snail. Photo: Kevin Lee.

wide impacts.[21] This assessment provides additional evidence pointing to the urgency of addressing this issue.

› The reduction of black carbon emissions is a high priority, since a reduction in the emissions of black carbon (and tropospheric ozone) is the fastest way to reduce the 'polar amplification' of global warming in the Arctic (Lenton 2012).

› High priority for conservation planning should be given to the protection of networks of large, representative tracts of habitat. This should include northern 'refugia' areas to support and maintain the resilience of Arctic ecosystems, such as Arctic islands and mountainous areas together with the remaining multi-year sea ice areas, where unique Arctic biodiversity has the best chance of surviving climate change.

› Furthermore, the reduction or minimization of all other stressors to biodiversity will help mitigate the effects of climate change (IPCC 2007c).

5.2.2. Pollutants originating outside the Arctic

Aside from the climate drivers dealt with in Section 5.2.1., the most important pollutants reaching the Arctic from southern countries are:

- Environmental contaminants which are persistent, bio-accumulative and subject to atmospheric or oceanic long-range transport.
- Aerosols causing ozone depletion and thereby increased UV radiation potentially harming living organisms.

In addition, atmospheric deposition of nitrate (a plant nutrient) brought to the Arctic from southern sources, which currently is at relatively low levels in the Arctic, can be expected to increase in the future (Callaghan 2005).

Most bio-accumulating contaminants found in the Arctic originate from industrialized areas in Eurasia and North America and are brought into the Arctic by atmospheric and ocean currents (AMAP 2010, 2011b). Bio-magnification takes place through food webs, resulting in the highest concentrations found in apex predators (and scavengers) including humans (Reid *et al.*, Chapter 3).

Significant levels of contaminants (heavy metals, organochlorines, brominated flame retardants, etc.) have been documented in several Arctic animals, but so far, there is little scientific evidence that contaminants have reached such levels that they have resulted in reduced populations. Exceptions to this may be glaucous gulls *Larus hyperboreus* on Bjørnoya, Svalbard (Verreault *et al.* 2010) and ivory gulls in Canada (Ganter & Gaston, Chapter 4; see also Miljeteig *et al.* 2012) together with marine benthic invertebrate species in areas with mine tailings (Josefson & Mokievsky, Chapter 8). In a number of other species the levels are high enough that detrimental effects to individuals may occur (Letcher *et al.* 2010, Dietz *et al.* 2013). However, some toxic contaminants such as the legacy POPs are declining across much of the Arctic (AMAP 2009c, Rigét *et al.* 2010, 2013), most likely as a result of international regulation of emissions, such as the Stockholm Convention on POPs, which was influenced by Arctic Council assessments under AMAP (e.g. Downie & Fenge 2003).

21 Unless carbon capture and storage (CCS) becomes economically realistic, these actions include that CO_2 from "less than half the proven economically recoverable oil, gas and coal reserves can (…) be emitted up to 2050", if the maximum increase of 2 °C is to be achieved (Meinshausen *et al.* 2009).

In contrast, the Arctic is a major sink for tropospheric mercury derived largely from industrial sources (e.g. coal combustion) (Ariya *et al.* 2004) and freshwater run-off, and mercury concentrations in marine animals are stable or increasing in the Canadian Arctic and W Greenland (Braune *et al.* 2005, Niemi *et al.* 2010, AMAP 2011b). A variety of recently emerging, but poorly studied, contaminants, such as polybrominated diphenyl ethers (PBDEs), are also increasing (Braune *et al.* 2005). See further in Section 5.1.4.

Carbon dioxide also has serious effects on the acidity of the oceans and thereby living conditions for calcareous organisms and maybe even fish (AMAP 2013, Christiansen & Reist, Chapter 6, Josefson & Mokievsky, Chapter 8, Lovejoy, Chapter 11, Michel, Chapter 14). These organisms (mollusks, echinoderms, etc.) are likely already under stress due to low temperatures because the cost of calcification varies inversely with temperature (Clarke 1992). Increasing temperature and acidification could mean that one stress factor is substituted by another, but whether or not they will balance is difficult to say. Furthermore, the solubility of gases, including CO_2, is higher in colder waters than warm waters, so that the Arctic Ocean is especially prone to harmful effects of acidification (Bates & Mathis 2009, Carmack & McLaughlin 2011, Lovejoy, Chapter 11). Global ocean acidification is now occurring at a pace likely unsurpassed over the past 55 million years, and regions of the Arctic Ocean are already showing the effects of acidification (AMAP 2013). The pteropods such as *Limacina helicina*, an important plankton species found in the top layers of the Arctic Ocean, appear to be particularly at risk (Comeau *et al.* 2011, Michel, Chapter 14). This may have serious negative effects including cascading effects on commercially harvested fish populations in some of the richest fishing regions on Earth.

Increased UV radiation due to ozone-depleting substances emitted to the atmosphere has negative consequences for plants (Newsham & Robinson 2009) and potentially to other living organisms in the Arctic as well (Wrona & Reist, Chapter 13).

Possible conservation actions

- Efforts to identify and assess emerging contaminants that may pose a threat to Arctic biodiversity should continue, combined with implementation of appropriate control mechanisms to limit their input into the Arctic.
- The successful international efforts already made to ban the most problematic substances should continue, and could be expanded to limit the discharge of the rest.
- Enhanced integrated, multi-disciplinary research and monitoring could be established to improve our understanding of the fate, distribution and effects

Given the number and size of northward flowing rivers in the Arctic and the significance of freshwater and diadromous fish species to both ecosystems and people in the area, cumulative impacts of bioaccumulating contaminants represent real and present threats (Christiansen & Reist, Chapter 6). Anadromous (sea-run) male northern Dolly Varden *Salvelinus malma malma* from the Babbage River, Yukon Territory, Canada in pre-spawning coloration. Photo: Neil Mochnacz, Fisheries and Oceans Canada.

of contaminants on biota and on ecosystem structure and function, including achieving an improved mechanistic understanding of interactions with other relevant environmental stressors (e.g. climate variability/change) and cumulative effects.

5.2.3. Invasive species

In this assessment, invasive species are defined as alien species intentionally or unintentionally introduced by humans that are likely to cause environmental or economic harm or harm to human health. This includes invasive species that have expanded north after being originally introduced by humans to sub-Arctic ecosystems. The range expansions of species native to the sub-Arctic are not considered 'invasive' in the strict sense used here, although many may cause the same negative impacts.

Next to habitat loss and modification, invasive species are globally considered the most significant threat to biodiversity (Vitousek *et al.* 1997, Clavero & Garcia-Berthou 2005, IUCN 2012), but to date this problem is less acute in the Arctic than elsewhere. However, some well-known examples of alien invasive species with serious effects in near-Arctic areas are American mink *Mustela vison* introduced for the fur trade into some areas in northern Europe and now found over Iceland, Finland and Norway, together with Nootka lupin in Iceland and Pacific red king crab in the Barents Sea (Lassuy & Lewis, Chapter 16).

Many terrestrial alien species already invasive in sub-Arctic ecosystems may move northward facilitated by climate change, human settlement and industrial activity. Some of these are likely to be 'human commensals' benefiting from increased human waste in the Arctic and function as new predators possibly impacting Arctic wildlife (Ims & Ehrich, Chapter 12). A warming Arctic has already facilitated a sharp increase in shipping and energy exploration activity, which directly increases the risk of biological invasions from species borne through pathways and vectors such as ballast water, hull or rig fouling, and associated shore-based developments such as ports, roads and pipelines (Lassuy & Lewis, Chapter 16). Furthermore, it is anticipated that northward expansion and range shifts for complex assemblages of parasites among terrestrial, freshwater and marine vertebrates will result in new faunal associations, a changing spectrum of hosts and varying impacts at landscape to regional scales (Hoberg & Kutz, Chapter 15). Pathogens and disease vectors, too, may invade or arrive with invasive alien species.

Examples of such invasive species in the sub-Arctic include several introductions (i.e. intentional translocations) of freshwater and diadromous fishes in Norway and the White Sea in Russia that may be relevant to the Arctic in the future (Christiansen & Reist, Chapter 6 and references therein). These include both introductions of alien species (e.g. pink salmon *Oncorhynchus gorbuscha*) to areas well outside their geographic range and also to relocation of species (e.g. European whitefish *Coregonus lavaretus*, vendace *Coregonus albula*) to new drainages adjacent to their native ranges. Initial intentions of such translocations are typically to increase local fishery or aquaculture opportunities. However, the effects are usually detrimental in that increased competition or predation occurs on native fish species often resulting in displacement or extirpation from the area.

Possible conservation actions

- Cost-effective early detection monitoring networks for invasive alien species linked to a common repository would facilitate immediate and thereby effective response.

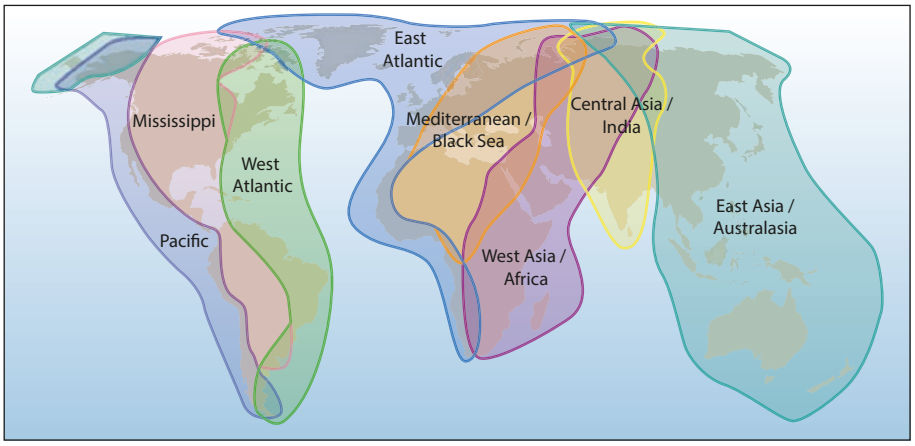


Figure 17. Major flyways of Arctic birds. Bird migration links Arctic breeding areas to all other parts of the globe (from ACIA 2005).

- Preventative approaches that block pathways of invasive species introduction are important to implement at both the national and international levels.[22]

- Expanded inventory efforts at points of entry into the Arctic (e.g. roads, airports and harbors) are needed to enhance rapid response capabilities to eradicate introductions such as rats on seabird islands early in the invasion process.

- For marine species, support for ongoing international efforts to reduce the risk of introducing alien species such as ballast water treatment and the effective cleaning and treatment of ship hulls and drilling rigs brought in from other marine ecosystems is important.

22 This could include more consistent use of basic prevention tools such as Hazard Analysis and Critical Control Points (HACCP) planning (ASTM 2009), which has been used effectively in animal and plant farming operations and is applicable to a wide range of operations.

5.2.4. Stressors on migratory species

The Arctic holds a high proportion of migratory species, and many of them spend more than half the year outside the Arctic (Fig. 17). The most serious threats to Arctic migratory species when outside the Arctic are habitat loss and degradation (Ganter & Gaston, Chapter 4). This is particularly evident for many waterfowl and shorebirds, for which losses of staging and wintering habitat (wetlands such as marshes and intertidal flats) are occurring at an alarming rate, especially in East Asia around the Yellow Sea (Syroechkovski 2006, Wetlands International 2012, MacKinnon *et al.* 2012), but also in other parts of the world. Furthermore, loss of coastal and intertidal habitat can be expected to increase considerably with climate-induced sea level rise, since man-made infrastructure such as seawalls precludes landwards displacement of these habitats. This effect will be compounded by increasing coastal development.

In addition, excessive harvest takes place in some places, particularly in East Asia. Conversely, regulation

of hunting in the form of shortened shooting seasons, improved reserve networks and limitations to harvest technology (bans on netting and trapping, limits to weapon capacity etc.) have caused several waterfowl population in the western Palearctic and North America to increase during the last half century (Ely & Dzubin 1994, Madsen *et al.* 1999, Mowbray *et al.* 2002, Alisauskas *et al.* 2009, Meltofte & Clausen 2011, Wetlands International 2012).

As mentioned above, overharvest has even led to the probable extermination of the Eskimo curlew and near extinction of the spoon-billed sandpiper (Ganter & Gaston, Chapter 4). Similarly, overfishing of Atlantic horseshoe crabs *Limulus polyphemus* at the final migration stop-over site in Delaware Bay has reduced the availability of crab eggs as prey for spring staging red knots *Calidris canutus rufa* on the American East Coast, thereby caused heavy reductions in the population. The Siberian crane *Leucogeranus leucogeranus* is one of the East Asian species suffering heavy population decline as a result of habitat loss and overharvest in combination with displacement from many potential staging and wintering areas due to human disturbance including hunting. The East Asian great knot *Calidris tenuirostris* population is also suspected to have suffered from loss of staging areas around the Yellow Sea (Moores *et al.* 2008).

For seabirds, the threat from oil spills (see Section 5.1.4) is at least as big outside the Arctic as inside. Millions of Arctic seabirds including seaducks winter in waters that carry a heavy traffic of oil tankers and ships in general such as the Baltic Sea and the waters off Newfoundland, where accidental as well as (illegal) intentional discharge of oil are a major concern (Wiese & Robertson 2004, Skov *et al.* 2011).

Recent rapid population increases of a number of goose species in the Arctic and sub-Arctic, caused by better feeding conditions in temperate wintering areas and made possible by improved protection of the geese both on the breeding grounds and during staging and wintering, have created 'overabundance', which is affecting their Arctic habitats (see Ganter & Gaston, Chapter 4 and Ims & Ehrich, Chapter 12). Although relatively limited in geographical extent, this has resulted in the degradation of sensitive marshland vegetation in some Arctic regions (e.g. around southwestern Hudson and James Bays in Canada (Batt 1997). Attempts have been made to reduce the lesser snow goose *Chen caerulescens* population by increased hunting on the staging and wintering grounds, but with limited success (Alisauskas *et al.* 2011). Similarly, a management plan for preventing the Svalbard population of pink-footed geese *Anser brachyrhynchus* from further increase is under development among the range states (AEWA 2012).

Other stressors include contamination with organochlorine pesticides of apex predators such as peregrine falcon *Falco peregrinus* during wintering in temperate and tropical areas resulting in reduced breeding success, although this problem has receded for most populations (Ganter & Gaston, Chapter 4). Also, although lead poisoning of wildlife as a result of ingestion of lead shot appears to be in decline at least in northern Europe and North America following national bans on lead shot for waterfowl hunting, it is still in use for hunting of some other species in many countries (Anderson *et al.* 2000, UNEP/AEWA 2008).

Most caribou/reindeer herds around the Arctic undertake extensive seasonal migrations with winter ranges often quite disjunct from calving and summer ranges. Calving grounds, and often the travel routes, are well defined and can receive site-specific conservation atten-

tion. Seasonal ranges could, however, decline in carrying capacity when caribou experience disturbance, barriers to movement and habitat modifications, resulting in reductions in survival (through facilitated predation and hunting) and reductions in productivity (through habitat alienation, displacement and changes in energy budgets). Climate change is a threat to caribou migration where herds cross sea-ice bridges at times of increasing ice melt. These risks will be compounded by an increase in commercial shipping (Poole *et al.* 2010). Industrial developments and landscape alterations also have the potential to alter caribou migration corridors.

Similar problems may exist but be limited in scope for whale and fish stocks, except that the past overharvest of whales took place all over the area of occurrence of these species, and hydroelectric plants may hamper or even prevent migratory fish from moving up and down rivers. Overharvest of migratory populations of diadromous fishes may occur when both harvested while at sea (e.g. Pacific salmon species) and upon their return to fresh waters to overwinter and reproduce (e.g. chars, whitefishes, Atlantic salmon *Salmo salar*) thus leading to locally significant impacts (Christiansen & Reist, Chapter 6). Managing such cumulative impacts for species exhibiting limited marine migrations in Arctic waters (i.e. chars and whitefishes) is difficult but achievable through regional cooperation. Management of species (e.g. Pacific and Atlantic salmons) exhibiting wide-ranging marine migrations outside of Arctic waters requires more complex actions.

Possible conservation actions

- Cooperation with non-Arctic states is crucial to address threats on the staging and wintering grounds of migratory species. This includes international cooperation through multi-lateral and bi-lateral agreements. One example is the Convention on the Conservation of Migratory Species of Wild Animals together with its agreements and management plans (see Scott 1998).
- Habitat loss is the most serious stressor today for most migratory birds, and hence conservation action should include conservation of wetlands and other important habitats for staging and wintering Arctic birds.
- Overharvest and poisoning of birds by lead shot should be reduced where these are still a problem.
- To protect Arctic seabirds from oil spills on their staging and wintering grounds, it is important that Arctic nations continue efforts to reduce this risk.
- For endangered species, such as the spoon-billed sandpiper, international recovery programs need to be developed and implemented (see also Section 5.1.2 and Tab. 1).
- Caribou/reindeer migrations could be facilitated by protecting calving grounds and major travel routes (see Section 5.1.3).
- Regulation of the take of fish and whale stocks through existing international agreements should be supported, adhered to and further developed in accordance with the best scientific advice.
- The large goose numbers established during the last half century need to be carefully monitored. Where not already existing, management plans could be developed, implemented and followed up in co-operation between range states of the populations involved.

6. KNOWLEDGE GAPS

Basic knowledge on the vast majority of Arctic biodiversity is limited. Often, only the distribution of mammals, birds and vascular plants is sufficiently documented. Comprehensive data for abundance, population densities and trends are generally available only for vertebrates considered to be of direct significance to people, for example for commercial or other harvest, and for many taxa even the taxonomic status is incomplete. Thus, substantial gaps in biodiversity knowledge are apparent, and a more synoptic approach is necessary to:

- Address critical gaps contributing to a fundamental and functional understanding of diversity as a basis for recognizing and predicting the effects of accelerating change driven by climate and other disturbances.
- Improve understanding of diversity (from species to populations) and interactions of vertebrates, invertebrates and microorganisms that collectively form the web of relationships within northern marine, freshwater and terrestrial systems.
- Improve understanding of the functioning of Arctic ecosystems as to provide a scientifically sound basis for ecosystem-based management.
- Build requisite knowledge that supports ecosystem sustainability and paths for mitigation and adaptation within Arctic societies responding to rapid change and increasing threats to food security.

There is an enormous deficit in our knowledge of species richness in many groups of organisms in the Arctic, and monitoring here is lagging far behind that in other regions of the world. Even for the better-studied Arctic species and ecosystems we have insufficient data on trends in distribution, abundance and phenology. Photo: Orsolya Haarberg/naturepl.com

The causes of some data gaps are found worldwide, whereas others emerge from factors more special for the Arctic, such as remote and harsh environments, challenging logistics and the dearth of permanent infrastructure for science. Extreme and difficult conditions increasingly converge with the continuing global decline in scientists with appropriate expertise to provide authoritative identifications as a basis for biodiversity survey, inventory and monitoring activities.

Specimen archives, both spatially broad and temporally deep extending into the Quaternary, must be developed in conjunction with permanent museum repositories holding geo-referenced samples backed by web-available databases for large-scale informatics analyses across the Arctic (e.g. Christiansen & Reist, Chapter 6, Hodkinson, Chapter 7, Daniëls *et al*., Chapter 9, Dahlberg & Bültmann, Chaper 10, Hoberg & Kutz, Chapter 15, Cook, Chapter 17). International cooperative agreements and participation by local communities are essential to efficiently build this high-latitude resource. In the absence of such resources as the functional basis for information systems, rapid and real-time progress

The marine Arctic is particularly little studied and monitored. Bowhead whales surfacing amongst melting ice with black guillemots resting on ice. Foxe Basin, Nunavut, Canada, July. Photo: Eric Baccega/naturepl.com

in developing a broad view of Arctic biodiversity is not possible. Specimen archives assembled over years and decades constitute essential baselines for documenting and assessing the causes of spatial and temporal change in northern systems, and they provide pathways to employ new and expanding analytical approaches to assess diversity.

A profound challenge to our understanding of Arctic ecosystem functioning and our capacity to perform ecosystem-based management, is the very few dedicated programs and research stations that maintain fully integrated ecosystem-based approaches to research and monitoring in the Arctic. Regularly repeated measurements according to sampling design that both targets specific hypothesis and allows for detection of surprises (Lindenmayer *et al.* 2010) are essential to monitor changes in community composition and structure, diversity, productivity, phenology and other critical aspects of biodiversity and ecosystem integrity. Further, knowledge about the effects of the range of drivers and stressors on Arctic biodiversity is basic to its management. In support of biodiversity assessment on the ground, remote sensing from satellites and aircraft can provide temporally and spatially replicated data essential for monitoring, with remarkable speed and cost-effectiveness.

Integrated data resources for archives (collections of specimens, survey, inventory and monitoring) along with field observations and census across circumpolar regions must be developed and coordinated. A potential model is seen in the Circumpolar Biodiversity Monitoring Program (CBMP), although this and similar resources must be explicitly tied to specimens, hard data and authoritative identifications to document current and changing ecological conditions (see Box 5).

In synergy, these form the foundations for comprehensive ecosystem-based approaches to research and monitoring that can reveal how biodiversity may be affected by stressors and disturbances that cascade though food webs. However, this requires more emphasis than present on ecosystem level integration through all stages of science-based inferences from sampling, through data management, statistical modeling and interpretation of empirical results.

Similarly, the International Study of Arctic Change (ISAC) formed by the International Arctic Science Committee (IASC) and the Arctic Ocean Science Board (AOSB) recommends increased efforts to understand and model the physical and biological interactions governing Arctic ecosystems and their relation to Arctic peoples and the rest of the globe (Murray *et al.* 2010).

The traditional knowledge of indigenous Arctic peoples contains a wealth of information on the uses of Arctic organisms including present and historic locations of fish spawning grounds, phenological events, etc., often indicated by place names. Several initiatives have been undertaken to better engage traditional knowledge and to reduce conflicts between local hunters and fishermen and government authorities devising regulations (Freese 2000, Klein 2005). One example is the co-management program *Opening Doors to Native Knowledge* in Greenland (Huntington *et al.*, Chapter 19). Improved knowledge of the conditions and actions that foster such collaboration and mutual understanding will help in the design and implementation of local conservation programs.

Commercial bioprospecting of organisms is already underway in Arctic ecosystems, particularly the marine environment, and coordinated careful consideration is needed to balance community and commercial interests (Leary 2008). The potential of the genetic resources present in the Arctic remains poorly understood, however, making it difficult to assess their value in this regard.

From the perspective of scientists, lack of information for particular areas can hamper acquisition of open and unbiased analysis and make accurate conclusions and predictions very difficult. Therefore, possibilities for acquisition, cooperation and sharing of data from all parts of the Arctic are important for scientific analysis as well as for resource management.

Possible actions

Detailed suggestions for filling specific knowledge gaps are provided in the various chapters of this assessment. Here, we describe why major categories of knowledge gaps must be filled, urgently and to the best of our collective ability. A great deal is known about Arctic biodiversity, as demonstrated by the depth and detail of the chapters of this assessment, and the need for vigorous and prompt conservation action is strongly supported by current knowledge. At the same time, much remains to be learned, which will help design and carry out more specific and effective conservation measures in the context of rapid change and increasing industrial development in the Arctic.

- The lack of basic knowledge about many aspects of Arctic biodiversity hampers our ability to evaluate the effectiveness of conservation actions. The threat of overharvest has been greatly reduced in the Arctic in part because sufficient knowledge exists to develop effective conservation measures and to build support for those actions. This success applies, however, only to a relatively few harvested species. Other conservation measures make up for a lack of specific knowledge with a broad approach, as is the case with protection of large areas of habitat. A comprehensive approach to gathering data about species and ecosystems is needed to better understand how environmental change and changes in human activity will affect Arctic biodiversity and the conservation thereof.

- The lack of monitoring and modeling capability for many aspects of Arctic biodiversity and their drivers of change makes it difficult to assess change, its cause and its implications, and what could be rational conservation actions. Change cannot be measured without a baseline. For many species and ecosystem processes, that baseline of knowledge does not exist. Similarly, modeling efforts have focused on the physical environment and a few key species or ecosystem parameters. A coordinated ecosystem-level oriented monitoring and modeling effort is needed to support biodiversity conservation efforts in a time of rapid change.

- The lack of specimens and museum collections means that a firm foundation for assessing biodiversity and changes thereto is missing. A solid baseline requires hard data and definitive specimens. This area has received insufficient attention to date. A collaborative approach to collection and archiving of specimens could help ensure that further change can be assessed and quantified.

- A great deal of research has been done on various aspects of Arctic biodiversity, but overall databases and knowledge bases do not exist for most topics. The circumpolar study of Arctic biodiversity is further hindered by barriers to the access of field sites. Broad support for open science, from field work to analysis to archives, would help address this issue and provide a means to pool collective knowledge and expertise.

- The shortage of trained professionals in appropriate fields related to biodiversity means that filling knowledge gaps will remain a challenge. Too few scientists are available to work on many aspects of biodiversity, from taxonomy and systematics to integrative problem solving at the ecosystem level. Greater efforts could be made to recruit and support specialists in these fields, so that needed knowledge can be generated in a timely fashion to support conservation of Arctic biodiversity.

- The lack of awareness of most aspects of Arctic biodiversity, combined with the limited degree to which Arctic residents are involved in biodiversity research and conservation, reduces public and political support for important conservation actions. Charismatic species get a great deal of attention, which can help support species-oriented conservation measures. A commitment to conserving overall biodiversity as a vital legacy for all of humankind, however, will require broader public understanding of what is at stake, and broader participation in generating information and solutions.

7. SUGGESTED CONSERVATION AND RESEARCH PRIORITIES

The erosion of global biodiversity is not the only global crisis of our time. It has been argued that changes in climate, biodiversity, infectious diseases, energy supplies, food, freshwater, human population and the global financial system are part of one contemporary global challenge, and that they need to be addressed as such (Steffen *et al.* 2011). If this is not done in an integrated and sustainable way, efforts to address one challenge may very well worsen one or more of the others considerably. Also, global markets seek the exploitation of Arctic resources, resulting in greater interconnections between the Arctic and the rest of the world.

To safeguard Arctic biodiversity and the services we receive from it, three spatial levels of stressors must be addressed: (1) global and circumpolar stressors like climate change and long-range transport of contaminants by air and sea water, (2) regional stressors like overexploitation, expanding boreal and invasive alien species, and (3) more 'localized' stressors like mineral extraction, oil development and ship accidents. Here we provide a set of suggested priorities for actions defined according to these three geographical scales. These priorities flow from the suggested actions in the technical chapters and this synthesis. They are intended to provide guidance to CAFF in development of recommendations from this report.

Arctic seals are closely associated with sea ice, and the accelerating loss of this habitat will have severe impacts on the living conditions of both biodiversity and people in the Arctic. Bearded seals. Photo: Steven Kazlowski/naturepl.com

The alleviation of stressors with circumpolar effects on species and ecosystems generally requires international cooperation for effective management (Steffen *et al.* 2011).[23]

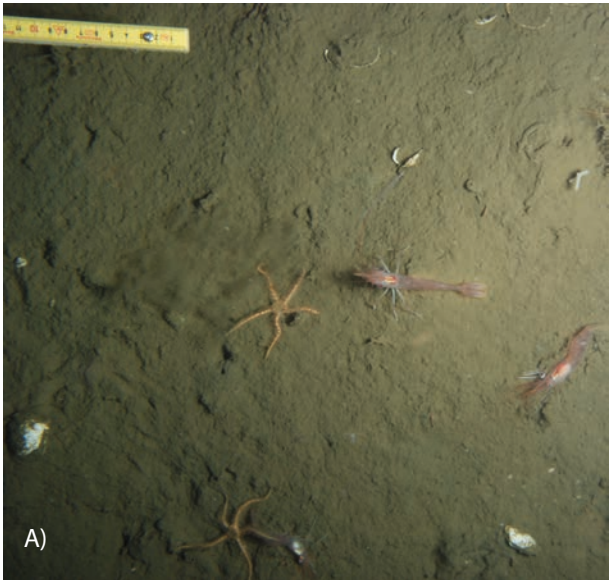
- Conserving the unique Arctic biome will require all possible efforts to curb human-induced global warming.
- Global and regional actions to reduce both legacy and new environmental contaminants entering Arctic ecosystems should continue and, where necessary, intensify under existing international conventions.
- Effective conservation of Arctic biodiversity needs to be global in scope and requires significant international cooperation to succeed. Any action to solve one global challenge should take others into account so that measures to solve one stressor do not worsen others.

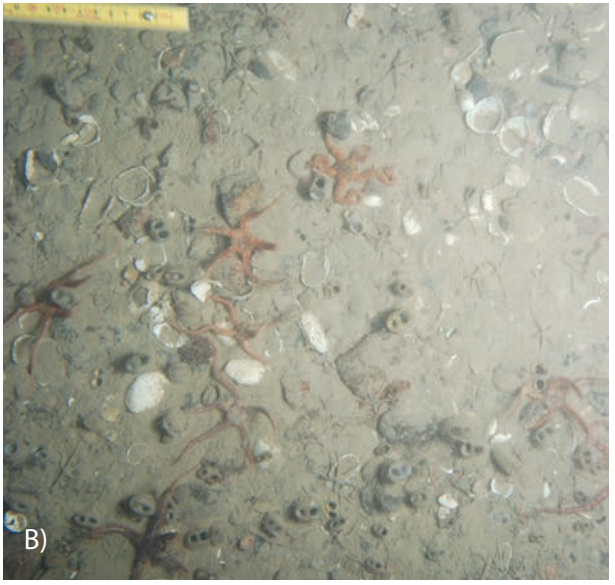
Since many fish, birds and mammals move between different regional and national jurisdictions, management can benefit from regional cooperation.

- To maximize the resilience of Arctic ecosystems, effective protection of large representative tracts of habitat, including hotspots for unique Arctic biodiversity and northern 'refugia' areas, is of paramount importance. This includes Arctic islands together with mountainous areas and multi-year sea-ice refuges, where unique marine Arctic biodiversity has the best chance of surviving climate change.
- A major oil spill in ice filled Arctic waters would be detrimental to biodiversity and very difficult to clean up, particularly under problematic weather, light and ice conditions. However, if oil development is undertaken, a precautionary approach adhering to regulations and guidelines specific to the Arctic and based on the best available science would reduce risks, including that development activities in the most sensitive areas are avoided.
- Focused harvest management of fish, birds and mammals is needed on those species and populations that have experienced major declines for which harvest is one of the causal factors (see Section 5.1.2).
- To protect staging and wintering wetland areas for Arctic waterbird migrants from both habitat loss and overharvest, concerted international efforts should be conducted to conserve a network of key areas and address overharvest.
- To effectively protect Arctic native species and ecosystems from devastating effects of invasive alien species, appropriate efforts are needed to prevent their establishment in the Arctic. Early detection and preventative actions should focus on areas of human activity and disturbance.

In the marine Arctic, protected areas are nearly nonexistent, and regionally ocean bottom trawling and non-renewable resource development pose serious challenges to Arctic marine biodiversity. Photographs of the sea floor from eastern Baffin Bay in W Greenland, showing different benthic habitats.
(A) soft mud, (B) soft sediment with shells and stones, (C) gravelly bottom and (D) boulder bottom (from Sejr *et al.* 2011).

23 See e.g. Johnsen *et al.* (2010) for overview and discussion of international agreements relevant to the Arctic, their coverage among Arctic states and their efficiency.


A)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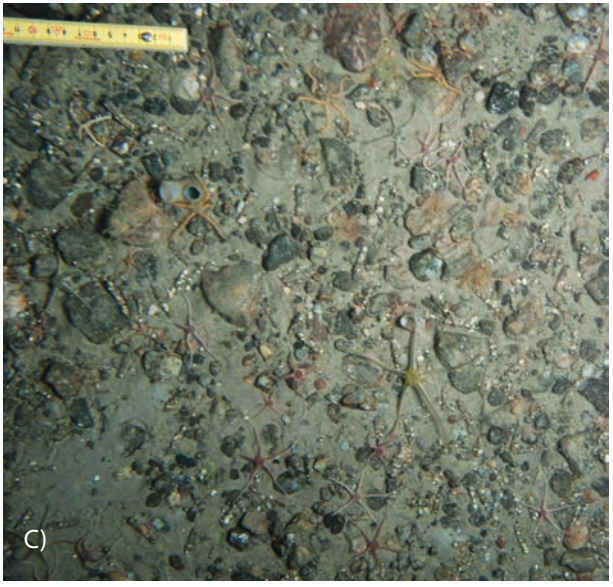
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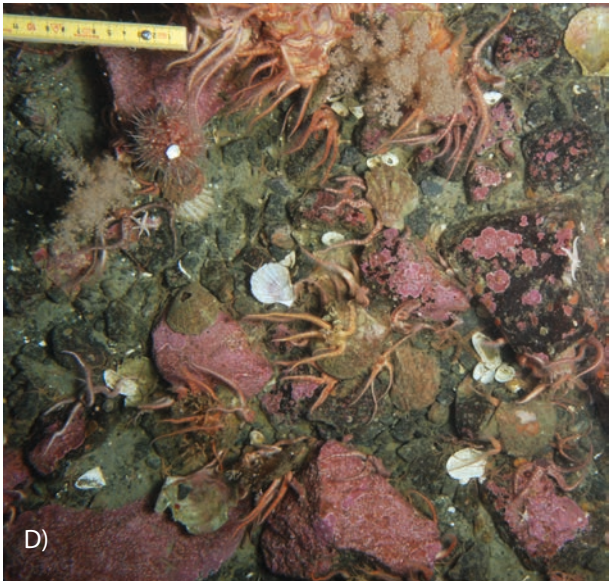
D)

Sabine's gull is a scarce breeder in much of the Arctic, from where it migrates to the southern hemisphere shelf seas to winter. Photo: Ryan Askren Wildlife and Nature Photography.

Although local stressors can entirely be managed by national or local authorities, bilateral or international cooperation on common standards can be beneficial.

- To protect Arctic biodiversity from severe impacts from local development and industrial activity, biodiversity conservation needs to be a cornerstone of natural resource management and land and marine planning.

- Improved monitoring and research is needed to survey, map, and monitor and understand Arctic biodiversity including integrated, repeated data collection following recommended standardized protocols and priorities, and involving Arctic citizens in the survey and monitoring, if we are to move ahead with science-informed decisions in the Arctic. Support for national and international coordinated efforts such as the CBMP and the BAR Code of Life is important to fill critical data gaps on population abundances and trends for many Arctic terrestrial and marine species as well as on changes in the functioning and services of Arctic ecosystems.

In order to effectively respond to these suggested priorities, international cooperation and direct action at the national level are required. Many such efforts are already underway, and the Arctic countries possess strong legal frameworks that can form the basis for effective conservation of Arctic biodiversity. The Arctic Council has also established mechanisms for regional cooperation and scientific collaboration on research and monitoring e.g. the CBMP. Nevertheless, such agreements and initiatives are of little use if not backed up by secure long-term funding, enforcement and popular support.

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The eyes of the world are turning northwards. In recent years, interest in the Arctic has increased dramatically within and outside of Arctic countries. This is reflected in the amount of attention given to Arctic biodiversity. While the landscapes and wildlife have been the subject of explorers, scientists, artists and photographers as well as the home of a variety of peoples for a long time, until recently Arctic biodiversity did not feature very prominently in national or international policy work. This, however, is changing, as the unique values of Arctic nature are increasingly discussed at high levels. At the same time, more and more attention has been paid to the interface between science and policy to ensure that policy is built on the best science available.

Biodiversity is life. It is the very foundation of our existence on Earth. In the Arctic, links between biodiversity and traditional ways of life are often seen more clearly than in many other parts of the world. These are examples of ecosystem services, the benefits that we receive from nature. Many ecosystems and ecosystem functions in the Arctic remain largely unstudied and involve little-known organisms, especially microbes. The Arctic Biodiversity Assessment presents current knowledge also on these processes and organisms and thus provides a base for further work.

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