Chapter 10

Principles of Conserving the Arctic's Biodiversity

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Summary

Biodiversity is fundamental to the livelihoods of arctic people. The Convention on Biological Diversity defines biodiversity as "the variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are a part: this includes diversity within species, between species and of ecosystems". A changing climate can affect all three levels of biodiversity. There are many predicted influences of climate change on the Arctic's biodiversity. These include (1) changes in the distribution ranges of species and habitats; (2) changes in the extent of many habitats; (3) changes in the abundance of species; (4) changes in genetic diversity; (5) changes in the behavior of migratory species; (6) some non-native species becoming problematic; and (7) the need for protected areas to be managed in different ways.

What should be done now before the anticipated changes occur? First, it is important to document the current state of the Arctic's biodiversity. Local inventories of biodiversity have generally not been carried out, although the inventory for Svalbard is a striking exception, recording both native and non-native species in both terrestrial and marine environments. Such work requires trained ecologists, trained taxonomists, circumpolar knowledge, and a focus on all three levels of biodiversity (genes, species, and ecosystems). Second, the changes that take place in the Arctic's biodiversity need to be identified. Management of the Arctic's biodiversity, in the sea, in freshwater, or on land, must work with ecological succession and not against it. Considerably more effort needs to be invested in developing predictive models that can explore changes in biodiversity under the various scenarios of climate change. Third, changes in the Arctic's biodiversity need to be recorded and the data shared. In a situation where so much uncertainty surrounds the conservation of biodiversity, knowledge of what has changed, where it has changed, and how quickly it has changed becomes critically important. Monitoring biodiversity, especially on a circumpolar basis, must be a goal, and a circumpolar monitoring network needs to be fully implemented so as to determine how the state of biodiversity is changing, what the drivers of change are, and how other species and people respond. Finally, new approaches to managing the Arctic's biodiversity need to be explored. Best practice guidelines should be available on a circumpolar basis. The Circumpolar Protected Area Network needs to be completed and reviewed so as to ensure that it does actually cover the full range of the Arctic's present biodiversity. An assessment needs to be made, for each protected area, of the likely effects of climate change, and in the light of this assessment the methods of management for the future. This poses questions of resources and priorities, but it is essential that the Arctic's ecosystems continue to exist and function in a way that such services as photosynthesis, decomposition, and purification of pollutants continue in a sustained manner.

10.1. Introduction

Arctic peoples obtain their primary source of food and many of the materials used in clothing and building from the plant and animal species indigenous to the Arctic. These species range from mammals, fish, and birds, to berries and trees. However, the relationship between arctic people and those arctic species upon which they depend is not simple since each of these species is in turn dependent on a range of other arctic species and on the ecological processes operating within the arctic ecosystems. The biological diversity of the arctic environment is thus fundamental to the livelihoods of arctic peoples. Relevant information from indigenous peoples on arctic biodiversity is given in Chapter 3.

The two major processes operating within ecosystems are photosynthesis and decomposition. Photosynthesis is the biochemical process whereby radiant energy from the sun is used to synthesize carbohydrates from carbon dioxide (CO_2) and water in the presence of chlorophyll. The energy fixed during photosynthesis is transferred from the primary producers through successive trophic levels by feeding and thus starts the food chains and food webs upon which all animal life depends. The organisms responsible are green plants – predominantly vascular plants in the terrestrial environment and algae in the freshwater and marine environments. The vascular plants, which include all flowering plants and ferns, are relatively well-known taxonomically and feature in most books on the terrestrial environment of the Arctic (e.g., CAFF, 2001; Sage, 1986). The non-vascular plants such as the mosses, liverworts, and lichens are less well-known taxonomically. The algae are taxonomically the least well-known plants of the Arctic; most are single-celled and many have a wide distribution range within the northern hemisphere (John et al., 2002).

Decomposition is the process whereby dead plant and animal material is broken down into simple organic and inorganic compounds, with a consequent release of energy. The carbon is released back into the atmosphere as CO_2, and nutrients such as nitrogen, phosphorus, and potassium are available for recycling. Decomposition processes are undertaken by an enormous range of organisms in soils and in aquatic sediments. These organisms include bacteria, actinomycetes, fungi, protozoa, nematodes, worms (especially enchytraeid worms), mollusks, insects (especially collembolans – springtails, and dipteran larvae – flies), crustaceans, and arachnids (especially mites). Species richness can be outstanding, with up to 2000 species within a square meter of grassland soil (Usher, 1996), which has led to soil being considered "the poor man's tropical rain forest". However, many of the species in soils and sediments are unknown and undescribed, and their roles in the soil or sediment ecosystem, and in the processes of decomposition, are very poorly understood. This means that, within a changing climate, there are many questions about the decomposition process that need addressing (Heal, 1999).

In addition to photosynthesis and decomposition, there are many other important ecological processes operating within arctic ecosystems, for example: pollutant breakdown and detoxification, the purification of water, the release of oxygen, and nutrient recycling.

The major ecosystems of the Arctic, and their biological diversity, are addressed in detail in other chapters: Chapter 7 addresses the terrestrial environment, focusing on the tundra and polar desert ecosystems; Chapter 8 addresses freshwater ecosystems; and Chapter 9 addresses marine systems. This chapter focuses on the principles of conserving biodiversity, exploring the ecosystems, species, and genes in the Arctic, and the threats faced in a changing environment. The starting point for this discussion is the Convention on Biological Diversity (SCBD, 2000), which states that its objectives are "… the conservation of biological diversity, the sustainable use of its components and the fair and equitable sharing of the benefits arising out of the utilization of genetic resources…" (Article 1).

The Convention on Biological Diversity defines "biological diversity" (often shortened to "biodiversity") as "the variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are a part; this includes diversity within species, between species and of ecosystems" (Article 2). This definition clearly implies that biodiversity, and both its conservation and utilization, must be viewed at three levels – the level of the gene, the species, and the ecosystem (or habitat).

A changing climate can affect all three levels of biodiversity, and Chapters 7, 8, and 9 address such issues. What the human population wishes to conserve, and the way that biodiversity conservation is practiced, will also be affected by a changing climate. The exploitation of the Arctic's biodiversity resources, and the potential for their exploitation in the future, will equally be affected, and these topics are considered in greater detail in Chapter 11 (wildlife conservation and management), 12 (hunting, herding, fishing, and gathering by indigenous peoples), 13 (marine fisheries and aquaculture), and 14 (forests and agriculture). The present chapter deals primarily with the first two tenets of the Convention on Biological Diversity, namely the conservation of biodiversity and its sustainable use by the peoples of the Arctic. The first involves all aspects of the Arctic's wildlife, from the smallest organisms (viruses, bacteria, and protozoa) to the largest plants and animals. The latter invokes the concept of stewardship: stewardship implies a sustainable form of management rather than the preservation of species and ecosystems without change. Climate change will result in changes in the productivity of ecosystems through photosynthesis and changes in the rates of decomposition. The balance between these two major processes will, to a large extent, determine the future nature of the arctic environment, the resources upon which arctic peoples (and

visitors) depend, and whether the Arctic exacerbates climate change by releasing greater quantities of CO_2 to the atmosphere or helps to control climate change by acting as a sink for atmospheric CO_2. Biodiversity is therefore both affected by and affects climate change.

The first two lines of approach to biodiversity conservation are often the development of lists of species and habitats to be given special protection (usually through legislation, and often on the basis of "Red Lists"), and the designation of protected areas where biodiversity conservation takes primacy over other forms of water and land use. By 1990, there had been significant achievements (IUCN, 1991) in establishing protected areas in the Arctic. Norway, Sweden, and Finland, for example, all had strict nature reserves (IUCN management category I), national parks (IUCN category II), and/or other nature reserves (IUCN category IV) within their arctic territories. In fact, the extent of these protected arctic areas is often considerably greater than the extent of equivalent protected areas further south. In Sweden, four of the seven national parks located within the Arctic are each larger than the total area of the 18 national parks south of the Arctic (Table 10.1). One of these, Abisko, has as its aim "to preserve the high Nordic mountain landscape in its natural state" (Naturvårdverket, 1988), while others have similar aims to preserve landscapes and, by implication, the biodiversity that those landscapes contain.

In 1996, Conservation of Arctic Flora and Fauna (CAFF) developed a strategy, with an associated action plan, for a Circumpolar Protected Area Network. CAFF's efforts, jointly with other international governmental and non-governmental organizations, and a range of local, regional, and national bodies, led to the establishment of nearly 400 protected areas (each greater than 10 km^2) by 2000 (CAFF, 2001). The selection process for potential protected areas has been studied in many parts of the world and tends to be a blend of science (what is most desirable to protect?) and pragmatism (what is possible to

Table 10.1. Details of the 25 national parks in Sweden (Hanneberg and Löfgren, 1998).

	Extent (ha)
National parks in the Arctic	
Abisko	7700
Muddus	50350
Padjelanta	198400
Pieljekaise	15340
Sarek	197000
Stora Sjöfallet	127800
Vadvetjåkka	2630
Average extent of the seven national parks in the Arctic	85603
Average extent of the 18 national parks south of the Arctic (range: 27 to 10440 ha)	2446

protect?), and is not always easy even with a broad measure of agreement between the public and government.

Internationally, many criteria have been proposed as a basis for selecting sites for protection and designation as nature reserves and national parks. These were reviewed by Margules and Usher (1981) and further developed by Usher (1986) into a "popularity poll" reflecting frequency of use (Table 10.2). Whereas some of these may be inappropriate in the Arctic (being better suited to the more fragmented environments of industrialized regions), the criteria ranked highest are all relevant to northern ecosystems. However, one of the difficulties of applying such criteria is that comprehensive habitat and species inventories may not exist, and so it is impossible to make meaningful comparisons or to determine the areas of greatest priority (see also section 10.5.1).

Table 10.2 essentially contains "scientific" criteria, without the socio-economic criteria necessary for assessing existing and proposed land and water use plans. So although it might be possible to establish a

Table 10.2. Criteria used for selecting areas of land or water for protection and designation as nature reserves and national parks (Usher, 1986). The 26 criteria are ranked from those most frequently used (1) to those used only once in the review of 17 published sets of criteria (19=).

Rank	Criterion or criteria
1=	• Diversity of species
	• Diversity of habitats
3=	• Naturalness
	• Rarity of species
	• Rarity of habitats
6	• Extent of habitat
7	• Threat of human interference or disturbance
8=	• Educational value
	• Representativeness
	• Amenity value for local human population
11	• Scientific value
12	• Recorded history
13=	• Size of population of species of conservation concern
	• Typicalness
15=	• Uniqueness
	• Potential value
	• Ecological fragility
	• Position in an ecological or geographical unit
19=	• Archaeological interest
	• Availability
	• Importance for migratory wildfowl
	• Ease of management
	• Replaceability
	• Silvicultural gene bank
	• Successional stage
	• Wildlife reservoir potential

range of assessments based on the scientific criteria listed in Table 10.2, to gain a balanced perspective it is also important to establish plans for land and water use and the aspirations of people living in the area. Local economies depend on the biodiversity resources, and in balancing the various criteria it is essential to include long-term views and to ensure that demands for short-term gains do not predominate. The possible effects of climate change on biodiversity also need to be included in assessments, especially effects that will be experienced over the longer term.

Thus, there are many competing pressures on the ability of an individual, group, organization, or nation to conserve the biodiversity of the Arctic. These can be summarized in six points:

- all species native to the Arctic need to be conserved (i.e., neither allowed to become extinct nor driven to extinction by human activity);
- the genetic variation within these species needs to be conserved because this ensures the greatest chance of species' adaptation to a changing environment and hence their long-term survival under a changing climate;
- the habitats of these species need to be conserved because each species is an integral part of a food web, being itself dependent on a set of other species and with a different set of species dependent upon it;
- human populations living in the Arctic are themselves an integral part of the Arctic's biodiversity and food webs;
- non-native species and external human pressures may present challenges to arctic genes, species, and ecosystems, and hence risk assessments are a vital factor in managing new pressures on the arctic environment; and
- protected areas are not a universal panacea for the conservation of the Arctic's biodiversity, but should be viewed as land and water managed for the primacy of nature in a broader geographical area where other land- and water-uses may have primacy.

CAFF (2002a) summarized these points by stating that "The overall goal of Arctic nature conservation is to ensure that Arctic ecosystems and their biodiversity remain viable and vigorous for generations to come and, therefore, able to sustain human socio-economic and cultural needs". Balancing this duality of biodiversity conservation and sustainable use, CAFF developed five strategic issues (see Table 10.3) and these are further developed throughout this chapter.

This chapter comprises four main sections. Section 10.2 provides a brief introduction to the special features of arctic ecosystems and arctic species that justify conservation attention; possible threats to the Arctic's biodiversity are considered in section 10.3. Eight issues are then addressed in relation to the management and conservation of the Arctic's biodiversity (section 10.4). The chap-

Table 10.3. The five key strategic issues facing nature conservation in the Arctic (as quoted from CAFF, 2002a).

Strategic issue	Overall goal
Conserving arctic species	*... to maintain vigorous populations of Arctic plant and animal species*
Conserving arctic ecosystems and habitats	*... to maintain and enhance ecosystem integrity in the Arctic and to avoid habitat fragmentation and degradation*
Assessing and monitoring arctic biodiversity	*... to monitor status and trends in Arctic biodiversity as an integral part of assessing the overall state of the Arctic environment*
Global issues	*... to understand and minimize the impacts of global changes and activities on Arctic biodiversity*
Engaging society	*... to promote circumpolar and global awareness of Arctic biodiversity issues*

ter concludes with an exploration of some general principles concerning the conservation of the Arctic's biodiversity, some of the implications, and a series of recommendations (section 10.5).

10.2. Conservation of arctic ecosystems and species

Earlier chapters focused on the terrestrial, freshwater, and marine environments of the Arctic, and their component species. Several physical characteristics distinguish polar environments from the environments of other regions: limited daylight for much of the year, low temperatures, and low levels of precipitation. Collectively, these limit biological productivity over a large part of the year because photosynthesis and decomposition are severely constrained. In contrast, the brief arctic summer, which experiences continuous daylight and warmer temperatures, generates a large pulse of primary productivity. These dramatic seasonal changes strongly influence the Arctic's biodiversity. For example, productivity in summer is sufficient to attract migratory species of birds and mammals to the region.

Recent glaciations have resulted in major losses of the resident arctic fauna and recolonization has been slow (particularly in the terrestrial and freshwater environments), owing to both the extreme environmental conditions and the low overall productivity of arctic ecosystems. This has resulted in the arctic ecosystems, in a global sense, being considered "simple", i.e., having relatively few species. The species that they do contain are mainly "specialists" in the sense that they have been able to adapt to the extreme conditions. Thus, there are few species at any particular trophic level, and overall species diversity in terrestrial, freshwater, and marine habitats is low.

The seasonal constraints result in similar life-history traits in many arctic plant and animal species. Compared to species living in temperate regions, species living in the Arctic throughout the year are typically long-lived, slow-growing, and have low rates of annual reproduction. These factors appear to be adaptive to environments that can vary greatly from year to year, and where productivity is constrained to a short period of time, even in a favorable year (MacArthur and Wilson, 1967; Pianka, 1970). Specifically, these life-history traits are suitable for plant and animal species living in environments where reproductive attempts within a single year

may need to be abandoned to ensure adult survival (Trathan et al., 1996; Weimerskirch, 2002).

Several of these traits may limit the capacity of species to respond to rapid environmental change. High adult survival rates, coupled with low rates of reproduction, make populations slow to recover from catastrophic events (Danchin et al., 1995; Jenouvrier et al., 2003). Also, the adaptations unique to species living in polar environments also limit their ability to respond to warming conditions or to the greater environmental variability projected to result from climate change scenarios for the Arctic (Laxon et al., 2003; Parkinson, 2000; Parkinson et al., 1999; Vinnikov et al., 1999).

The rest of section 10.2 considers the special features of arctic habitats that make their biological diversity vulnerable to climate change. In their analysis of the European Arctic, Hallanaro and Pylvänäinen (2002) recognized nine broad habitat types. Six of these have not been significantly affected by human activities: habitats above and beyond (i.e., north of) the treeline; forests; wetlands; lakes and rivers; coasts and shores; and the sea. The other three have been strongly affected: farmland; urban areas; and mosaic landscapes.

In this chapter the Arctic is considered in terms of five broad habitat groupings, including marine environments; freshwater environments; environments north of the treeline; boreal forests; and habitats intensively modified by people. The term *wildlife* was defined in Anon (2001a) as "in a more scientific sense…wildlife refers to all non-domesticated organisms. It includes mammals, birds, fish, amphibians, and reptiles, as well as vascular plants, algae, fungi, bacteria, and all other wild living organisms". Anon (2001a) defined *habitats* as "all the elements of the Earth that are used by wildlife species to sustain themselves throughout their life cycles. This includes the spaces (i.e., terrestrial and aquatic) that they require as well as the properties of those places (e.g., biota, climate, soils, ecological processes and relationships). Habitats function in providing such needs as food, shelter, and a home place. Habitats can be thought of as distinctive places or ecosystems…". These broad definitions are used in this chapter.

Although it might seem simple to identify terrestrial, freshwater, and marine habitats, as well as the wildlife that occurs in each, in practice it is not because each

habitat merges into another. For example, catchments or watersheds on land are terrestrially defined, but water percolating through the soil or running off the soil surface eventually enters streams and rivers. So where do terrestrial habitats end and freshwater habitats begin? Similarly, rivers enter estuaries where they are subject to tides, and species characteristic of rivers meet species characteristic of the sea. Where do freshwater habitats end and marine habitats begin? Along the shore the sea and the land interact, and there may be no clear demarcation between terrestrial and marine habitats. The situation is further complicated by anadromous species, such as Atlantic salmon (*Salmo salar*). These spawn in rivers, and the young pass through the estuaries on their way to the sea where they mature before returning several years later to their natal rivers to begin the cycle again. The reverse occurs with catadromous species, such as the eel (*Anguilla anguilla*), which spawns at sea. There are thus gradients, rather than clear boundaries between the wildlife of terrestrial, freshwater, and marine environments, and a pragmatic approach to allocating species and habitats to these broad groupings is taken within sections 10.2.1 to 10.2.4.

10.2.1. Marine environments

The arctic marine environment covers about 13 million km^2 (CAFF et al., 2000), of which about 45% is a permanent ice cap that covers part of the Arctic Ocean. Seasonal sea ice forms during winter, and recedes during the short arctic summer, exposing large areas of open water. The marine environment is thus dominated by sea ice (CAFF, 2001) and by the dynamics of that ice and especially the location of the ice edge. The transition zone between the sea ice and the open water has intense algal growth in spring and summer, and it is the primary production by these phytoplankton that supports the arctic marine food webs. Only in exceptional cases can the energy that drives the marine food webs be obtained from other sources. CAFF (2001) recorded the recent discoveries of "hot vents" and "cold seeps" in the Arctic. At these sites, bacteria are capable of deriving energy from methane (CH_4) or hydrogen sulfide (H_2S) gases that emerge as bubbles or in solution from the vents and seeps. These bacteria are then fed on by other organisms and so form the basis of some very specialized and localized food webs. Research on marine biodiversity is usually expensive, which is probably why comparatively less is known about marine biodiversity than terrestrial biodiversity (Anon, 2001a).

Projected changes in sea ice, temperature, freshwater, and wind will affect nutrient supply rates through their effects on vertical mixing and upwelling. These will in turn result in changes in the timing, location, and species composition of phytoplankton blooms and, subsequently, in the zooplankton community and the productivity of fishes. Changes in the timing of primary production can affect its input to the pelagic community as well as the amount exported to and taken up by the benthic community. The retention:

export ratio also depends on the advection of plankton and nutrients within the water body (Shuert and Walsh, 1993) and on the temperature preferences of the grazing zooplankton; these both determine the degree of match or mismatch between primary and secondary production (see Chapter 9).

The projected disappearance of seasonal sea ice from the Barents and Bering Seas, and so the elimination of ice-edge blooms, would result in these areas having blooms resembling those presently occurring in more southerly seas (Alexander and Niebauer, 1981). The timing of such blooms will be determined by the onset of seasonal stratification, again with consequences for a match or mismatch between phytoplankton and zooplankton production. If a mismatch occurs, due to early phytoplankton blooms, the food webs will be highly inefficient in terms of food supply to fish (Hansen B. and Østerhus, 2000). Both export production and protozoan biomass is likely to increase. However, both the areal extent of export production and grazing by copepods are projected to increase slightly because of the larger ice-free area (see Chapter 9).

Future fluctuations in zoobenthic communities will be related to the temperature tolerance of the animals and to the future temperature of the seawater. Whereas most boreal species have planktonic larvae that need a fairly long period to develop to maturity, arctic species do not (Thorson, 1950). Consequently, boreal species should be quick to spread with warm currents during periods of warming, while the more stenothermal arctic species (i.e., those only able to tolerate a small temperature range) will quickly perish. Shifts in the distribution of the fauna are likely to be quicker and more noticeable during periods of warming than periods of cooling. Change in the abundance or biomass of benthic communities is most likely to result primarily from the impact of temperature on the life cycles and growth rates of the species concerned. If warming occurs, thermophilic species (i.e., those tolerating a wide temperature range) will become more frequent (see Chapter 9). This will force changes to the zoobenthic community structure and, to a lesser extent, to its functional characteristics, especially in coastal areas.

Climate change affects fish production through direct and indirect pathways. Direct effects include the effects of temperature on metabolism, growth, and distribution. Food web effects could also occur, through changes in lower trophic level production or in the abundance of top-level predators, but the effects of these changes on fish are difficult to predict. However, generalist predators are likely to be more adaptable to changed conditions than specialist predators (see Chapter 9). Fish recruitment patterns are strongly influenced by oceanographic processes such as local wind patterns, mixing, and prey availability during early life stages; these are also difficult to predict. Recruitment success could be affected by changes in the timing of spawning, fecundity rates, larval survival rates, and food availability.

Poleward extensions of the range of many fish species are very likely under the projected climate change scenarios discussed in Chapter 4. Some of the more abundant species that are likely to move northward under the projected warming include Atlantic and Pacific herring (*Clupea harengus* and *C. pallasi* respectively), Atlantic and Pacific cod (*Gadus morhua* and *G. macrocephalus* respectively), walleye pollock (*Theragra chalcogramma*) in the Bering Sea (Blindheim et al., 2001), and some of the flatfishes that might presently be limited by bottom temperatures in the northern areas of the marginal arctic seas. The southern limit of colder-water fish species, such as polar cod (*Boreogadus saida*) and capelin (*Mallotus villosus*), are likely to move northward. Greenland halibut (*Reinhardtius hippoglossoides*) might possibly shift its southern boundary northward or restrict its distribution more to continental slope regions (see Chapter 9). Migration patterns are very likely to shift, causing changes in arrival times along the migration route (Holst et al., 2002). Qualitative predictions of the consequences of climate change on fish resources require good regional atmospheric and ocean models of the response of the ocean to climate change. There is considerable uncertainty about the effects of non-native species moving into a region in terms of their effects on the "balance" within an ecosystem.

The impacts of the projected climate change scenarios on marine mammals and seabirds in the Arctic are likely to be profound (Vibe, 1967), but are difficult to predict in precise terms. Patterns of change are non-uniform and highly complex. The worst-case scenarios for reductions in sea-ice extent, duration, thickness, and concentration by 2080 threaten the existence of entire populations of marine mammals and, depending on their ability to adapt, could result in the extinction of some species (Jenkins, 2003).

Climate change also poses risks to marine mammals and seabirds in the Arctic beyond the loss of habitat and forage bases. These include increased risk of disease for arctic-adapted vertebrates owing to improved growing conditions for the disease vectors and to contact with non-native species moving into the Arctic (Harvell et al., 1999); increased pollution loads resulting from an increase in precipitation bringing more river borne pollution northward (Macdonald R. et al., 2003); increased competition from the northward expansion of temperate species; and impacts via increased human traffic and development in previously inaccessible, ice-covered areas. Complexity arising from alterations to the density, distribution, or abundance of keystone species at various trophic levels, such as polar bears (*Ursus maritimus*) and polar cod, could have significant and rapid consequences for the structure of the ecosystems in which they currently occur.

Although many climate change scenarios focus on the potentially negative consequences for ecosystems, environmental change can also bring opportunities. The ability of some species to adapt to new climate

regimes is often considerable, and should not be underestimated. Many marine vertebrates in the Arctic, especially mammals and birds, are adapted to dealing with patchy food resources and to a high degree of variability in its abundance.

Ice-living seals are particularly vulnerable to changes in the extent and character of the sea ice because they use it as a pupping, molting, and resting platform, and some species also forage on ice-associated prey. Of the arctic pinnipeds, ringed seals (*Phoca hispida*) are likely to be the most affected because so many aspects of their life history and distribution are tied to sea ice (Smith and Stirling, 1975). They require sufficient snow cover to construct lairs and the ice must be sufficiently stable in spring for them to rear young successfully. Early break-up of the sea ice could result in premature separation of mother–pup pairs and hence increased neonatal mortality. Ringed seals do not normally haul out on land and to do this would be a very dramatic change in their behavior. Land breeding would expose ringed seal pups to much higher predation rates.

Changes in the extent and type of sea ice affect the distribution and foraging success of polar bears (Ferguson et al., 2000a,b; Mauritzen et al., 2001; Stirling et al., 1993). The earliest impacts of warming will occur at their southern limits of distribution, such as at James and Hudson Bays; and this has already been documented by Stirling et al. (1999). Late sea-ice formation and early break-up also mean a longer period of annual fasting. Reproductive success in polar bears is closely linked to their fat stores. Females in poor condition have smaller litters, as well as smaller cubs that are less likely to survive. There are also concerns that direct mortality rates might increase. For example, increased frequency or intensity of spring rains could cause dens to collapse, resulting in the death of the female as well as the cubs. Earlier spring break-up of sea ice could separate traditional den sites from spring feeding areas, and if young cubs were forced to swim long distances between breeding areas and feeding areas this could decrease their survival rate. The survival of polar bears as a species is difficult to envisage under conditions of zero summer sea-ice cover. Their only option would be to adopt a terrestrial summer lifestyle similar to brown bears (*Ursus major*), from which they evolved. But competition, risk of hybridization with brown and grizzly bears (both *U. major*), and an increase in human interactions, would also pose a threat to their long-term survival.

The effects of climate change on seabird populations, both direct and indirect, are very likely to be detected first near the limits of the species range and the margins of their oceanographic range (Barrett and Krasnov, 1996; Montevecchi and Myers, 1997). The southern limits of many arctic seabirds are likely to retract northward, also causing breeding ranges to shift northward (Brown, 1991). Changes in patterns of distribution, breeding phenology, and periods of residency in the Arctic are likely to be some of the first observed responses to climate

change. Seabirds will also be affected by changes in prey availability and so can serve as indicators of ecosystem productivity. Since warmer (or colder) water would affect the distribution of prey species, the distribution of individual seabird species is likely to reflect changes in the distribution of macrozooplankton and fish populations. Changes in sea level may restrict the use of current breeding sites, but may increase the suitability of other sites that are not currently used owing to predator access or for other reasons.

With climate change already underway, planning for the conservation of marine biodiversity is an imperative. Series of actions are being proposed (CAFF et al., 2000; Anon, 2001a). These can be grouped into five key issues, namely:

- the implementation of an inventory of the Arctic's biodiversity and of schemes for monitoring trends in the biodiversity resource, including appropriate indicators;
- the completion of a circumpolar network of marine and maritime protected areas;
- the development of circumpolar guidelines for managing arctic biodiversity in a sensitive manner, bearing in mind the needs of local communities and the fact that "controlled neglect" may be an appropriate means of management;
- the establishment of fora for developing integrated management schemes for coasts and seas; and
- the review of marine regulatory instruments, with recommendations for further actions where necessary.

Conservation is unlikely to be easy (CAFF, 2001), but as many as possible of these five key issues should be developed on a circumpolar basis. This is particularly the case for the marine environment because many of the species tend not to be localized, but to be widely distributed throughout the Arctic Ocean as a whole. Indeed, some species have regular, seasonal patterns of migration. Satellite tracking has shown that walrus (*Odobenus rosmarus*) and narwhal (*Monodon monoceros*) can move great distances within the Arctic Ocean in relatively short periods of time (Anon, 2001b). Similarly, polar bears, ringed seals, and beluga whales (*Delphinapterus leucas*) have been shown to exhibit extensive and rapid circumpolar movements.

The main requirement for the conservation of marine biodiversity is the need to take a holistic approach. The majority of national parks and reserves are predicated primarily upon the protection of coastal birds and mammals (Bernes, 1993). This needs to be expanded to include the ecosystems upon which these birds and mammals depend, and upon which the commercially-exploited fish populations also depend. It is not just the vertebrate animals that are important, but the whole range of biodiversity, and especially those small and often unknown organisms that are either trapping solar energy by photosynthesis or decomposing organic mat-

ter to enable the recycling of nutrients. It is the totality of the biodiversity of the marine habitats and ecosystems of the Arctic that support the sustainable production of the biological resources upon which the indigenous peoples, and others, depend. This holistic approach is underlined in the final sections of Chapter 9 which discuss the effects of climate change on phytoplankton; zooplankton production; benthic organisms; fish production; marine mammal distribution, especially in relation to sea-ice cover; and seabird distribution and prey availability.

Although there are many unknowns, it is likely that many of the vertebrate animals will move northward, with many of these species likely to become less abundant. However, for the phytoplankton, it is the extent of the mixing of the ocean layers that will determine the increases and decreases for the various taxonomic groups.

10.2.2. Freshwater environments

The Arctic has many types of freshwater habitat. There is a wide range of wetlands, including mires, marshes, sedge and reed beds, floodplain "grasslands", salt marshes, and coastal lagoons, as well as a large number of rivers, streams, and lakes. In fact, excluding the freshwater locked up in permanent ice in the Antarctic, a large proportion of the earth's liquid freshwater resources occur in the Arctic.

There is no universally accepted definition of a "wetland". Hallanaro and Pylvänäinen (2002) described a wetland as "areas where the water table lies near the surface for much of the year. Shallow water bodies can also be considered as wetlands if they are mainly covered by vegetation. In wetlands at least half of all of the plants should be hydrophytes, which can withstand or may even depend on high water levels". With such a loose definition, there can be many gradients from a wetland to some other sort of habitat. For example, as wetlands border onto colder areas, permafrost could become common, whereas near the coast the influence of sea ice will be greater, and toward the taiga there will be an assortment of wet woodland habitats.

Lakes and rivers are abundant in the Arctic. Norway is estimated to have in excess of 200 000 lakes with a surface area greater than 0.01 km^2 but less than 1 km^2, and 2457 lakes larger than this. Sweden is estimated to have 2908 rivers and the Republic of Karelia 1210 rivers. The 18 largest lakes in Europe are all in northern Europe, although some are located outside the Arctic (located between 60º and 66º N). Such statistics demonstrate the extent of the liquid freshwater resource in the Arctic.

Thus, there is a great range in the type and extent of arctic freshwater environments (see Chapter 8 for further details), and this extent is perhaps proportionally greater than in other geographical areas. For example, the rivers, lakes, and wetlands of Siberia are mainly fed by thaw and summer rains, which account for up to 80% of total annual flow (Zhulidov et al., 1997) and

which do not usually penetrate the impermeable permafrost barrier. Rivers in eastern Siberia typically freeze over in winter, flowing mainly, if not solely, in summer. The larger rivers in western Siberia have greater flows, controlled by discharges from their substantial catchments that extend into more southerly latitudes. The Rivers Ob and Yenisey provide significant contributions to the total freshwater discharge from Asia to the Arctic Ocean. Another example, is the Mackenzie Delta in North America, which is the second largest delta in the Arctic and subarctic (Lewis, 1991), being 200 km long and 65 km wide (Prowse, 1990). The delta has about 50% lake coverage (Mackay, 1963) and extensive wetlands. The small coastal rivers in the western Mackenzie Delta freeze over in winter. The spring break-up in the upstream parts of the Mackenzie River catchment causes rapid increases in water and suspended sediment discharges into the delta. These flood low-lying land and can recharge delta lakes.

These examples illustrate two of the special features of arctic freshwater environments. First, that the ecosystems can be frozen for much of the year, meaning water is available for relatively short periods of time. Second, that there is considerable variability, both within and between years, in terms of flooding, drying out, freezing, freeze–thaw cycles, and the periods of time over which these occur.

The dynamics of many of the lotic (river) and lentic (lake) environments in the Arctic are related to permafrost, and freezing can reduce or even halt the flow of rivers. The relationships between river flow, lake depth, and the onset or cessation of freezing conditions are also features of the arctic environment. Sources of water during the summer include, in addition to rain, late or perennial snow patches, glaciers, thawing of permafrost, and groundwater discharges (Rydén, 1981; van Everdingen, 1990). The projected increases in temperature are likely to result in these water sources becoming greater contributors to the annual water budgets of freshwater ecosystems. Many of the lentic environments are relatively shallow, and so the species within them have to be able to withstand considerable environmental variability, especially when the water bodies freeze.

Arctic freshwater ecosystems are species-poor compared to similar ecosystems in temperate and tropical areas (Bazely and Jefferies, 1997). This makes them particularly suitable for trophic studies, as for example the research by Kling et al. (1992) using isotopes of nitrogen and carbon. As Bazely and Jefferies (1997) reported, aquatic food chains in the Arctic are long, which is unusual given the low overall productivity per unit area. This paradox may reflect the pulse-regulated nature of the ecosystems, whereby seasonal resource acquisition and population growth are restricted to short periods. During unfavorable periods for growth and reproduction, low maintenance costs (or migration) enable populations to survive. It is postulated that this "idling" survival strategy allows extended food

chains to occur because high-energy demands by organisms do not occur year-round.

A crucial feature of the biodiversity of the Arctic's freshwater environment is the fish, generally occurring at high trophic levels and providing an important resource for the human population. Given the slow growth rates and low overall productivity, these fish populations can easily be over-exploited. Chapter 8 outlines the possible effects of climate change on a number of fish stocks, both those resident in freshwater and those that are diadromous (migrating between freshwater and sea water). Anadromous behavior (migrating from salt to freshwater, as in the case of a fish moving from the sea into a river to spawn) is most prevalent in northern latitudes (McDowall, 1987) because the ocean is more productive than the freshwater environments.

Climate change will affect arctic freshwater habitats by causing local extinctions and by changing the distribution ranges of species (see Chapter 8). Changes in the amount of precipitation and the length of snow lie will be important. The effects of increased precipitation for freshwater habitats will be primarily geomorphological, especially in the increased sediment loads in rivers and the increased deposition of sediments in lakes, at hydroelectric dams, and in estuaries. Such changes will affect habitats and the species they support, and so are likely to impact adversely on the biodiversity of the Arctic. The effects of decreased precipitation could be even more severe, resulting in the drying of wetlands, oxidation of organic compounds in sediments, and so a further release of CO_2 to the atmosphere. Changes in temperature are likely to affect the physiology of individuals, altering population dynamics and interactions between species. Temperature effects are very likely to be most pronounced in relation to fish, potentially opening up arctic freshwater ecosystems to fish species that currently have a more southern distribution.

Conservation of the biodiversity of freshwater habitats in the Arctic has been hampered by the lack of a common classification of habitats, especially for the wetlands. With each country using different definitions, it is difficult to determine trans-Arctic trends and to compare differences between regions. Classification schemes can be contentious, but it is vital that schemes are adopted as soon as possible (Naiman et al., 1992). For conservation, classification of habitats or species provides a framework for communication, management and, where necessary, legislation or regulation. This is important because of the many threats to arctic freshwater biodiversity. An analysis of environmental trends in the Nordic countries viewed threats to the freshwater environment from a two-dimensional perspective (Fig. 10.1). The vertical axis shows the area over which the threat operates and the horizontal axis represents the perceived seriousness of the threat. The illustration includes 14 current threats to biodiversity and ten long-term threats to the natural resources of the Nordic countries. The position of the ellipses on each diagram

is therefore analogous to a risk assessment for that particular threat. The diagram does not show how these threats will change as the climate changes, but it is likely that many of the ellipses will move to the right.

Such predictions contain many uncertainties. Nevertheless, Chapter 8 concludes with a series of nine predictions about the effects of climate change on freshwater environments and their biodiversity:

- microbial decomposition rates are likely to increase;
- increased production is very likely to result from a greater supply of organic matter and nutrients;
- shifts in invertebrate species' ranges and community compositions are likely to occur;
- shifts in fish species' ranges, composition, and trophic relations will very probably occur;

Fig. 10.1. A representation of the impacts of various threats to the freshwater environment of the Nordic nations. The vertical axis is a logarithmic representation of the extent, ranging from 100 to 100000 km². The horizontal axis represents the perceived severity of the threat. Thus in each diagram threats to the lower left are of least concern, while those to the upper right are of greatest concern. (a) current threats to biodiversity, (b) long-term threats to natural resources. (Based on Bernes, 1993; reproduced with permission from The Nordic Council of Ministers, Denmark).

- spawning grounds for cold-water fish species are likely to diminish;
- an increased incidence of mortality and decreased growth and productivity from disease/parasites are likely to occur in fish species, and will possibly occur in aquatic mammals and waterfowl;
- subsistence, sport, and commercial fisheries will possibly be negatively affected;
- probable changes in habitat are likely to result in altered migration routes and timing of migration for aquatic mammals and waterfowl; and
- probable changes in timing of habitat availability, quality, and suitability are very likely to alter reproductive success in aquatic mammals and waterfowl.

These issues pose many challenges, and neither traditional knowledge nor scientific knowledge are able to meet these challenges completely. In addition to the need for more research, the development of generic models is essential if research in one area, on one species, or on one habitat, is to be applied to other areas, to other species, or to other habitats.

10.2.3. Environments north of the treeline

Arctic organisms must either survive or avoid the long, cold winters. Adaptations range from avoidance behavior (long-distance migration, migration from tundra to forest, migration down the soil profile) to specific physiological, morphological, and life history traits in both plants and animals. Species with specific adaptations to cold conditions often lack the flexibility to adapt to new conditions, particularly interactions with immigrant, competitive species from the south. For example the displacement of Arctic fox (*Alopex lagopus*) by red fox (*Vulpes vulpes*), and many arctic plant species that are shade intolerant (see Chapter 7).

In addition to the constraints of low temperatures on biodiversity, the contrast between summer and winter conditions is also important. The photoperiod is likely to constrain budburst, frost hardening, and reproduction in some potentially immigrant shrubs and trees. It is also likely to affect the endocrinology of mammals leading to constraints on reproduction and the onset of appetite. Short growing seasons select for plants that are perennials and have long development periods, for example three to four years from flower bud initiation to seed set. Marked temperature differences between summer and winter conditions currently select for plants that accumulate and store resources: up to 98% of biomass can be below ground. Such storage organs are likely to become a respiratory burden with warmer winters, and slow-growing plant species with multi-year development are eventually likely to be displaced by faster growing species, including annuals.

Overall, species richness in the Arctic north of the treeline is low (see Chapter 7). About 3% of the species making up the global flora occur in the Arctic. However,
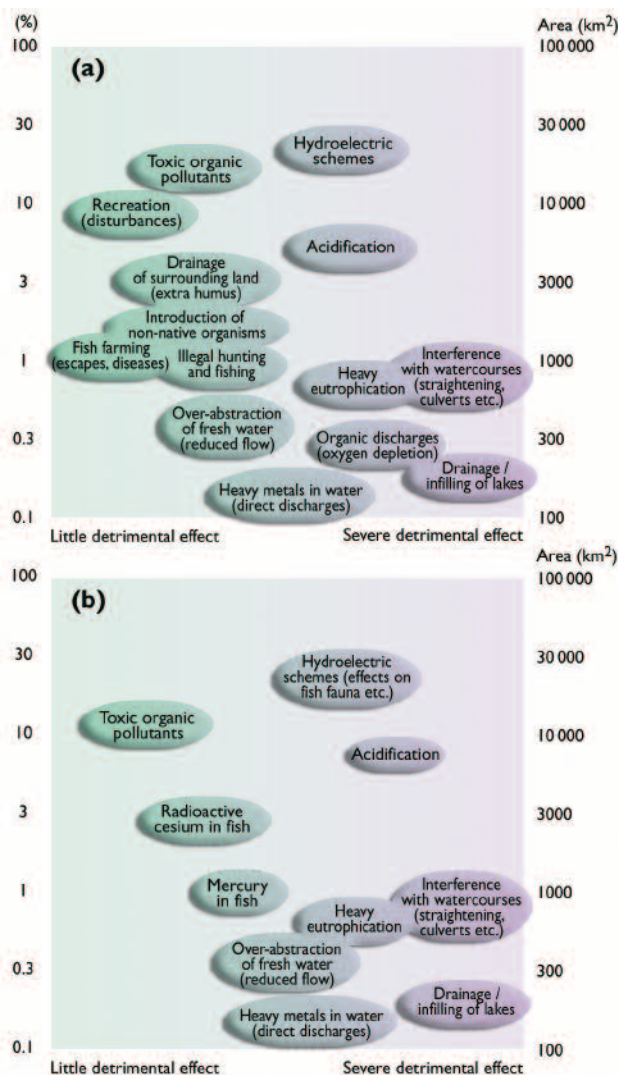
lower taxonomic groups are better represented than higher orders: only 0.7% of the flowering plant species occur in the Arctic compared with 1.6% of the cone-bearing plants. At a scale of 100 m^2, however, the diversity of the flora of some arctic communities can equal that of temperate or boreal latitudes owing to the generally small size of arctic plants. Within the Arctic, the diversity of animals (about 6000 species) is twice that of plants. Again, with lower taxonomic groups better represented. Springtails, at 6% of the global total, are better represented than advanced invertebrate groups such as beetles with 0.1% of the global total. Climatic warming is very likely to increase the total number of species in the Arctic as species with more southern ranges shift northward, but the overall composition of the flora and fauna is vulnerable to the loss of arctic species at lower taxonomic orders (Cornelissen et al., 2001). Some taxonomic groups are particularly species rich in a global context: any impact of climate warming on such species, for example, willows (*Salix* spp.), sawflies, stoneflies, wading birds, and salmonid fish, is likely to affect their diversity at the global level.

An important consequence of the decline in numbers of species with increasing latitude is a corresponding increase in dominance. For example, one species of collembolan, *Folsomia regularis*, may constitute 60% of the total collembolan density in polar deserts (Babenko and Bulavintsev, 1997). Examples for plants include the cotton-grass *Eriophorum vaginatum*, and *Dryas* species. These "super-dominants" are generally highly adaptable, occupy a wide range of habitats, and have significant effects on ecosystem processes. Lemmings (*Lemmus* spp. and *Dicrostonyx* spp.) are super-dominant species during peak years in their population cycles (Stenseth and Ims, 1993).

Trophic structure is less complex in the Arctic than further south. In all taxonomic groups, the Arctic has an unusually large proportion of carnivorous species and a low proportion of herbivores (Chernov, 1995). As herbivores are strongly dependent on the response of vegetation to climate variability, warming is likely to alter the trophic structure substantially as well as the dynamics of arctic ecosystems. The herbivore-based system in most tundra habitats is dominated by one or two lemming species (Batzli et al., 1980; Oksanen et al., 1997; Wiklund et al., 1999), while the abundance of phytophagous (plant-eating) insects relative to plant biomass is small on arctic tundra (Strathdee and Bale, 1998). Large predators such as wolves, wolverines, and bears are less numerous in the tundra than the boreal forest (Chernov and Matveyeva, 1997) and predation impacts on tundra ungulates are usually low. Thus, the dynamics and assemblages of vertebrate predators in arctic tundra are almost entirely based on lemmings and other small rodent species (*Microtus* spp. and *Clethrionomys* spp.) (Batzli, 1975; Wiklund et al., 1999), while lemmings and small rodents consume more plant biomass than other herbivores. Climate has direct and indirect impacts on the interactions among trophic levels, but there is greater uncertainty about the responses to climate change of animals at higher trophic levels.

Mechanical disturbance to plants and soils (animals can avoid or respond to such problems) occurs at various scales. Large-scale slope failures, such as active layer detachment, destroy plant communities but open niches for colonization by new generations of existing species or immigrant species with ruderal characteristics (fast growth, short life span, large reproductive capacity, and widespread dispersal of seeds). Such disturbances can also lead to recruitment of old genotypes of species producing long-lived seed that has been buried for hundreds of years (Vavrek et al., 1991). Sorting of stones and sediments in the active layer from daily to seasonal freeze–thaw cycles causes patterning of the ground and the creation of a mosaic of habitats at the landscape scale and a range of niches at the centimeter to meter scale (Matveyeva and Chernov, 2000). Such sorting, together with longer term permafrost degradation, movement of soils on slopes, and displacement by moving compacted snow and ice, exerts strong forces on plant roots. Above ground, wind-blasted ice crystals can erode plant tissues that extend above the protective snow cover. Mechanical impacts in the soil select for species without roots (mosses, lichens, algae), species with very shallow and simple root systems (e.g., *Pinguicula* spp.), and species with mechanically elastic roots (e.g., *Phippsia algida* and *Tofieldia pusilla*) (Jonasson and Callaghan, 1992). Amelioration of the mechanical impacts is likely to lead to displacement of specialized species by more competitive neighboring species.

Super-dominant species such as lemmings have large effects on ecosystem processes (Batzli et al., 1980; Laine and Henttonen, 1983; Stenseth and Ims, 1993). Lemming peak densities exceed 200 individuals per hectare in the most productive *Lemmus* habitats of Siberia and North America (Batzli, 1981) and the standing crop may approach 2.6 kg dry weight per hectare. Lemmings have a high metabolic rate and *Lemmus* spp. in particular has low digestive efficiency (about 30%, compared to 50% in other small rodents). Consequently, their consumption rate and impact on the vegetation exceeds that of all other herbivores combined (with the exception of the local effects of geese near breeding colonies). Also, lemmings destroy more vegetation than they ingest and after population peaks typically 50% of the above-ground biomass has been removed by the time of snow melt (Turchin and Batzli, 2001). In unproductive snowbeds, which are favored winter habitats of the lemming *Lemmus lemmus* (Kalela, 1961), between 90 and 100% of the moss and graminoids present during winter may have been removed (Koskina, 1961).

In forest near the treeline, insect defoliators can have devastating impacts on the ecosystem. The autumnal moth (*Epirrita autumnata*) shows cyclicity in its populations and outbreak proportions occur approximately every 10 to 11 years (Tenow, 1972, 1996). Many thousands of hectares of forests are defoliated in outbreak

years and defoliated forests require about 70 years to attain their former leaf area. However, insect outbreaks in sub-arctic Finland, followed by heavy reindeer browsing of regenerating birch shoots, have led to more or less permanent tundra (Kallio and Lehtonen, 1973; Lehtonen and Heikkinen, 1995).

These outbreaks are important for predators, such as snowy owl (*Nyctea scandiaca*) and arctic fox, which both prey on lemmings, and parasitoids such as the wasp *Cotesia* sp., which lays its eggs in caterpillars of the autumn moth. Changes to the populations and population trends of species such as lemmings and forest insect pests are very likely to have far reaching consequences for the biodiversity of the vegetation they consume, and for their predators and parasitoids, as well as for ecosystem processes like nutrient cycling.

The geography of the Arctic forces a range of constraints on the ability of vegetation zones and species to shift northward. In mainland Fennoscandia and many parts of the Russian Arctic, apart from Taymir and the western Siberian lowland, the strip of tundra between the boreal forest and the ocean is relatively narrow. Trees already occur close to the Arctic Ocean at Prudhoe Bay and Khatanga. Any northward movement of the forest will completely displace the tundra zone, and hence its biodiversity, from these areas. On the western Siberian plain, extensive bog ecosystems limit the northward expansion of forest and in arctic Canada, the high Arctic archipelago presents a natural barrier to dispersal of plants and range extensions of animals, while the barrens (polar desert and prostrate dwarf shrub tundra with less than 50% of the ground covered by vegetation) consist of soils that will constrain forest development for perhaps hundreds of years.

Continuous and discontinuous permafrost are characteristic of the Arctic. Permafrost, particularly its effect on the thickness of the active layer, limits the depth and volume of biologically available soil and reduces summer soil temperatures. These constraints limit plant rooting, the activity of soil flora, fauna, and microbes, and ecosystem process such as decomposition. Soil movements associated with permafrost dynamics are discussed in Chapter 7. Thawing of permafrost can have dramatic effects on biodiversity, depending upon drainage, precipitation changes, and, consequently, soil moisture. Permafrost thawing associated with waterlogging can prevent the northward advance of the treeline and even initiate a southward retreat (Crawford et al., 2003). In other areas, such as the North Slope of Alaska, where precipitation is only about 125 mm/yr, permafrost thawing is likely to lead to drying and in some areas novel communities, reminiscent of the tundra-steppe, could form.

In addition to the effects of permafrost on biodiversity, biodiversity can also affect permafrost. A complete cover of vegetation, particularly highly insulative mosses, buffers soil temperatures from climate warming. In extreme cases, vegetation can lead to permafrost growth and a thinning of the active layer.

Arctic terrestrial ecosystems have the same types of feedback to the climate system as many other ecosystems, but the magnitude of these feedbacks is greater than most others. Per square meter, the tundra stores about half as much carbon as the boreal forests (about 9750 g/m^2 and 20500 g/m^2, respectively, 15900 g/m^2 at the interface between tundra and boreal forest according to McGuire et al., 1997). However, most of the carbon in the tundra occurs in the soil (about 94%), whereas about half (46%) of the carbon in the boreal forest occurs in the vegetation. The carbon stored in the tundra (about 102 Pg) is about 40% of that stored in the boreal forests (excluding the boreal woodlands). The tundra, boreal forest, and boreal woodlands together store 461 Pg of carbon; this is equivalent to about 71 years of annual global carbon emissions (based on emission data for the 1960s) of CO_2 from fossil fuels (about 6.5 Pg of carbon per year). In contrast to the boreal forest, tundra has a high albedo and reflects about 80% of incoming radiation and this can lead to local cooling. Displacement of tundra vegetation by shrubs increases winter soil temperatures by 2 °C (Sturm et al., 2001).

Feedbacks that change the rate of climate change (although probably not the direction) will affect the rates of changes in biodiversity. For example, the effect of shrubs on soil temperatures is expected to increase decomposition rates and nutrient cycling, and so further shrub expansion. Also, it is possible that glacial dynamics (as well as more generally the dynamics of frozen ground) will have an effect (Chernov, 1985). Glaciers have expanded and contracted in response to climatic variations. For example, in Iceland the maximum extent of the glaciers in historical times occurred in 1890. The majority of the glaciers contracted during the first half of the 20th century, particularly during the warm 1930s. Then from about 1940 the climate cooled, slowing the retreat of the glaciers, and some even started to advance again (Jóhannesson and Sigurðsson, 1998). This dynamic behavior of glaciers can have a marked effect on the biodiversity of nunataks (hills or mountains completely surrounded by glacial ice), which often contain a large proportion of the regional biodiversity. For example, there are over 100 species of vascular plants growing on Esjufjöll, a 9 km long nunatak within the glacier Vatnajökull, which is more than 20% of Iceland's total vascular plant flora (Einarsson, 1968).

Glacial dynamics are not entirely related to temperature. In Norway, there is some evidence that inland glaciers are currently retreating while coastal glaciers are advancing in response to greater quantities of snowfall. This indicates the difficulties of predicting the effects of climate change on glaciers. The different rates of warming at different seasons of the year, as well as changes in seasonal precipitation patterns, especially for snow, will

Fig. 10.2. Pine (*Pinus sylvestris*) forest in the Arctic. This area of almost natural forest is on an island in Inarijärvi, Europe's eighth largest lake, near Inari in Finland (68° 55' N). (Photo: M.B. Usher, July 1999).

Fig. 10.3. The mosaic structure of northern boreal forest; pine and birch forest associated with mires and small areas of open water north of Inari, Finland (69° 12' N). (Photo: M.B. Usher, July 1999).

all determine the future dynamics of glaciers. These in turn influence the nunataks, the extent of areas of new ground available for primary ecological succession after glacial retreat, and the loss of ecosystems covered by advancing glaciers.

10.2.4. Boreal forest environments

The Arctic encompasses the northern edge of the boreal forest and the woody communities, often containing shrubby trees, that are associated with the northern treeline. These northern forests are often dominated by four coniferous genera: the pines (*Pinus* spp.), spruces (*Picea* spp.), larches (*Larix* spp.), and firs (*Abies* spp.), as well as by two broadleaved genera, the birches (*Betula* spp.) and the aspens (*Populus* spp.), most of which have transcontinental distributions across Eurasia or North America (Nikolov and Helmisaari, 1992). An example of a pine-dominated forest near Inari, Finland (about 69° N) is shown in Fig. 10.2. This is typical of the near-natural forest, with slow-growing trees, dead wood, and natural regeneration in gaps where the dead and moribund trees allow sufficient light to penetrate to the forest floor. The forests frequently give way to mires and small lakes leading to a mosaic structure of forest and wetland. Figure 10.3, also near Inari in Finland, shows this transition, with both pine trees and birch woodland in the distance. The boreal forest region has a distinctive set of biodiversity characteristics at each of the three levels of biodiversity – genetic diversity, species diversity, and ecological communities. These are the key to assessing vulnerability of the boreal forest biodiversity to climate change.

When two or more distinct ecological communities or habitats are adjacent, there is a unique opportunity for organisms to live and reproduce in a diverse landscape. Landscape diversity is controlled by the physical arrangement of ecological communities. Climate change, by influencing the distribution of forest species, communities, and conditions, is a major factor controlling landscape diversity.

The extensive ecotone between boreal forest and tundra (a treeline 13 500 km long) is a prominent feature of the northern boreal region (some of the major climate-related fluctuations of the treeline are discussed in Chapter 14). The juxtaposition of trees and tundra increases the diversity of species that can exploit or inhabit the tundra. For example, insectivorous ground-dwelling birds that feed in the tundra but nest in trees are able to survive because of the mixture of habitats. Local human inhabitants can obtain shelter and make useful items for outdoor activities at this interface. The probability of climate warming causing the development of new treeline communities is described in Chapter 14. During recent decades of warming, the white spruce (*Picea glauca*) limit in Alaska (and almost certainly in western Canada) has developed two populations with opposite growth responses to the warming. Under extreme levels of projected warming, white spruce with negative growth responses would be likely to disappear from the dry central part of the northern boreal forest. In moister habitats, white spruce with positive growth responses to warming would expand in distribution. It is possible that part of the southern tundra boundary in North America would no longer border spruce forest but

would border aspen (*Populus tremuloides*) parkland instead (Hogg and Hurdle, 1995).

The changes in boreal forests caused by fire and insect disturbance produce higher order effects due to the patterns and timing of the habitat conditions that they create at larger scales. Microtine rodents, birds, and hares (*Lepus timidus*) in the Fennoscandian boreal region undergo cyclic population fluctuations, generally on a three- to four-year cycle (Angelstam et al., 1985). Many factors contribute to these population cycles, including predator numbers, food plant quantity and/or quality, pathogens, parasites, and habitat heterogeneity. Some weather and climatic factors, such as snow depth, also directly influence animal numbers. In the future, population cycles of boreal animals are likely to remain primarily under the control of predators, although overall numbers of animals will respond to the overall amount of suitable habitat produced by events, such as forest fires, that are in turn related to climate warming. A ten-year study of trophic structure in the boreal forest in the Kluane area of southwest Yukon Territory, Canada, examined the ten-year animal population cycle. In this region the boreal community is a top-down system driven by the predators, and snowshoe hare (*Lepus americanus*) is a keystone species without which much of the community would collapse (Krebs et al., 2001). Hares influence all other cycles, and hare cycles are themselves controlled by the interaction of predator effect and food supply with little or no climate or fire effect detected. However, by the end of the study, 30% of the white spruce forest in the study area had been killed by spruce bark beetle (*Dendroctonus rufipennis*), which was probably related to climate warming (see Chapter 14). The change in habitat condition in the Kluane study area is one of the largest disturbances resulting from climate warming in the region over the last few centuries.

Specific areas of the boreal region are more species-rich than others (Komonen, 2003). Areas that have not been glaciated or which were deglaciated earliest are generally more species rich than more recently deglaciated areas (Komonen et al., 2003), suggesting that risks of major migrations of the boreal forest increase the probability of species loss. Boreal regions with a diversity of geological and soil substrates, such as Far East Russia, the Scandes Mountains, and the northern Rocky Mountains of North America, are relatively species-rich compared to more uniform areas such as the Canadian Shield or the Ob Basin. Boreal areas that have experienced interchange between the ecosystems (Asian Steppes, North American Plains) or continents (Beringia) are relatively species-rich.

Total species richness in the boreal region is greater than in the tundra to the north and less than in the temperate deciduous forest to the south, in line with levels of total ecosystem productivity (Waide et al., 1999). The southern boreal region contains more species than the northern boreal region, and one effect of climate warming is likely to be the addition of species to what is now the northern boreal region. A global summary of changes in phenology (the distribution and timing of events) across a number of organism groups already indicates the existence of a coherent signal of warming (i.e., poleward and upward migration, earlier activity in spring) (Root et al., 2003). However, the processes that eliminate boreal species (fire, insects, and drought) operate quickly, while those that add species (migration) operate more slowly. This raises the possibility that climate warming, in certain areas, could result in reduced species richness in the short term followed later by species gains as long as migratory barriers were not limiting. However, intensive forest management in Fennoscandia is one of the main causes of decline in the most rare or endangered boreal forest species there (Nilsson and Ericson, 1992) and managed forest landscapes do pose movement and connection barriers to the species in them (Hanski and Ovaskainen, 2000).

The conservation of certain boreal forest habitats is particularly important for maintaining species diversity, and climate change can bring serious challenges in this respect. Of the major ecological regions of the earth, boreal forest is distinctive for being conifer dominated (Juday, 1997). Older conifer forests on productive sites are the focal habitats of biodiversity conservation across the boreal region for several reasons. They are particularly rich in canopy lichens, mosses, and bryophytes; in the fungi responsible for decomposing wood; and in specialized insects, for woodpeckers and other cavity-nesting animals, and for insectivorous songbirds (Berg et al., 1994; Essen et al., 1992).

The reason that old-growth (or natural) forests are so important for the conservation of biodiversity lies in the holistic approach to nature conservation. Natural forests, with their J-shaped stem-number curve (a few old, large trees and many small, young trees) provide a range of habitats that support a range of different species of plants and animals. Old trees provide nesting holes for some bird species, diseased and moribund trees provide a substrate for many species of fungi, dead wood provides a resource for saproxylic (wood-feeding) insects, and some moth species will only lay their eggs on the foliage of young trees, etc. Wood-feeding arthropods form a diverse taxonomic group that is under pressure throughout Europe (Pavan, 1986; Speight, 1986) and elsewhere. In contrast, managed forests of younger trees tend to have little dead wood, few nesting holes for birds, and less light reaching the forest floor and thus a less well developed dwarf shrub, herbaceous, moss, and lichen flora, which in turn supports fewer invertebrates. A focus on the beetles of the northern forests (Martikainen and Kouki, 2003) has demonstrated both that these semi-natural forests contain a relatively large number of rare species and that there are difficulties in making accurate inventories.

Owing to the natural rate of stand-replacing disturbances (fire and insects) in the boreal forest, old-growth conifer stands are not necessarily abundant even in

landscapes with little direct human impact. Human modification of the boreal forest landscape typically makes these old forests rarer because management for wood products is usually based on the good returns from cutting large conifers. In parts of the boreal region, where commercial forest management is established or expanding, productive stands of mature and old conifers are already rare (eastern Canada, northern Fennoscandia; Linder and Ostlund, 1992) or the target for early harvest (Siberia; Rosencranz and Scott, 1992). One of the major effects of climate warming on boreal forests is to increase tree death from fire and insects, and conifer stands are more flammable and often more susceptible to insect-caused tree death than broadleaved forests. Thus the ecosystem of greatest conservation interest, old conifer forest, is the one at most risk of decline due to climate warming.

Fire is a natural and recurrent feature of boreal forests, aiding the maintenance of biodiversity in these northern forests. Fire is expected to pass through a forest every 100 to 200 years (Korhonen et al., 1998). Some species are adapted to using the resources of burnt forests – charred trees which are still standing, trees which have started to decay, and the early stages of ecological succession following fire. Because fires in managed forests are usually extinguished quickly, burnt forest habitats have become rare and the species that depend on them are increasingly threatened and even locally extinct. In Finland, 14 species, mostly beetles (Coleoptera) and bugs (Hemiptera), associated with burnt areas in forests are threatened with extinction (Korhonen et al., 1998).

However, can extensive fires be tolerated in managed forests when the trees are required for extraction and as the raw material for the timber industry? Growth rates of trees near the transition from forest to tundra are extremely slow, which makes management of these far northern forests uneconomic (except for the initial exploitation of the few trees large enough to be used in timber mills, etc.). However, with climate change (and eutrophication by nitrogen deposition) productivity is likely to increase, and so the management of these northern forests becomes a potentially more viable economic activity, with consequent effects on forest biodiversity.

Fire itself is not the risk factor for the maintenance of boreal forest species diversity, but rather the altered characteristics of fire that can result from climate warming, especially amount, frequency, and severity. Conifer dominance itself promotes the occurrence of large, landscape-scale fires through characteristics such as flammable foliage and ladder fuels (defined by Helms (1998) as "combustible material that provides vertical continuity between vegetation strata and allows fire to climb into the crowns of trees or shrubs with relative ease"). Many boreal trees and other plants show adaptations to fire such as seed dormancy until fire, serotinous cones, fire-resistant bark, and sprouting habit. Many understory plant species of the boreal forest have means of persistence from underground structures following fire or are

effective re-colonizers (Gorshkov and Bakkal, 1996; Grime, 1979; Grubb, 1977; Rees and Juday, 2002). Fire in the boreal forest sustains a set of species in early post-fire communities that are distinct from later successional species. These include species from a range of groups, including birds, beetles, spiders, and vascular and non-vascular plants (Essen et al., 1992; Haeussler and Kneeshaw, 2003; Rees and Juday, 2002). Changes in natural fire regimes by human management interacting with climate warming can disrupt the specific fire regimes that sustain these species. For example, in some circumstances climate warming combined with human fire suppression results in less frequent but more intense fire. This change can kill species adapted to periodic light ground fires.

The boreal landscape also includes areas that never burn. These fire-free areas are important for the persistence of fire-sensitive species. Fire-free refuges occur across most of Fennoscandia (Essen et al., 1992); in the southeast Yukon Territory such an area contains an exceptionally rich flora (Haeussler and Kneeshaw, 2003). With the more frequent, more extensive, and more intense fires projected to result from climate warming, current fire refuges are likely to burn for the first time in recent history, thus reducing or locally eliminating fire-sensitive species.

After a sustained period of enhanced burning caused by climate warming, some boreal forests are likely to undergo type conversion from conifer to broadleaf tree dominance as a result of the depletion of fuels (see Chapter 14). An abrupt shift in forest composition of that type would significantly decrease the amount of old conifer habitat present at a given time from the large landscape perspective, possibly decreasing populations of some dependent organisms to critically low levels.

The boreal forest is characterized by large numbers of individuals of the few tree species with wide ecological amplitude, in contrast to tropical forests that sustain a small number of individuals of many species. Genetic diversity in any species is in part the result of opportunity for gene recombinations and so follows the laws of probability. In the boreal forest, probability favors the survival of large numbers of different gene combinations because of the characteristically large populations of each species (Widen and Svensson, 1992). To the degree that these genotypes reflect specific adaptations to local environments, they promote the survival and success of the species (Li et al., 1997). For example, foresters have developed seed transfer guidelines in order to define areas in which it is safe to collect seed for planting in a given site, based on their practical experience of failures in tree plantations from seed collected outside the local environment; boreal Alaska includes several hundred seed transfer zones (Alden, 1991), suggesting that a high degree of local adaptation may be typical.

The optimum growth and survival of the major boreal tree species across their large and varied natural distributions requires the survival of a large proportion of current genes, including genes that are rare today but

would help survival of the species under future environmental conditions. One of the main risks for boreal forest from climate change is that major areas of the current distribution of boreal tree species might become climatically unsuitable for their survival faster than populations of the species could migrate, resulting in the loss of many adaptive genes. Fire and insect outbreaks are known to be triggered by warm weather (see Chapter 14), and gene loss would be likely to result from larger areas of more complete tree death. Gene survival in a changing climate becomes even more difficult if the native gene diversity is already diminished, as is usually the case in a managed forest and where human activities have reduced forests to remnants (Lieffers et al., 2003). In human-dominated landscapes the appropriate genes for an adaptive response of boreal forest plants to some aspects of climate change may already be rare if the trait was not associated with traits selected for in the forest management program. In addition, when the landscape is fragmented by human activities (for example by roads, pipelines, power lines, industrial and agricultural development, and excessive grazing), even the plant species with adaptive genes are very unlikely to migrate effectively under future climate change.

Nearly all the boreal forest tree species are open wind pollinated, which facilitates a wide distribution of genes (Widen and Svensson, 1992). The present boreal forest is the product of major periods of global warming and cooling that forced the boreal organisms to migrate far to the south of current limits and back several times. These climatic displacements imply that today's plants have considerable adaptive abilities as they have survived past climate changes. Even so, some loss of genes is almost inevitable in populations of trees and other plants coping with the major and rapid environmental changes that have been projected (see Chapter 4).

From the geological record, Spicer and Chapman (1990) considered that climate change is most strongly expressed at the poles. There is a dynamic equilibrium between the climate, the soils, and the vegetation. Arctic soils are crucial to the functioning of the terrestrial ecosystems (Fitzpatrick, 1997). Heal (1999) considered that "soil biology has changed dramatically since…the 1970s" and "the emphasis and approach has changed from descriptive to predictive, structure to function, organism to process, local to global". Much of the descriptive data collected in the 1970s were summarized by Swift et al. (1979), where the soils of the tundra and taiga were compared with those of temperate and tropical areas. However, these shifts in emphasis highlight that scientific knowledge of arctic soils is out of date, and is particularly weak because the information gained during the International Biological Programme (the first international collaborative research program of the International Council of Scientific Unions, running from 1964 to 1974, with a focus on "the biological basis of productivity and human welfare" – see Clapham, 1980 and Bliss et al., 1981) in the 1970s lacks experimental evidence relevant to the cur-

rent issues of climate change. Evidence for the change in ecological thinking is evident in the studies by Robinson and Wookey (1997) on Svalbard, in which the emphasis was on decomposition and nutrient cycling.

Soils have frequently been neglected when biodiversity and its conservation are considered (Usher, in press). However, soils often contain the most species-rich communities in the Arctic, and so need to be considered in any planning or action for conserving biodiversity. However, many fundamental questions remain (Heal, 1999). What are the physical drivers of change? How will the ecological processes that occur within soil respond to climate change? How will the populations and communities of soil organisms adapt to climate change? It is known that environmental perturbations can change the dominance and trophic structure of the nematode community (Ruess et al., 1999a) in the subarctic soils of northern Sweden, and that such changes can have a large impact on microbial biomass and microbial turnover rates (Ruess et al., 1999b). In the boreal forest, there appears to be little correlation between taxonomic diversity and the process rates within the soils (Huhta et al., 1998), but it is not known whether this is typical of other arctic soils

It is widely held that diversity promotes ecosystem function, and so that biodiversity loss threatens to disrupt the functioning of ecosystems (Luck et al., 2003). More research is needed on arctic soils to determine whether the many species in these soils are all required, or whether there is some "redundancy" whereby the ecosystem could function efficiently with far fewer species. Also, with climate change, it becomes increasingly important to understand the carbon fluxes through arctic and subarctic soils – will there be net accumulations of soil carbon or net losses of carbon in the form of CO_2 or CH_4 to the atmosphere? Such knowledge is critical for the development of conservation policies and for the management of arctic ecosystems and their biodiversity.

10.2.5. Human-modified habitats

The concept of the Arctic as a pristine environment is a widespread fallacy. Humans have long been involved in the Arctic, both directly and indirectly, with little effect on its biodiversity, although hunting and gathering activities, and grazing of domesticated stock, must have had some effect. Damming of rivers to create fish traps is one of the few examples of early intensive environmental modification by people, as is the effects of over-grazing in Iceland. It is only since about 1800 that people have had significant impacts on arctic biodiversity through intensive intentional, or unintentional, modification of terrestrial, freshwater, or marine environments. The main environmental modifications have been through:

- expansion of land management for agriculture (including herding) and forestry, both of which have been very limited;

- expansion of marine and, to a lesser extent, freshwater commercial fisheries, especially with the advent of recent technologies;
- aquaculture as an emerging marine industry; and
- industrial, urban, and recreational developments, which have expanded considerably in recent decades, resulting in modifications to most types of habitat, regional production and dispersal of contaminants, and associated expansion of communication networks.

The actual proportions of terrestrial, freshwater, and marine habitats that are directly managed for human use in the Arctic are still very small, in contrast with the situation in other areas of the world (except the Antarctic), where agricultural habitats growing crop plants abound, and where derelict land, left over from activities such as mining, quarrying, or municipal development, is not uncommon. Agriculture within the Arctic is very limited; forestry is slightly more frequent. Around settlements and industrial developments there have been substantial changes to the natural environment, and non-native (weed) species have been able to establish in these disturbed habitats. However, the projected changes in climate are very likely to result in significant expansion and intensification of these human activities across the region, particularly where climate warming is most marked. The greatest potential impacts on biodiversity are likely to be through fragmentation of terrestrial ecosystems and the expansion of marine traffic as sea-ice conditions become less severe in the Northeast and Northwest Passages. There are at least four fundamental characteristics of arctic biodiversity that make it sensitive to these developments.

1. Many arctic plants and animals have slow growth rates and are long-lived as adaptations to the short summer season. These characteristics limit their capacity to respond to relatively rapid changes in their environment, especially when these recur over relatively short time periods. Recurrent disturbance tends to select for species with ruderal characteristics, some of which are found in species living in sites where freeze–thaw cycles predominate.
2. The low productivity of most habitats forces fauna to forage or hunt over large areas. Finding suitable habitats for breeding and shelter further extends the range requirements. Thus fragmentation of habitats and limitations to movement could potentially affect many species.
3. The flora and fauna have been selected to survive under extreme climatic conditions. This has given them a competitive advantage in the Arctic over species from warmer climates. Climate warming is very likely to result in a gradual northward shift in arctic species as a result of a natural northward shift in the ranges of more southerly species. However, the projected increase in human activities will also result in the introduction of non-native species, some of which are

expected to compete successfully with the native species. This is analogous to the experience of species introductions on isolated islands.
4. Some species that breed in the Arctic migrate to lower latitudes to avoid the extreme winter conditions. Migration places significant energetic stress on the animals; this means that the animals have evolved specific routes which provide access to transit feeding areas. The modification of habitats by people, both within and outside the Arctic, can have significant impacts on particular migratory species or populations.

These four characteristics of the flora and fauna of the Arctic make them particularly sensitive to the expansion of human activities in the region. For example, the effects of over-grazing by domestic livestock are clearly evident in Iceland where the vegetation cover has been lost and soil erosion is severe (Arnalds et al., 2001). This has led to desertification, with more than 50% of Iceland's land area (excluding that under permanent ice) being classified as either in "poor condition" or "bad condition". The history of desertification in Iceland was outlined by Arnalds (2000), and stands as a reminder of what can happen when the land's vegetative cover is damaged. The vegetation in other areas of the Arctic has evolved in the presence of large herbivorous mammals, unlike Iceland's vegetation, a factor which was thought by Arnalds (2000) to be significant.

Climate change is likely to cause gradual expansion at the northern boundary and contraction at the southern boundary of the range of arctic species. In contrast, the expansion of human activities in response to climate change is very likely to cause more rapid northward movement and the introduction of non-native species. The latter will occur mainly through accidental transport and release of individual organisms and propagules beyond their current, natural distribution limits. Such introductions, although having a very low probability of survival (the 10%:10% rule, resulting in only 1% becoming problematic (Williamson, 1996)), will occasionally result in the establishment of populations that expand rapidly, causing invasions which are highly predictable in general but highly unpredictable in detail. Thus, a key lesson is "to expect the unexpected".

Conservation action needs to both prevent serious loss of biodiversity and hence ecosystem function, and to restore past damage. The work of the Soil Conservation Service in Iceland demonstrates the difficulty of restoring grossly damaged ecosystems, how long the process is likely to take, and the potential problems that can be caused by non-native, invasive species. In a changing environment it is also necessary to recognize that a few of the wild relatives of cultivated plants occur in the Arctic (Heywood and Zohary, 1995). Being on the northern edge of their ranges, these might have particular genetic traits that prove valuable in breeding new varieties of crop plants for use under different climatic conditions.

10.2.6. Conservation of arctic species

The Arctic is generally species-poor compared with other large geographical areas of the world. There are, however, a number of charismatic species that capture people's imagination; including the polar bear, the reindeer or caribou (*Rangifer tarandus*), the gyrfalcon (*Falco rusticolus*), and the apparently frail Arctic poppy (*Papaver polare*). Terrestrial mammals number only 48 species, although some might be more properly considered as subarctic species, straying into the Arctic by a short distance only. Of these 48 species, 9 occur in Greenland, 29 in Alaska, 31 in the Canadian Arctic, and 33 in the Russian Arctic. Sage (1986) lists these species, but noted some taxonomic uncertainties which could result in these numbers changing slightly following further taxonomic research. Corresponding figures for breeding birds, noting the caveat that some species breed only very occasionally in the Arctic, are 183 for the Arctic as a whole, and 61, 113, 105, and 136 for Greenland, Alaska, Canada, and Russia respectively.

Arctic species, especially mammals and birds, feature strongly in books on wildlife (e.g., CAFF, 2001; Sage, 1986) and ecology (e.g., Chernov, 1985; Stonehouse, 1989). The purpose of this section is not to list the species of the Arctic, but to reinforce the ecological characteristics of the species that live in the Arctic. An understanding of these characteristics is essential for the conservation management of the Arctic's biodiversity.

The main characteristic essential for a species to survive in the Arctic is the ability to cope with cold temperatures. Most species have evolved strategies for surviving the arctic winter, i.e., cold tolerance, with the remainder developing strategies for cold avoidance. There are many ways of developing cold tolerance. For mammals that spend the whole year in the Arctic, this often involves depositing a layer of fatty tissue under the skin, as occurs in species of whales and seals. These species provide a valuable resource for the local human populations that harvest them for meat and for the oil that can be extracted from the blubber. A similar physiological system is used in some seabirds, such as the Atlantic puffin (*Fratercula arctica*), a vital oily food in the diet of the former inhabitants of the North Atlantic island of St. Kilda (Quine, 1989).

Invertebrate animals have a different system of cold tolerance. They accumulate glycerol in their tissues and, although they are usually susceptible to freezing, are able to "supercool" whereby the body fluids remain liquid at temperatures well below the freezing point (Sømme and Conradi-Larsen, 1977a). The majority of the alpine, arctic, and antarctic insects and mites are able to supercool, developing glycerol concentrations of up to 42 µg/mg of fresh weight and being able to survive temperatures below -15 ºC (Sømme, 1981). This has an effect on the life cycles of these invertebrates in that they cannot reach the reproductive state until they are two to three years old, largely because they have to empty their guts before they supercool and have relatively limited opportunities for growth during the short arctic summer (Birkemoe and Sømme, 1998; Sømme and Birkemoe, 1999). However, it is known that some species enter a reproductive diapause when reared at constant temperature in the laboratory (e.g., the collembolan *Hypogastrura tullbergi*), and that this diapause can only be terminated by exposure to cold (Birkemoe and Leinaas, 1999). This poses the question as to whether, with the warming of the terrestrial environment, some invertebrate species may be unable to breed. Hodkinson et al. (1998) have reviewed the whole subject in relation to invertebrates that live in arctic soils.

Cold avoidance is a strategy adopted by a number of species of vertebrate animals. Arctic rodents, such as the insular vole (*Microtus abbreviatus*) of the Alaskan and
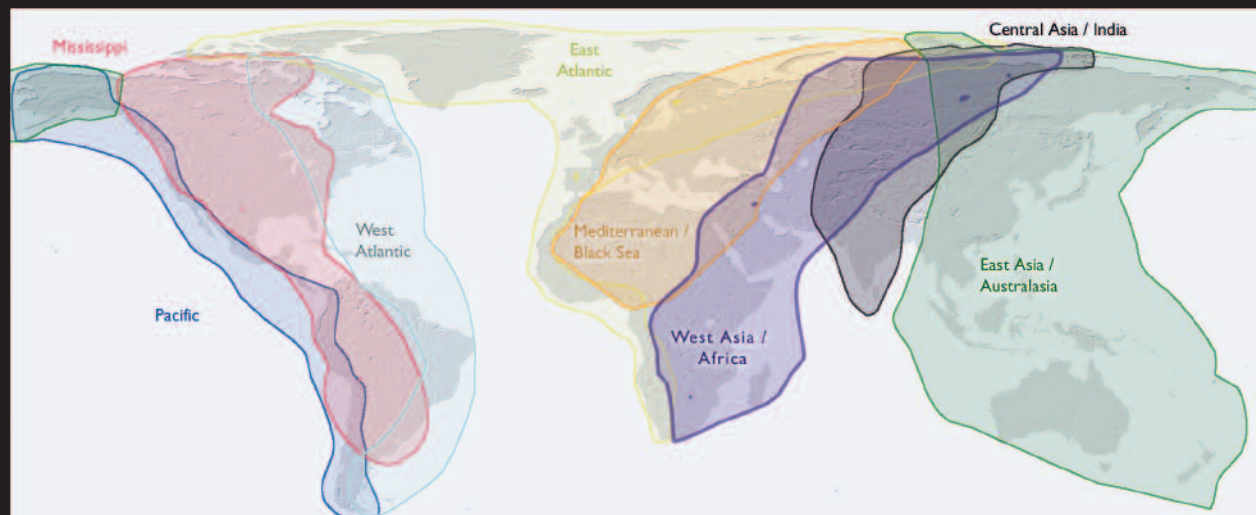

Fig. 10.4. The eight main international flyways used by shorebirds (waders) on migration. Within each flyway reasonably constant routes are used between the breeding grounds and the wintering grounds, although the southbound and northbound routes might differ. Each flyway comprises many different individual routes used by the different species and by different populations within a species. All arctic areas used by breeding shorebirds are included in these eight flyways. (Based on Thompson D. and Byrkjedal, 2001).

Canadian Arctic, avoid the coldest conditions by living within or under the snow (Stonehouse, 1989). Reindeer and caribou migrate to the forest on the southern edge of the Arctic, to over-winter in the more sheltered conditions of the boreal forest, before migrating north in the spring to the arctic tundra grazing grounds. Many of the fish species of the Arctic Ocean follow the edge of the sea ice in its seasonal movements southward during the autumn/winter and northward in the spring/summer.

Some species of bird have perfected the cold avoidance strategy by undergoing long-distance migrations. BirdLife (2002) featured the movement of the buff-breasted sandpiper (*Tryngites subruficollis*) which nests predominantly in the Canadian Arctic (with a small population in the Alaskan Arctic), but over-winters in South America in an area stretching from southern Brazil, through the northeast corner of Argentina, and into Paraguay. This is an example of one of the eight recognized flyways, known as the Mississippi Flyway, for shorebirds that breed in the Arctic (Thompson D. and Byrkjedal, 2001). Figure 10.4 shows the routes between the arctic breeding grounds, the staging areas which allow the birds to feed while they are *en route*, and the wintering grounds (which are often in the Southern Hemisphere). Conservation efforts for these migratory species must be international so that the species gain protection along the whole of flyway as well as in the arctic breeding grounds.

It is more difficult to characterize the strategies of plants in terms of cold tolerance or cold avoidance. Virtually all arctic plants are perennial, and so are able to reproduce over several years or remain in a vegeta-

Fig. 10.5. The snow gentian is one of the very few species of vascular plants in the Arctic that have an annual life history; germinating, flowering, and setting seed within the short growing season of the arctic summer. (Photo: M.B. Usher, July 1997).

tive state until climatic conditions in a particular year favor reproduction. Perennial plants have overwintering organs, such as roots and buds, which are protected by snow or soil from the coldest temperatures. One of the very few annual species is the snow gentian (*Gentiana nivalis*), which occurs in the north American Arctic and Greenland; in Europe it is predominantly a mountain species (Fig. 10.5). The snow gentian flowers and sets seed rapidly in the summer, and is said to have a seed bank so that it can survive climatically adverse years without flowering or with very restricted flowering, and hence demonstrates extreme year-to-year variability in population size (Raven and Walters, 1956).

Anoxia is a potential problem for species that over-winter in the Arctic. Marine mammals surface in order to obtain fresh air, and use a number of ways to maintain breathing holes in sea ice. The migration of fish in relation to the extent of the sea ice may also be related to the oxygen content of the seawater as well as to temperature. Terrestrial invertebrates have also developed mechanisms to cope with anoxia: for example, the two mite species studied by Sømme and Conradi-Larsen (1977b) survived for at least three months at 0 °C under anoxic conditions, whereas a species from further south in Norway died within six to eight days under similar conditions. Arthropods form lactate under anoxic conditions, with concentrations rising to nearly 2 µg/mg fresh weight, indicating this as a possible mechanism for coping with the anaerobic conditions that might prevail in arctic soils during winter.

As well as developing strategies for cold tolerance and cold avoidance, arctic species need to cope with freeze–thaw cycles in spring and autumn, and warm conditions in summer when there might be excess water due to the ice melt or desiccation due to low precipitation (Hodkinson et al., 1998). Over the year, each species has to be able to survive many ecological conditions. This is particularly evident in two features of arctic populations: extended life cycles and extreme year-to-year variability in population size.

It has already been mentioned that very few arctic plant species are annuals, and that the soil arthropods are generally not reproductive until two or three years old (whereas in temperate Europe and North America such species would have at least one generation per year). An example of the extended life cycle was given by CAFF (2001) where the life cycle of "woolly bear" larva of the moth *Gynaephora groenlandica* can vary from 7 to 14 years. In much of northern Europe and America such "woolly bears" (of other moth species) have an annual life cycle.

There is often extreme year-to-year variability in the sizes of arctic populations. This is particularly evident in relation to the occasional outbreaks of the autumnal moth, *Epirrita autumnata*. The larvae of this moth can cause widespread defoliation of downy birch (*Betula pubescens*) trees, for example in Arctic Finland, and in the most severe cases the trees subsequently die. These two

features of arctic populations – the extended life cycles and the extreme fluctuations in size – both make conservation management, and particularly the monitoring of species, more difficult.

Although the Arctic might be species-poor compared to other regions of the world, there are very few arctic species that are currently threatened with extinction. BirdLife (2002) produced a world map, shaded from white (no species of bird known to be threatened with extinction), through shades of yellow and orange, to red (where at least 25 species are threatened). The majority of the Arctic is white, although there are some areas of pale yellow in the Russian Arctic. How this map might change with climatic warming is not known, but the situation in the Arctic at the start of the 21st century is healthier than in virtually any other major geographical region. If the arctic environment is conserved, with particular attention given to arctic ecosystems (Muir et al., 2003), it is possible that a smaller proportion of the Arctic's species will be threatened with extinction than in other geographical areas.

This ecosystem approach to conservation has been defined as "the comprehensive integrated management of human activities based on best available scientific knowledge about the ecosystem and its dynamics, in order to identify and take action on influences which are critical to the health of the ecosystems, thereby achieving sustainable use of ecosystem goods and services and maintenance of ecosystem integrity" (as quoted by Muir et al., 2003). The ecosystem approach can thus be applied either to the marine environment or to the terrestrial and freshwater environments of the Arctic, and is discussed further in section 10.5. It is fundamental to the conservation of any species that its ecosystem is conserved, with its variety of species and the genetic variability of those species. As relatively few arctic species are currently threatened with extinction, the Arctic must be one of the places where an ecosystem approach can most readily be adopted, bringing together the human, plant, animal, microbial, marine, freshwater, and terrestrial perspectives.

10.2.7. Incorporating traditional knowledge

Other chapters within this assessment address the impacts of climate change on indigenous peoples and local communities, as well as on their traditional lifestyles, cultures, and economies. Other chapters also report on the value of traditional knowledge, and the observations of indigenous peoples and local communities in understanding past and future impacts of climate change. This section focuses on the relationship between biodiversity and climate change, impacts on indigenous peoples, and the incorporation of traditional knowledge.

There has been increasing interest in recent years in understanding traditional knowledge. Analyses often link traditional knowledge with what is held sacred by local peoples. Ramakrishnan et al. (1998) explored these links

with a large number of case studies, largely drawn from areas of India, but also including studies based in other parts of Asia, Africa, the Middle East, and southern Europe. A focus on northern America, again with a number of case studies, was reported by Maynard (2002). The many case studies demonstrate that traditional knowledge is held by peoples worldwide, except perhaps in the most developed societies where the link between people and nature has largely been broken. A recognition of this breakdown is the first step toward restoring biodiversity and its conservation in a changing world using knowledge that has been built up over centuries or millennia. As Ramakrishnan et al. (2000) reported "although the links between traditional ecological knowledge on the one hand, and biodiversity conservation and sustainable development on the other, are globally recognized, there is a paucity of models which demonstrate the specificity of such links within a given ecological, economic, socio-cultural and institutional context". They state that "we need to understand how traditional societies…have been able to cope up with uncertainties in the environment and the relevance of this about their future responses to global change". These concepts point the way to a greater integration of the knowledge of indigenous peoples into the present and future management of the Arctic's biodiversity.

A recent report by the Secretariat for the Convention on Biodiversity on interlinkages between biological diversity and climate change (SCBD, 2003) specifically addresses projected impacts on indigenous and traditional peoples. The term "traditional peoples" is used by the Intergovernmental Panel on Climate Change in its report on climate change and biodiversity (IPCC, 2002) to refer to local populations who practice traditional lifestyles that are often rural, and which may, or may not, be indigenous to the location. This definition thus includes indigenous peoples, as used in the present assessment. The SCBD report began by noting that indigenous and traditional peoples depend directly on diverse resources from ecosystems for many goods and services. These ecosystems are already stressed by current human activities and are projected to be adversely affected by climate change (SCBD, 2003). In addition to incorporating the main findings of the IPCC report (IPCC, 2002), the SCBD report concluded as follows:

1. The effects of climate change on indigenous and local peoples are likely to be felt earlier than the general impacts. The livelihood of indigenous peoples will be adversely affected if climate and land-use change lead to losses in biodiversity, especially mammals, birds, medicinal plants, and plants or animals with restricted distribution (but have importance in terms of food, fiber, or other uses for these peoples) and losses of terrestrial, coastal, and marine ecosystems that these peoples depend on.

2. Climate change will affect traditional practices of indigenous peoples in the Arctic, particularly fisheries, hunting, and reindeer husbandry. The ongoing interest among indigenous groups relating

to the collection of traditional knowledge and their observations of climate change and its impact on their communities could provide future adaptation options.

3. Cultural and spiritual sites and practices could be affected by sea-level rise and climate change. Shifts in the timing and range of wildlife species due to climate change could impact the cultural and religious lives of some indigenous peoples. Sea-level rise and climate change, coupled with other environmental changes, will affect some, but not all, unique cultural and spiritual sites in coastal areas and thus the people that reside there.

4. The projected climate change impacts on biodiversity, including disease vectors, at the ecosystem and species level could impact human health. Many indigenous and local peoples live in isolated rural living conditions and are more likely to be exposed to vector- and water-borne diseases and climatic extremes and would therefore be adversely affected by climate change. The loss of staple food and medicinal species could have an indirect impact and can also mean potential loss of future discoveries of pharmaceutical products and sources of food, fiber, and medicinal plants for these peoples.

The SCBD report commented directly on the incorporation of traditional knowledge and biodiversity by noting that the collection of traditional knowledge, and the peoples' observations of climate change and its impact on their communities, could provide future adaptation options. Traditional knowledge can thus be of help in understanding the effects of climate change on biodiversity and in managing biodiversity conservation in a changing environment, including (but not limited to) genetic diversity, migratory species, and protected areas. The report also noted the links between biodiversity conservation, climate change, and cultural and spiritual sites and practices of indigenous people, emphasizing that shifts in the timing and range of wildlife species could impact on the cultural and religious lives of some indigenous peoples. A detailed consideration of the links between cultural and spiritual sites and practices on the one hand and indigenous peoples on the other has been published recently (CAFF, 2002b). Although this report focused on sacred sites of indigenous peoples in the Yamal-Nenets Autonomous Okrug and the Koryak Autonomous Okrug in northern Russia, it also examined wider arctic and international aspects with some consideration given to the conservation value of sacred sites for indigenous peoples in Alaska and northern Canada.

Local people have knowledge about biodiversity, although it might neither be recognized as such nor formulated using the terminology of scientific biodiversity, that can be of great assistance in the management of arctic biodiversity. Muir (2002b) discussed the models and decision frameworks for indigenous participation in coastal zone management using Canadian experience, and pointed out that commercial harvesting of fish and marine mammals, as well as the effects of tourism, can conflict with local peoples' subsistence harvesting rights for fish and marine mammals. Traditional knowledge is multi-faceted (Burgess, 1999) and very often traditional methods of harvesting and managing wildlife have been sustainable (Jonsson et al., 1993). It is these models of sustainability that need to be explored more fully as the biodiversity resource changes, and the potential for its sustainable harvesting changes with a changing climate.

10.2.8. Implications for biodiversity conservation

In terms of conserving arctic ecosystems and habitats, CAFF (2002a) stated that "the overall goal is to maintain and enhance ecosystem integrity in the Arctic and to avoid habitat fragmentation and degradation". This goal is elaborated by recognizing the holistic nature of biodiversity conservation, including not just the flora and fauna, but also the physical environment and the socio-economic environment of people living within the area. It is the socio-economic factors that particularly affect arctic ecosystems, exerting pressures that have the potential to degrade habitats, to force declines in population sizes and numbers of species, and to reduce the functioning of ecosystems. Habitat fragmentation is probably the greatest threat to arctic ecosystems, which seem particularly ill-equipped to deal with it.

Although an important means of conserving the natural and cultural heritage is through protected areas, it is not a panacea. The arctic countries, through CAFF, have promoted the establishment of the Circumpolar Protected Area Network (CPAN), which aims to link protected areas throughout the Arctic; to ensure adequate representation of the various biomes; and to increase the public's understanding of the benefits and values of protected areas throughout the Arctic.

This is a useful start to the conservation of the arctic biodiversity, but many productive areas, such as coastal zones and marine ecosystems, are currently very underrepresented in the CPAN (CAFF, 2002a). At best, protected areas will only cover a relatively small proportion of the total land and sea area of the Arctic, and so conservation thinking is required beyond the established protected areas. This means that conservation of biodiversity must be integral to all aspects of social policy, including health and education of local people, planning for visitors and the associated developments, control and regulation of developments, and all aspects of the use of land, water, and air. Biodiversity conservation must be an important aspect of thinking, or as CAFF (2002a) stated, there needs to be a principle of "conservation first".

CAFF recommended that "the Arctic States in collaboration with indigenous people and communities, other Arctic residents, and stakeholders (1) identify important freshwater, marine and terrestrial habitats in the Arctic and ensure their protection through the establishment of protected areas and other appropriate conservation measures, and (2) promote an ecosystems approach to

resource use and management in the circumpolar Arctic, through, *inter alia*, the development of common guidelines and best practices". This provides a way forward, but the generalities need to be expanded into the detail needed for the practical application of biodiversity conservation alongside the sustainable development of the Arctic, and the sustainable use of its resources, for the benefit of local people and visitors alike. A consensus approach, as fostered at an Arctic Council meeting on freshwater, coastal, and marine environments (Muir et al., 2003), needs to be promoted and developed on a circumpolar basis.

10.3. Human impacts on the biodiversity of the Arctic

The projected climatic changes in the Arctic, particularly the projected decrease in sea-ice extent and thickness, will result in increased accessibility to the open ocean and surrounding coastal areas. This is very likely to make it easier to exploit marine and coastal species, over a larger area and for a greater proportion of the year. Decreased extent and thickness of sea ice and increased seawater temperatures will, however, also result in changes in the distribution, diversity, and productivity of marine species in the Arctic and so will change the environment for hunters and indigenous peoples. However, increased traffic and physical disturbance caused by increased access to the marine areas is likely to pose a more significant threat to biodiversity than increased hunting pressure. On land, snow and ice cover in winter enable access into remote areas by snowmobile and the establishment of ice roads; however, in summer, transportation and movement become more difficult. A shorter winter season and increased thawing of permafrost in summer, potentially resulting from a warming climate, could reduce hunting pressure in remote areas.

There are at least four types of pressure acting on marine, coastal, freshwater, and terrestrial habitats that affect both their conservation and biodiversity: (1) issues relating to the exploitation of species, especially stocks of fish, birds, and mammals, and to forests; (2) the means by which land and water are managed, including the use of terrestrial ecosystems for grazing domesticated stock and aquatic ecosystems for aquaculture; (3) issues relating to pollutants and their long-range transport to the Arctic; and (4) development issues relating to industrial development and to the opening up of the Arctic for recreational purposes. These factors were discussed by Hallanaro and Pylvänäinen (2002) and Bernes (1993), who included hydroelectricity generation as a major impact on freshwater systems.

10.3.1. Exploitation of populations

Exploitation and harvest of living resources have been shown to pose a threat to arctic biodiversity. Species like the Steller sea cow (*Hydrodamalis gigas*), in the Bering Sea, and the great auk (*Pinguinus impennis*), in the North Atlantic, were hunted for food by early western explor-

ers and whalers, and became extinct in the 18th and 19th centuries, respectively. Increasing demands for whale products in Europe, and improvements to the ships and harvesting methods intensified the exploitation of several arctic baleen whale species from the 17th century onward. Over-exploitation resulted in severely depleted populations of almost all the northern baleen whale species, and few have recovered their pre-17th century population sizes. For example, even though a few individuals have been observed in recent years, the bowhead whale (*Balaena mysticetus*) is still considered extinct in the North Atlantic. The Pacific population is bigger, but still considered endangered. Both subpopulations used to number in the tens of thousands. Many baleen whales, feeding on zooplankton, were a natural part of the arctic ecosystems 400 years ago. Their large biomass implies that they may have been a "keystone" species in shaping the biodiversity of the Arctic Ocean.

Many populations of charismatic arctic species have been over-exploited over the last few hundred years. The history of the slaughter of walruses (*Odobenus rosmarus*) in the North Atlantic and Pacific is well documented (Gjertz and Wiig, 1994, 1995). The walrus survived because its range of distribution included inaccessible areas, and the species is now expanding back into its previous distributional range due to its protection and to a ban on harvesting the animals in many areas. The International Polar Bear Treaty (1973) protected the polar bear (*Ursus maritimus*) after several sub-populations became severely depleted due to hunting (Prestrud and Stirling, 1994). Some subspecies of reindeer/caribou have also been close to extinction due to hunting pressure both in the European and North American Arctic (Kelsall, 1968). Similarly, several goose populations have approached extinction due to hunting on the breeding and wintering grounds (Madsen et al., 1999).

There have also been effects on a number of tree species. Wood has always been a valued commodity and since the first human populations were able to fell trees and process the felled trunks, forests have been cut for their timber. During the last few centuries, systems of forest management have developed to enable the forest to be regenerated more rapidly, either naturally or artificially by planting young trees. The need to exploit these

Table 10.4. Percentage distribution of age classes of coniferous forests in countries with arctic territory (Hallanaro and Pylvänäinen, 2002). The index, *I*, is the ratio of the percentage of trees over 80 years old to the percentage less than 40 years old, and so indicates the naturalness of the forests.

	0–40 yr	41–80 yr	81–100 yr	>100 yr	Index (*I*)
Murmansk (Russia)	31	19	5	45	1.61
Norway	33	21	13	33	1.39
Finland	32	33	13	22	1.09
Karelia (Russia)	40	19	7	34	1.02
Sweden	52	22	10	16	0.50

Fig. 10.6. The reef forming deep-sea coral, *Lophelia pertusa* (white coral, upper left hand corner), occurs on the continental shelf and shelf break off the northwest European coast. The red gorgonian, *Paragorgia arborea*, occurs on these reefs. The brittle star, *Gorgonocephalus caputmedusae* (yellow, center), frequently occurs on top of the gorgonians to take advantage of stronger currents. (Photo: CAFF, 2001; reproduced with permission from CAFF, Iceland).

Fig. 10.7. Fragments and larger pieces of dead coral, *Lophelia pertusa*, from a trawling ground on the Norwegian continental shelf at a depth of about 190 m. The benthic communities have been severely disturbed and are virtually devoid of larger animals. (Photo: CAFF, 2001; reproduced with permission from CAFF, Iceland).

forests for wood is demonstrated by the age structure of the trees in national forest estates (Table 10.4). Natural (unmanaged) forests have a large proportion of old trees compared to young trees, whereas managed forests have a large proportion of younger trees (often managed on rotations of 40 to 80 years). Table 10.4 appears to indicate a positive correlation between northerliness and naturalness (indicated by the index, *I*).

Since around the 1970s, modern management systems, improved control, and changed attitudes have largely diminished threats from sports hunting and harvesting for subsistence purposes. Most of the previously over-exploited populations are recovering or showing signs of recovery. However, there are still examples where hunting is a problem. In accordance with the International Polar Bear Treaty, local and indigenous peoples are allowed to hunt polar bears. In Canada, populations in some of the 14 management areas were over-exploited in the 1990s, and hunting was stopped periodically in some of these areas (Lunn et al., 2002). Similarly, in Greenland, uncertainties about the number of polar bears taken, and about their sex and age composition, have created concerns about the sustainability of the current harvest (Lunn et al., 2002). In southwestern Greenland, seabird populations have been over-exploited for a number of years by local peoples and the populations of guillemots (*Uria* spp.) have decreased by more than 90% in this area (CAFF, 2001).

Arctic and subarctic oceans, like the Barents, Bering, and Labrador Seas, are among the most productive in the world, and so have been, and are being, heavily exploited. For example, (1) commercial fish landings in Canada decreased from 1.61 million tonnes in 1989 to 1.00 million tonnes in 1998 (Anon, 2001a); (2) the five-fold decline in the cod (*Gadus morhua*) stock in the Arctic Ocean between about 1945 and the early 1990s; and (3) the huge decline (more than 20-fold) in the herring

(*Clupea harengus*) stock in the Norwegian Sea (Bernes, 1993). A report on the status of wildlife habitats in Canada stated that "Canadian fisheries are the most dramatic example of an industry that has had significant effects on the ocean's habitats and ecosystems" (Anon, 2001a).

Considerable natural annual variability in productivity, mainly due to variations in the influx of cold and warm waters to the Arctic, is a considerable challenge for fisheries management in the Arctic. Collapses in fish populations caused by over-exploitation in years of low productivity have occurred frequently and have resulted in negative impacts on other marine species. The stocks of almost all the commercially exploitable species in the Arctic have declined, and Bernes (1993) went as far as to state that several fish stocks are just about eliminated. Hamre (1994) suggested that the relative occurrence of species at some trophic levels has been displaced. Such changes in the few commercially-valuable fish species can have tremendous impacts on the coastal communities which are dependent upon the fishing industry for their livelihoods (CAFF, 2001). Even though supporting information is scarce, it is likely that the disappearance of the big baleen whales and the heavy exploitation (or over-exploitation) of fish stocks over many years have changed the original biodiversity and ecosystem processes of the subarctic oceans.

Heavy exploitation of benthic species, such as shrimps and scallops, also affects other species in the benthic communities. Bottom trawls damage species composition and so affect the food web. An example is the damage that can be caused to the cold water coral community. This coral reef habitat, often in deep water near the edge of the continental shelf, supports many other species such as gorgonians and brittle stars (Fig. 10.6). Passes over this community with a trawl leave only fragments of dead coral that can support no other species (Fig. 10.7). It has been estimated that, within commercial fishing grounds, all points on the sea floor are trawled at least twice per year.

10.3.2. Management of land and water

Changes in both land and water use influence biodiversity in the Arctic. This is different to the situation in most of the more southern biomes where changes in land use predominate (Sala and Chapin, 2000). In the Arctic, the limited expansion of forestry and agriculture is likely to be restricted to particularly productive environments, although there is greater potential for aquaculture in the Arctic.

In the Arctic, the original change in land use might not be obvious and impacts may be progressive and long-lasting. Thus the gradual increase in grazing pressure, particularly by sheep, has resulted in the loss of sward diversity and eventual soil erosion. This was probably a contributory factor in the extinction of agricultural colonies in Greenland between AD 1350 and 1450. In Iceland, "desert" with unstable and eroding soils resulted from a combination of removal of the 25% forest cover and the introduction of sheep since settlement in the 9th century. Soil rehabilitation is now a priority, but is a long, slow process. Establishment of long-term grass swards has had some success, and planting birch (*Betula pubescens*) and native willows (*Salix lanata* and *S. phylicifolia*) is proving a successful conservation measure, using mycorrhizal inocula, for re-establishing species and habitat diversity of grasslands, shrublands, and woodlands that were lost through overgrazing (A. Aradottir, Icelandic Soil Conservation Service, pers. comm., 2004; Enkhtuya et al., 2003) although non-native species can cause problems.

Draining of peatlands, and other wetlands including marshes and salt marshes, has been widely undertaken to bring the land into productive use, mainly for forestry but to a limited extent also for agriculture. In general there is an inverse correlation between the extent of drainage and northerliness. Data for relatively small areas are not available, but national data are presented in Table 10.5. The index, P, gives an indication of how much of the national peatland has been drained, which in the most northerly areas is relatively small. Drainage has a major impact on biodiversity. Invariably

Fig. 10.8. In Norwegian Finnmark the number of reindeer trebled between 1950 and 1989 resulting in extensive overgrazing of the vegetation. The ground to the left and above the fence had been overgrazed, while that to the right and in the foreground had been protected from grazing. Note the presence of shrubs and the green nature of the herbaceous ground cover. (Source: Hallanaro and Pylvänäinen, 2002; reproduced with permission from Georg Bangjord, Statens Naturoppsyn, Norway).

most of the species characteristic of the wetland are lost, except where small populations survive in drainage ditches. The newly created habitats are more prone to invasion by non-native species, and soil erosion may become more problematic. Migratory bird species may lose nesting places, and the land cannot retain as much water as before and so runoff increases during and immediately after storms. Drainage therefore has a major effect on the functioning of ecosystems, as well as encouraging biodiversity loss, usually for very limited economic gains at a time when climate change is likely to increase both the risk and rate of desertification in the Arctic. Biodiversity conservation in the Arctic should recognize the importance of wetlands as functional ecosystems with their full biodiversity complement.

Overgrazing on the tundra can be severe; the subject has been reviewed by Hallanaro and Usher (in press). In Finland, there were around 120 000 reindeer at the start of the 20th century. This increased to around 420 000 animals by 1990, but subsequently declined to around 290 000 animals by 2000. The effects of overgrazing are clearly shown wherever areas of countryside are fenced off. Figure 10.8 shows an area of Norwegian Finnmark where the density of reindeer trebled between 1950 and 1989. Overgrazing eliminates ground cover by shrubs and dwarf shrubs, as well as reducing the cover of herbs,
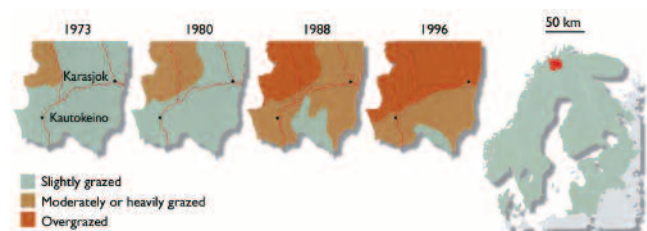
Table 10.5. Extent of peatland (Data: Hallanaro and Pylvänäinen, 2002). The index, P, is the proportion of the total peatland not drained (the figure in the second column minus the sum of the figures in the third and fourth columns) to the total peatland area. Because different countries use different definitions for peatland, the data are not comparable between countries, although the values of P are comparable between countries.

Country	Total area of peatland (million hectares)	Area drained for forestry	Area drained for agriculture	P
Iceland	1.00	Small	0.13	0.86
Karelia (Russia)	5.40	0.64	0.09	0.86
Norway	3.00	0.41	0.19	0.80
Sweden	10.70	1.50	0.60	0.80
Finland	10.40	5.70	0.60	0.39

Fig. 10.9. Changes in grazing pressure in Finnmarksvidda, northern Norway, between 1973 and 1996. The increase in areas of lichen communities assessed as being overgrazed rises from none in 1973 to approximately two-thirds of the area in 1996. (Source: Hallanaro and Pylvänäinen, 2002; reproduced with permission from The Nordic Council of Ministers, Denmark).

grasses, and lichens. A more detailed analysis of the area where this photograph was taken is shown in Fig. 10.9. Over the 23 years from 1973 to 1996, the area changed from one having around a sixth of the land being moderately to heavily grazed (with the remainder being slightly grazed), to one having around two-thirds being overgrazed, a little under a third being moderately to heavily grazed, and only a small proportion (probably less than 5%) being slightly grazed.

The long-term effects of overgrazing are unknown, but if it results in the elimination of key species, such as shrubs, the recovery of the overgrazed ecosystems will be very slow. If all the key plant species remain in the community, even at very low densities, and are able to re-grow and set seed after the grazing pressure is lifted, then recovery could be faster. Two factors are important – the intensity of the grazing pressure and the period of time over which it occurs. Experimental exclosures have shown that, once grazing pressure by large herbivores is lifted, the regrowth of shrubs and tree species can be remarkable. Outside the fence, willows are reduced to small plants, of no more than a couple of centimeters high and with a few horizontal branches of up to 20 cm. These plants have few leaves and generally do not flower. Inside the fence the willows grow to at least 40 cm high, and are full of flowers with abundant seed set (Fig. 10.10). It is unknown how long these dwarf, overgrazed plants can both survive and retain the ability to re-grow after the grazing pressure is reduced. There have been no studies on the associated invertebrate fauna of these willows. So, it also unknown whether the phytophagous insects and mites are able to survive such a "bottleneck" in the willow population, or for how long they can survive these restricted conditions.

Although the vascular plants are the most obvious, it is the lichen component of arctic habitats that can be most affected by overgrazing. In areas with reindeer husbandry, the lichen cover has generally thinned on the winter grazing grounds. In the most severely impacted

Fig. 10.10. Whortle-leaved willow (*Salix myrsinites*) fruiting and growing in a grazing exclosure on limestone grassland that had been heavily overgrazed. After about 20 years without grazing by sheep or deer, this willow forms an understorey with other shrubs to a sparse woodland of birch (*Betula pubescens*) and rowan (*Sorbus aucuparia*) trees. (Photo: M.B. Usher, June 1998).

areas the lichens have been almost completely grazed out of the plant communities, or have been trampled, exposing bare ground which is then subject to erosion. Lichens, which are capable of surviving the harshest of environmental conditions, are frequently the most important photosynthetically active organisms in tundra ecosystems. Albeit slow-growing, many lichen species only thrive at low temperatures, and there is concern that if climate change results in a reduction in the number of lichen species or individuals, there could be a massive release of CO_2 to the atmosphere (Dobson, 2003). The combination of very low growth rates, overgrazing by domesticated or wild mammals and birds, and climate change indicates that large areas of the Arctic are susceptible to huge habitat changes in the future. Potentially, the lichen cover could be replaced by bare ground, with the risk of erosion by wind and running water, or by species that are currently not native to the Arctic.

Forests provide shelter during the coldest months of the year, and some of the mammals that feed on the tundra in summer migrate to the forests in winter. Pressure on herbaceous ground vegetation, especially on the lichens, can be severe. This is likely to be more of a problem in managed forests where the trees are grown closer together, less light reaches the forest floor, and the herbaceous and lichen layer is thus sparser. Overgrazing of the forest floor vegetation, including the young regeneration of tree species, is a problem in some areas and a potential problem in all other areas. Overgrazing, however, may not just result from agricultural and forestry land use; it may also result from successful conservation practices. For example, the population of the lesser snow goose (*Chen caerulescens*) in northern Canada rose from 2.6 million in 1990 to 6 million in 2000 as a result of protection. In summer, the geese feed intensively on the extensive coastal salt marshes (of western Hudson Bay), but large areas are now overgrazed, the salinity of the marshes is increasing, and vegetation has deteriorated. These examples demonstrate the potential fragility of ecosystems in which the food web is dominated by a few key species – a situation not uncommon in the Arctic.

The introduction of species into species-poor northern ecosystems is a disturbance which can have major impacts on the existing flora and fauna. The impact of introduced foxes and rats on seabird populations on arctic islands is particularly strong. A similar situation also occurs when new species are introduced into isolated freshwater ecosystems or when conditions change within a lake. For example, opossum shrimps (*Mysis relicta*) were introduced into dammed lakes in the mountains of Sweden and Norway by electric companies to enhance prey for burbot (*Lota lota*) and brown trout (*Salmo trutta*). Unexpectedly, the shrimps ate the zooplankton that was a food source for Arctic char (*Salvelinus alpinus*) and whitefish (*Coregonus lavaretus*), leading to an overall decline in fish production. Arctic char provide many interesting insights into arctic species. The resident population in Thingvallavatn, Iceland, was isolated from the sea 9600 years ago by a volcanic eruption, and became

trapped within the lake. There are now four distinct forms that, although closely related genetically, are very different with respect to morphology, habitat, and diet. The Arctic has been described as a "theatre of evolution" as the few resident species capitalize on those resources that are not contested by other species. This encourages genetic diversification, a feature that is strongly shown by the Arctic char, a genetically diverse species and the only freshwater fish inhabiting high-arctic waters (Hammer, 1989, 1998).

The subtle and sensitive interactions within food webs are illustrated by an experiment at Toolik Lake LTER (Long Term Ecological Research) site in Alaska. Lake trout (*Salvelinus namaycush*) play a key role controlling populations of zooplankton (*Daphnia* spp.), snails (*Lymnaea elodes*), and slimy sculpin (*Cottus cognatus*). To test the hypothesis that predation by lake trout controls populations of slimy sculpin, all large trout were removed from the lake. Instead of freeing slimy sculpin from predation, the population of burbot rapidly expanded and burbot became an effective predator, restricting slimy sculpin to rocky littoral habitats, and allowing the density of its prey, chironomid larvae, to remain high. This is an example of changes in "top-down" control of populations by predators, contrasting with "bottom-up" control in which lower trophic levels are affected by changes in nutrient or contaminant loading (Vincent and Hobbie, 2000; see also Chapter 8).

Disturbance resulting from management in marine ecosystems has not been widely studied, other than by observing the impacts of trawling on seabed fauna and habitats (Figs. 10.6 and 10.7) and preliminary consideration of the potential impacts of invasive species through aquaculture, ballast water, and warming (Muir et al., 2003). Impacts of trawling are not particularly apparent in shallow waters where sediments are soft and organisms are adapted to living in habitats that are repeatedly disturbed by wave action. In deeper waters, undisturbed by storms and tides, large structural biota have developed, such as corals and sponges, and which provide habitats for other organisms. These relatively long-lived, physically fragile communities are particularly vulnerable to disturbance and are not adapted to cope with mechanical damage or the deposition of sediment disturbed by trawls.

Fish farming also affects marine ecosystems. This can be local due to the deposition of unused food and fish feces on the seabed or lake floor near the cages in which the fish are farmed. Such deposits are poor substrates for many marine organisms, and bacterial mats frequently develop. There can also be polluting effects over wider areas due to the use of veterinary products. Over a wider area still, escaped fish can interbreed with native fish stocks, thereby having a genetic effect. Thus, commercial fishing and fish farming can have adverse effects on arctic biodiversity. Sustainable management practices may be difficult to develop, but their introduction and implementation are essential if the fishery industries are to persist into the future.

There is a particular need to assess the potential problems faced by migratory fauna. The challenges met by migratory species are illustrated by the incredible dispersion of shorebirds to wintering grounds in all continents (Fig. 10.4). Recent evidence on waders from the East Atlantic flyway compares the population trends in seven long-distance migrant species that breed in the high Arctic with 14 species that have relatively short migrations from their breeding grounds in the subarctic. The long-distance migrants all show recent population declines and are very dependent on the Wadden Sea on the Netherlands coast as a stopover feeding ground. The waders with shorter migrations are much less dependent on the Wadden Sea and show stable or increasing populations. The emerging hypothesis is that waders with long migrations are critically dependent on key stopover sites for rapid refueling. For the Wadden Sea, although the extent available has not changed, the quality of resources available has declined through expansion of shellfish fisheries (Davidson, 2003).

There is evidence of a similar impact on migratory waders at two other sites. In Delaware Bay, a critical spring staging area in eastern North America, the impact is again due to over-exploitation of food resources by people. Similarly, the requirements of people and waders are in conflict in South Korea where a 33 km seawall at Saemangeum has resulted in the loss of 40 000 hectares of estuarine tidal flats and shallows. This site is the most important staging area on the East Asian Australasian Flyway, hosting at least 2 million waders of 36 species during their northward migration. At least 25 000 people are also dependent on this wetland system.

Thus, there are many forms of physical and biological disturbance in the Arctic (as well as in southern regions used by arctic species during migration). Such disturbances arise directly or indirectly from human intervention and the management of land and water. Although deliberate intervention can generate unexpected consequences, there is no doubt that conservation management is essential if the biodiversity of the Arctic is to be protected. In particular, implementation of international agreements, such as the Convention on the Conservation of Migratory Species of Wild Animals (also known as the Bonn Convention) and the Ramsar Convention on Wetlands, is increasingly urgent as a means to protect wetland and coastal areas.

10.3.3. Pollution

Pollution levels in the Arctic are generally lower than in temperate regions (AMAP, 1998, 2002). Locally, however, pollution from mining, industrial smelters, military activities, and oil and gas development has caused serious harm or posed potential threats to plant and animal life. Long-range transport of pollutants from sources outside the Arctic, in the atmosphere, rivers, or ocean currents, is also of concern (Anon, 2001a; Bernes, 1993). Particular problems include nitrogen and phosphorus causing eutrophication (especially in the

Baltic Sea), organic wastes from pulp mills creating an oxygen demand in the benthos, the effects of toxic metals (especially mercury), and bioaccumulation of organic compounds such as polychlorinated biphenyls (PCBs).

A recent report on the status of wildlife habitats in the Canadian Arctic (Anon, 2001a) listed four major classes of pollutant in the Arctic: mercury, PCBs, toxaphene, and chlorinated dioxins and furans (Table 10.6). Two main points are evident from Table 10.6: that pollutants are carried over long distances in the atmosphere and that pollutants accumulate in arctic food chains. Pollution is an international issue that needs to be resolved in a multi-national manner. However, wildlife is possibly more tolerant than might first appear because no arctic species are known to have become globally extinct due to pollution. However, the trends in pollutant uptake (see Table 10.6) are of concern.

Emissions of sulfur from industrial smelters and mining in the Russian Arctic have caused environmental disasters, killing vegetation and damaging freshwater ecosystems (AMAP, 1998). These impacts have, however, been restricted to relatively small areas surrounding the

Table 10.6. Major groups of pollutants in freshwater ecosystems and species in the Canadian Arctic (Anon, 2001a).

Mercury
- mercury is the most important metal in arctic lakes from a toxicological viewpoint
- observations show, and models confirm, that about a third of the total mercury that enters a high-arctic lake is retained in the sediments, around half is exported downstream, and the rest is lost to the atmosphere
- mercury concentrations consistently exceed guideline limits in fish for subsistence consumption or commercial sale
- mercury concentrations in fish tend to increase with increasing fish size

PCBs
- subarctic lakes first show PCB concentrations in the 1940s (±10 years)
- high-arctic lakes show no significant PCB concentrations until the 1960s (±10 years)
- PCB concentrations in fish tend to increase with increasing fish size

Toxaphene
- toxaphene is the major organochlorine contaminant in all fish analyzed
- highest toxaphene levels are generally seen in fish that are strictly piscivorous
- toxaphene concentrations in fish tend to increase with increasing fish size

Chlorinated dioxins and furans
- chlorinated dioxins and furans are found in fishes from some Yukon lakes
- levels of chlorinated dioxins and furans in fish throughout the Canadian Arctic are low compared to levels in fish obtained either near bleached Kraft mills or in the lower Great Lakes

sources. Long-range transport of sulfur and acid rain to the Arctic has reduced in recent years. The problems of acidification due to sulfur deposition are well known and ameliorative procedures have been established (Bernes, 1991). Acidification results in lakes becoming clear and devoid of much of their characteristic wildlife, so causing considerable local loss of biodiversity. Data from well water in Sweden (Bernes, 1991) showed a north–south gradient in acidification, with fewest effects in the north. Liming the inflow waters of some lakes has seen a recovery or partial recovery in pH, the aquatic plant and animal communities, and recolonization and recovery of the fish populations. An analysis of Scandinavian rivers (Bernes, 1993) also showed a north–south gradient, with relatively few acidified rivers in the arctic areas.

Pollution is also a threat to the boreal forests. The problems of increased aerial deposition of nitrogen have been well documented (e.g., Bell, 1994), and result in both eutrophication and acidification. The acidifying effects of sulfur deposition tend to be least severe in the Arctic, owing to its distance from areas where sulfur oxide (SO_x) gases are emitted. However, there are areas of the Arctic where the degree of acid deposition exceeds the soil's capacity to deal with it, i.e., the critical load (Bernes, 1993).

Levels of anthropogenic radionuclides in the Arctic are declining (AMAP, 2002). Radionuclides in arctic food chains are derived from fallout from atmospheric nuclear tests, the Chernobyl accident in 1986, and from European reprocessing plants. Radiocesium is easily taken up by many plants, and in short food chains is transferred quickly to the top consumers and people, where it is concentrated. Radiocesium has been a problem in arctic food chains, but after atmospheric nuclear tests were stopped 40 years ago, and the effects of the Chernobyl accident have declined, the problem is diminishing. Hallanaro and Pylvänäinen (2002) discussed the effects of the nuclear tests in Novaya Zemla, Russia and the Chernobyl accident, and concluded that neither had "resulted in any evident changes in biodiversity".

Oil pollution in the Arctic has locally caused acute mortality of wildlife and loss of biodiversity. Long-term ecological effects are also substantial: even 15 years after the Exxon Valdez accident in Alaska, toxic effects are still evident in the wildlife (Peterson et al., 2003). A more acute form of pollution is due to major oil spills, although minor discharges are relatively common. Devastation of wildlife following an oil spill is obvious, with dead and dying oiled birds and the smothering of intertidal algae and invertebrate animals. The type of oil spilled, whether heavy or light fuel oil, determines the effects on the fish. Light oils that are partially miscible with seawater can kill many fish, even those that generally occur only at depth (Ritchie and O'Sullivan, 1994). Less sea ice resulting from a warming climate is likely to increase accessibility to oil, gas, and mineral resources, and to open the Arctic Ocean

to transport between the Pacific and Atlantic Oceans. Such activities will increase the likelihood of accidental oil spills in the Arctic, increasing the risk of harm to biodiversity. A warmer climate may, however, make combating oil spills easier and increase the speed at which spilled oil decomposes.

With the possible exception of mercury, heavy metals are not considered a major contamination problem in the Arctic or to threaten biodiversity (AMAP, 2002). The Arctic may, however, be an important sink in the global mercury cycle (AMAP, 2002). Mercury is mainly transported into the Arctic by air and deposited on snow during spring; the recently discovered process involves ozone and is initiated by the returning sunlight (AMAP, 2002). Mercury deposited on snow may become bioavailable and enter food chains, and in some areas of the Arctic levels of mercury in seabirds and marine mammals are increasing.

Persistent organic pollutants (POPs) are mainly transported to the Arctic by winds. Even though levels in the Arctic are generally lower than in temperate regions, several biological and physical processes, such as short food chains and rapid transfer and storage of lipids along the food chain, concentrate POPs in some species at some locations. AMAP (2002) concluded that "adverse effects have been observed in some of the most highly exposed or sensitive species in some areas of the Arctic". Persistent organic pollutants have negative effects on the immune system of polar bears, glaucous gulls (*Larus hyperboreus*), and northern fur seals (*Callorhinus ursinus*), and peregrine falcons (*Falco peregrinus*) have suffered eggshell thinning. The ecological effects of POPs are unknown.

The direct effects of pollutants on trees are compounded by the effects of diseases and defoliating arthropods, and by interactions between all three. Across Europe, these have been codified into the assessment of crown defoliation and hence crown density (e.g., Innes, 1990). Each country prepares an annual report to allow the international situation to be assessed and trends determined. These assessments provide a measure of forest condition and changes in condition. These assessments are currently made in the main timber producing areas of Europe, but it would be of benefit to establish an international forest condition monitoring network across the boreal forests of the subarctic.

A warmer Arctic will probably increase the long-range transport of contaminants to the Arctic. Flow rates in the big Siberian rivers have increased by 15 to 20% since the mid-1980s (see Chapter 6) due to increased precipitation. Northerly winds are likely to increase in intensity with climatic warming, bringing more volatile compounds such as some POPs and mercury into the Arctic. Conservation action must aim to reduce the amounts of the pollutants resulting in chronic effects from entering arctic ecosystems, and to reduce the risk of accidents for pollutants resulting in acute effects.

10.3.4. Development pressures

Biodiversity in the Arctic is affected by pervasive, small-scale, and long-lasting physical disturbance and habitat fragmentation as a side-effect of industrial and urban developments and recreation. Such disturbances, often caused by buildings, vehicles, or pedestrians, can alter vegetation, fauna, and soil conditions in localized areas. A combination of these "patches" can result in a landscape-level mosaic, in effect a series of "new" ecosystems with distinctive, long-term, biodiversity characteristics. These are becoming more widespread in the Arctic and in some cases can, through enhanced productivity and vegetation quality, act as "polar oases" having a wide influence on local food webs.

Forbes et al. (2000) reviewed patch dynamics generated by anthropogenic disturbance, based on re-examination of more than 3000 plots at 19 sites in the high and low arctic regions of Alaska, Canada, Greenland, and Russia. These plots were established from 1928 onward and resurveyed at varying intervals, often with detailed soil as well as vegetation observations. Although these patches have mostly experienced low-intensity and small-scale disturbances, "none but the smallest and wettest patches on level ground recovered unassisted to something approaching their original state in the medium term (20–75 years)". Forbes et al. (2000) concluded that "in terms of conservation, anthropogenic patch dynamics appear as a force to be reckoned with when plans are made for even highly circumscribed and ostensibly mitigative land use in the more productive landscapes of the increasingly accessible Arctic".

Development in the marine environment of the Arctic is currently very limited. However, a recent report on the status of wildlife habitats in the Canadian Arctic (Anon, 2001a) stated that "the Arctic landscapes and seascapes are subject to…oil and gas and mining developments [which] continue to expand". Muir's (2002a) analysis of coastal and offshore development concluded that pressures on the marine environment are bound to increase. There will be further exploration for oil and gas. If substantial finds are made under the arctic seas then development is likely to take place. While most known oil reserves are currently on land, offshore exploration, such as that west of the Fylla Banks 150 km northwest of Nuuk in Greenland (Anon, 2001b), will continue to have local impacts on the seabed. Muir (2002a) also predicted that marine navigation and transport are likely to increase in response to both economic development and as the ice-free season extends as a result of climate change, with the consequent infrastructure developments.

Recreational use of arctic land by people, largely from outside the Arctic, is increasing. Although hikers and their associated trails potentially present few problems, this is not the case for the infrastructure associated with development and for off-road vehicles. Potential problems with trails are associated with vegetation loss along

and beside the trail. This leads to erosion of the skeletal soils by wind, frost, or water. There is current discussion about the use of trekking poles (Marion and Reid, 2001) and whether, by making small holes in the ground that can fill with water, followed by freeze–thaw cycles, they increase the potential for erosion.

Use of off-road vehicles has increased with their greater accessibility. They can also exert greater environmental pressures than trampling by people. As a result various laws and regulations have been introduced to reduce or eliminate the damage that they cause. In Russia, off-road vehicles are frequently heavy, such as caterpillar tractors. Although it is forbidden to use these in treeless areas in summer, violations are thought to be common. Norway has prohibited off-road driving throughout the year, although different rules apply to snowmobiles. Use of the latter is becoming more frequent, with 10–11 per thousand of the population owning them in Iceland and Norway by the late 1990s; this increases to 17 in Finland, 22 in Sweden, and 366 in Svalbard. The Fennoscandian countries have established special snowmobile routes to concentrate this traffic and so prevent more widespread damage and disturbance to snow-covered habitats.

Implications of infrastructure development and habitat fragmentation, especially the construction of linear features such as roads and pipelines, are less clearly understood. However, Nellemann et al.'s (2003) research gave some indications about effects on reindeer. Reindeer generally retreat to more than 4 km from new roads, power lines, dams, and cabins. The population density dropped to 36% of its pre-development density in summer and 8% in winter. In areas further than 4 km from developments, population density increased by more than 200%, which could result in overgrazing of these increasingly small "isolated" areas. If reindeer, easily able to walk across a road, behaviorally prefer to avoid roads, what are the effects of such developments on smaller animals, vertebrates and invertebrates, that are less capable of crossing such obstacles? This indicates that arctic habitats must be of large extent if they are to preserve the range of species associated with such habitats. How large should habitats be? Two developments 8 km apart, on the basis of Nellemann et al.'s (2003) research, can only accommodate 8% of the wild reindeer density (using winter data), and so developments will have to be more distant from each other if there is not to be undue pressure on the reindeer population and the habitats into which they move. Nellemann et al.'s (2001) conclusion was that the impacts of development in the Arctic extend for 4 to 10 km from the infrastructure. So, two developments separated by 20 km may leave no land unimpacted. Developments must therefore be carefully planned, widely separated, and without the fragmentation of habitats by roads, trails, power lines, or holiday cabins.

As well as potential impacts from development, habitats will change with a changing climate. An example of where this is important for tourism is in the Denali

National Park, the most visited national park in Alaska. Bus tours provide the main visitor experience by providing viewing of wildlife and scenery along the park road. The Denali park road begins in boreal forest at the park headquarters and extends through treeline into broad expanses of tundra offering long vistas. Climate-driven changes in the position of forest versus tundra would have significant effects on the park by changing the suitability of certain areas for these experiences. A tree-growth model for the park has been developed based on landscape characteristics most likely to support trees with positive growth responses to warming versus landscapes most likely to support trees with negative responses (M.W. Wilmking, Columbia University, pers. comm., 2004). The results were projected into the 21st century using data from the five general circulation models climate scenarios used in the ACIA analysis. The scenarios project climates that will cause dieback of white spruce at low elevations and treeline advance and infilling at high elevations. The net effect of tree changes is projected to be a forest increase of about 50% along the road corridor, thus decreasing the possibility for viewing scenery and wildlife at one of the most important tourist sites in Alaska. The maps of potential forest dieback and expansion should be useful for future planning.

Developments have two important implications for conservation, and both can potentially be implemented *a priori*. First, what regulations are needed to reduce environmental risks? A study for the Hudson Bay area of Canada (Muir, 2000) provided possible mechanisms for safeguarding local communities, biodiversity, and the environment, while not totally restricting development. Second, how can competing interests be reconciled? Muir (2002a) advocated forms of integrated management, although stating that such "approaches to integrated management which reconcile economic and conservation values will be complex and consultative". There is a need for biodiversity conservation interests to form an integral part of any consultations over the use of the marine, coastal, freshwater, and terrestrial resources of the Arctic.

10.4. Effects of climate change on the biodiversity of the Arctic

This section examines how climate change might affect the biodiversity of the Arctic. The effects are grouped into six categories: potential changes in the ranges of species and habitats (section 10.4.1); changes in their amounts, i.e., the extent of habitats and population sizes (sections 10.4.2 and 10.4.3); possible genetic effects (section 10.4.4); changes in migratory habits (section 10.4.5); likely problems from non-native species (section 10.4.6); and implications for the designation and management of protected areas (section 10.4.7).

The discussions should be read alongside the appropriate sections of Chapters 7 (tundra and polar desert ecosystems), 8 (freshwater ecosystems), and 9 (marine systems), which also include analyses of the effects of

climate change. This section should also be read along-side the appropriate sections of Chapters 11 (wildlife conservation and management) and 14 (forests and agriculture). In this chapter analyses are oriented toward the conservation of arctic genes, arctic species, and arctic ecosystems.

10.4.1. Changes in distribution ranges

In a warming environment it is generally assumed that the distribution range of a species or habitat will move north-ward, and that locally it will move uphill. Although such generalizations may be true, they hide large differences between species and habitats, in terms of how far they will move and whether they are actually able to move.

Some of the earlier studies were undertaken in Norway and investigated the "climate-space" then occupied by a few communities and plant species. The "climate-space" comprised two factors – altitude and distance inland (Holten and Carey, 1992). Figure 10.11 shows the effect of a probable climate change scenario on the distribution of blueberry (*Vaccinium myrtillus*) heaths. The heath is pre-dicted to move uphill, with its mean altitude changing from about 760 m to about 1160 m. The questions for the conservation of this type of heathland are whether all heaths below 700 m will cease to exist (and how quickly this will happen) and whether the heaths can actually establish at altitudes of between about 1300 and 1600 m. Similar studies for other plant species generally predict that they will move to occupy a climate-space that is at a higher altitude and further inland (Holten, 1990).

Norway spruce (*Picea abies*) presently occurs throughout Fennoscandia and Russia, more or less as far north as the shore of the Arctic Ocean. If winter temperatures rise by 4 °C, the distribution range projected for Norway
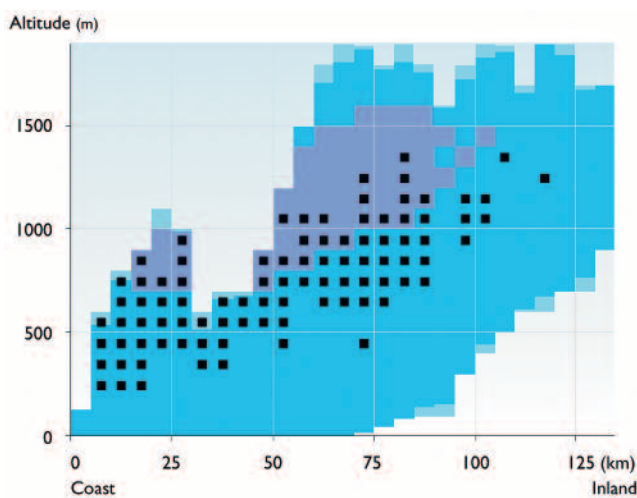
spruce virtually halves, with the majority of the south-ern and southwestern populations disappearing (Holten and Carey, 1992). Owing to the barrier caused by the Arctic Ocean, Norway spruce cannot expand its distri-bution northward, and so is squeezed into a smaller area. Holten and Carey (1992) also projected the distri-bution of beech (*Fagus sylvatica*), a tree whose present distribution is more southern. They forecast that this species will spread northward into the Arctic, and may potentially replace the spruce in some of the more coastal areas. The distribution range of the beech thus expands as it shifts north and moves into the Arctic, there being apparently no barriers to its expansion (except perhaps for the size of its seed which makes dis-persal more difficult).

In modeling changes in distribution ranges, attempts are made to identify the "climate-space" which a species or habitat currently occupies, and then to identify where that climate-space will occur under scenarios of climate change, for example in 2050 or 2100. Such models assume that the species or habitat currently occupies its optimal climate-space, and that the species or habitat will be able to move as the climate changes. This brings up a range of questions about the suitability of areas for mov-ing through and of barriers, such as mountains for terres-trial species and habitats, or the difficulty of moving from lake to lake, or river to river, for freshwater species. Such models have been used to project what might happen to species on nature reserves (Dockerty and Lovett, 2003), in mountain environments (Beniston, 2003), and to the species of the major biomes isolated on nature reserves (Dockerty et al., 2003). Dockerty et al. (2003) predicted that the relict arctic and boreo-arctic montane species in temperate regions are all likely to have a decreased prob-ability of occurrence in the future.

Arctic species and habitats are thus likely to be squeezed into smaller areas as a result of climate change. However, there are some caveats. Cannell et al. (1997), exploring interactions with pollutant impacts (the CO_2 fertilization effect and nitrogen deposition), concluded that the movement of plant species may be less than expected, but that the stress-tolerant species, including those characteristic of the Arctic, are likely to be lost. Oswald et al. (2003) also explored possible changes in

Fig. 10.11. A correlative model showing the current (black squares) and predicted (shaded purple) range of *Vaccinium* heaths in Norway. The grid cells represent steps of 100 m in alti-tude on the vertical axis and 5 km distance from the sea on the horizontal axis. The model is derived from the then most proba-ble scenario of climate change in Norway, i.e., a 2 °C increase in July temperatures and a 4 °C increase in January temperatures (Holten and Carey, 1992).

Fig. 10.12. A representation of extent of understanding and the quality or quantity of data when applied to modeling problems. For the majority of potential applications in conservation the level of understanding of the system is low and the quantity of data small, and so the modeling would fall in the lower left cor-ner of Zone 4 (Usher, 2002a).
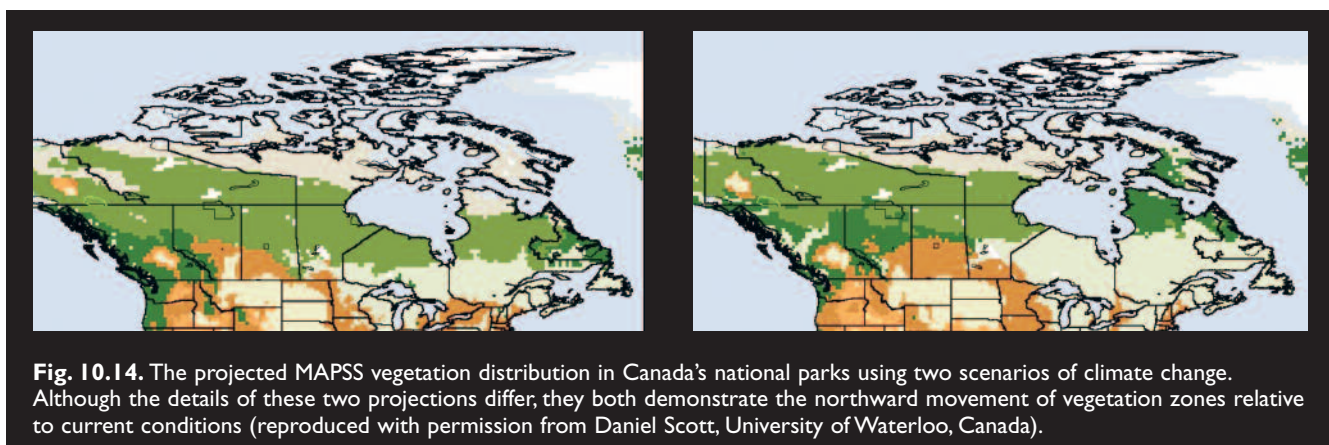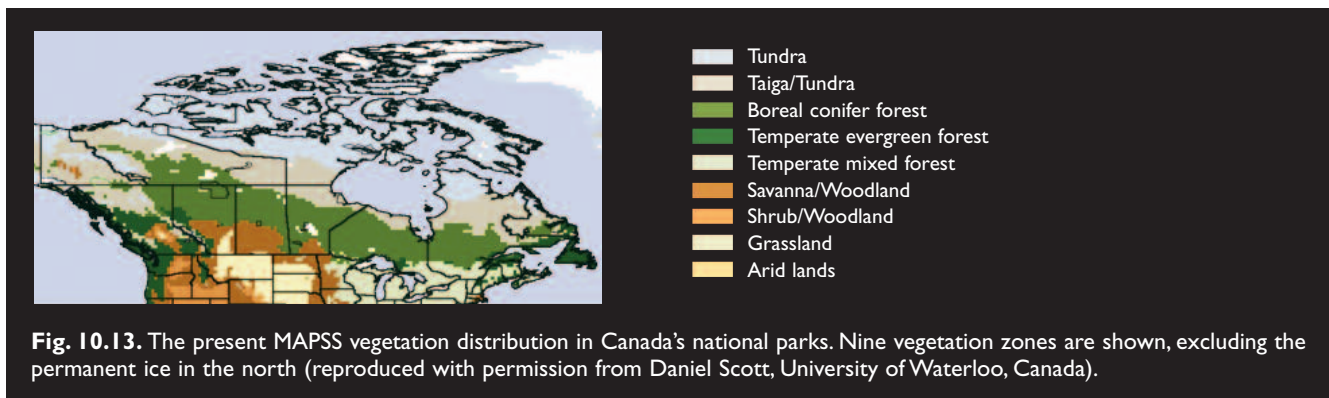
plant species in northern Alaska, and concluded that the responses of species and habitats are likely to be heterogeneous. The continued northward push of the more southern species and habitats has been outlined by Pellerin and Lavoie (2003) in relation to changes in ombrotrophic bogs due to forest expansion. It is these individualistic responses to climate change (Graham and Grimm, 1990), by species and habitats, which make prediction difficult. Individualistic responses appear to be the norm rather than the exception for plants and invertebrate animals (Niemelä et al., 1990).

The individualistic responses of species may produce novel effects. This is illustrated using the example of a simple and hypothetical community with a broadly similar abundance of three species: A, B, and C (community A+B+C). Under a climate change scenario with species moving northward, if species A moved rapidly, species B moved more slowly, and species C hardly moved at all, this could result in a community dominated by species A with species B as a sub-dominant (community A+b) in the north and a community dominated by species C with species B as a sub-dominant (community C+b) more or less where A+B+C used to occur. It is possible that neither A+b nor C+b would be recognized as communities, and so, in the geographical contraction of A+B+C, two new communities – A+b and C+b – had arisen, both of which were novel. Climate change could thus give rise to some new habitat types, and although this might not change the overall biodiversity of the Arctic at the species level, there could be changes to biodiversity at the habitat level.

Current distribution ranges of plants and animals in the marine environment depend upon the ocean currents as well as on the extent of the sea-ice cover at different times of the year. With the projected decrease in sea-ice cover and the more northerly position of the ice edge, the distribution of the algae, phytoplankton, invertebrates, and fish will also change. An analysis of the effects of climate change on marine resources in the Arctic (Criddle et al., 1998) left much in doubt, stating that "the effects of climate variation on some Bering Sea fish populations are fairly well known in terms of empirical relationships but generally poorly known in terms of mechanisms". The authors proposed a program of research to help predict the effects of climate change on the commercially-exploited fish stocks and more widely on marine biodiversity as a whole.

The lack of knowledge on this topic was addressed by Starfield and Bleloch (1986). They presented a simple model of the context within which most conservation work could be undertaken (Fig. 10.12). Conservation generally has little understanding of the system to be conserved, and managers have poor data upon which to build models. The conservation of biodiversity falls in zone 4. This is the zone where statistical models are most helpful, indicating expectations with some probability attached and often very wide confidence limits.

What are the implications for conservation? The most detailed assessment of changes in distribution ranges of species and ecosystems in relation to conservation are probably the studies on national parks and other conser-

Fig. 10.13. The present MAPSS vegetation distribution in Canada's national parks. Nine vegetation zones are shown, excluding the permanent ice in the north (reproduced with permission from Daniel Scott, University of Waterloo, Canada).

Legend:
- Tundra
- Taiga/Tundra
- Boreal conifer forest
- Temperate evergreen forest
- Temperate mixed forest
- Savanna/Woodland
- Shrub/Woodland
- Grassland
- Arid lands

Fig. 10.14. The projected MAPSS vegetation distribution in Canada's national parks using two scenarios of climate change. Although the details of these two projections differ, they both demonstrate the northward movement of vegetation zones relative to current conditions (reproduced with permission from Daniel Scott, University of Waterloo, Canada).

vation areas in Canada (Scott and Lemieux, 2003; Scott and Suffling, 2000; Scott et al., 2002). The large scale of biomes and environmental conditions in Canada facilitate the definition of spatial patterns by models with a grid resolution of 0.5° latitude by 0.5° longitude. The studies of 36 national parks and other designated conservation areas involved the application of two global vegetation models (BIOME3 and MAPSS) which represent the effects of enhanced CO_2 on nine or ten biome types consistent with IPCC analysis. The different number of biomes is because BIOME3 combined boreal and taiga/tundra biomes which were separated in MAPSS. Five general circulation models (three equilibrium models: UKMO, GFDL-R30, and GISS; two transient models: HadCM2 and MPI-T106) were applied, providing some direct cross-reference to the present assessment.

A northward movement of the major biomes was projected in all five scenarios, changes in the dominant biomes of tundra, taiga/tundra, and boreal conifer forest were particularly clear (compare Fig. 10.13, which shows present conditions, with Fig. 10.14, which shows two projections for the northerly movement of the Canadian vegetation zones). As is the case for the ACIA-designated climate models (see Chapter 4), although the trends were similar between models, the actual values and local spatial patterns showed considerable variation. Regardless of the vegetation and climate change scenarios used, the potential for substantial changes in biome representation within the national parks was shown repeatedly. At least one non pre-existing biome type appeared in 55 to 61% of parks in the MAPSS-based scenarios and 39 to 50% in the BIOME3-based scenar-

Table 10.7. Potential impacts of climate change on the arctic national parks and other protected areas (H.G. Gilchrist, Canadian Wildlife Service, pers. comm., 2004).

Impact	Effects of impact
Northward treeline extension	Up to 200–300 km movement in the next 100 years (where movement is not impeded by soil condition)
Increased active layer and permafrost thawing	May extend northward by 500 km, causing altered drainage patterns
Sea-level rise	Variable, either moderated by isostatic rebound or exacerbated by subsidence
Reduced sea- and lake-ice seasons	Altered sea mammal distributions (especially for polar bears and ringed seals), as well as more northerly distribution of ice-edge phytoplankton blooms, zooplankton, and fish
Increased snow pack and ice layers	Reduced access to browse for ungulates
Greater severity and length of insect seasons	Increased harassment of ungulates and potential for pest outbreaks in boreal forests
Altered migration patterns	Diminished genetic exchange among arctic islands
Altered predator–prey and host–parasite relationships	Changes in species abundance, and potentially the establishment of novel interactions between pairs of species

ios. Representation of northern biomes (tundra, taiga/tundra, and boreal conifer forest) in protected areas was projected to decrease due to the overall contraction of these biomes in Canada. Projections for the southern biomes were more variable but their representation in protected areas generally increased.

The seven arctic national parks range in size from Vuntut in Yukon Territory at 4345 km² to Quttinirpaaq (formerly Ellesmere Island) at 37 775 km² in Nunavut. The parks cover a range of conditions from high arctic polar desert and glaciers to taiga, extensive wetlands, coastal areas, lakes, and rivers. They also contain, and were often designated to conserve, a variety of species and populations; for example, they contain one of the greatest known musk oxen (*Ovibos moschatus*) concentrations, calving grounds for Peary caribou (*Rangifer tarandus pearyi*), migration corridors and staging areas, one of the largest polar bear denning areas, spawning and over-wintering sites for Arctic char, considerable species richness with over 300 plant species in one area, plus important historical, cultural, and archaeological sites and unique fossils from Beringia. Some of the significant impacts of climate change within the arctic national parks are outlined in Table 10.7.

10.4.2. Changes in the extent of arctic habitats

The previous section showed that distribution ranges of many arctic habitats are likely to decrease with climate change and that this generally implies a reduction in the overall extent of the habitat. The response of each habitat is likely to be individualistic (Oswald et al., 2003), and to depend upon the dynamics of the populations and communities, as well as on a range of species interactions such as competition, predation, parasitism, hyperparasitism, and mutualism. Habitat extent will depend upon the individualistic responses of the component species, and these in turn will depend upon the physiological responses of the individuals that form those species populations (see section 10.4.3).

In the marine environment far less is known about the potential effects of warmer temperatures, increased atmospheric CO_2 concentrations, and increased irradiance by ultraviolet-B (UV-B) on the species populations and habitats. A review of marine nature reserves by Halpern and Warner (2002) showed that changes in population sizes and characteristics can be fast. Compared with undesignated areas, their study indicated that the average values of density, biomass, organism size, and diversity all increased within one to three years of designation. These rapid responses, the result of protection through conservation designation, indicate that marine organisms and marine habitats have the potential to respond quickly to changed environmental conditions.

Change will occur, and in general it appears that arctic habitats are likely to have smaller population sizes within smaller distribution ranges. What will replace them? Habitats that currently occur in the sub-Arctic or in the

northern boreal zone are likely to move northward, and their responses to climate change are likely to be individualistic. So it is possible that habitats currently south of the Arctic might migrate northward and occur "naturally" within the Arctic, as for example with the northward movement of beech forest (section 10.4.1).

This will make it difficult to establish, if indeed there is a distinction, whether species and habitats of the Arctic in the future are native or non-native (see section 10.4.6). Owing to the different responses of habitats and species, it is likely that novel species assemblages will occur in the future, being habitat types that are currently unknown or not envisaged. Thus, the current habitat classifications are likely to have to change as novel habitat types evolve in response to rapid climate change. This has considerable implications for species and habitat conservation and for management today, and may lead to alterations in the priorities for biodiversity conservation in the future. While the name of a species is more or less stable, and so easily incorporated into legislative frameworks (i.e., appended lists of protected species), a habitat's name and description is less stable, implying a need for periodic reviews of legislative frameworks.

10.4.3. Changes in the abundance of arctic species

As sections 10.4.1 and 10.4.2 imply, it is the species composition of an area that will change, forcing changes to the communities in which they occur. The individualistic responses of the species (Oswald et al., 2003) will depend upon the dynamics of the species populations, the competitive or mutualistic interactions between species, and the biochemical and physiological responses of the individuals.

Biochemistry and physiology are fundamental to how an individual responds to its environment and to changes in that environment. Rey and Jarvis (1997) showed that young birch (*Betula pendula*) trees grown in an atmosphere with elevated CO_2 levels had 58% more biomass than trees grown in ambient CO_2 concentrations. They also found that the mycorrhizal fungi associated with the roots of the experimental trees differed; those grown in elevated CO_2 levels were late successional species, while those grown in ambient CO_2 levels were the early successional species. This showed the complexity of understanding the effects of climate change on the conservation of biodiversity. Normally, with regenerating birch trees, the whole successional suite of fungi would be expected to occur on the young trees' roots as they emerge from the seed, establish themselves, grow, and then mature. Does the work of Rey and Jarvis' (1997) imply that more attention needs to be given to protecting the early successional mycorrhizal species? They will clearly be needed in the ecosystem if climate cools or CO_2 levels fall in the future.

Other physiological studies have detected a 4 to 9% thickening of the leaves of lingonberry (*Vaccinium*

vitis-idaea) under enhanced UV-B radiation, whereas the deciduous blueberry and bog blueberry (*V. uliginosum*) both had 4 to 10% thinner leaves under similar conditions (Björn et al., 1997). Growth of the moss *Hylocomium splendens* was strongly stimulated by enhanced UV-B radiation, as long as there was additional water, whereas the longitudinal growth of the moss *Sphagnum fuscum* was reduced by about 20%. Björn et al.'s (1997) results for lichen growth under enhanced UV-B radiation were variable, leading them to conclude that "it is currently impossible to generalize from these data". They also investigated the decomposition of litter from *Vaccinium* plants grown under normal conditions and under conditions of enhanced UV-B radiation. Litter from the *V. uliginosum* plants treated with UV-B radiation had a decreased α-cellulose content, a reduced cellulose/lignin ratio, and increased tannins compared to the control litter, and so was more resistant to decomposition. Slower decomposition was also observed for *V. myrtillus* litter. Björn et al. (1997) did not investigate the palatability of the leaves to invertebrate animals. Moth larvae, particularly those in the family Geometridae (the "loopers" or "spanworms"), are a large component of the diet of many passerine birds in the boreal forest and near the forest/tundra margin. If the larval population densities are reduced due to a lack of palatability of the leaves on which they feed, the effects of UV-B radiation could be far-reaching on the below- and above-ground food webs of the terrestrial Arctic.

Changes in phenology, the time of year when events happen, will also affect the size of populations. A number of studies have already shown that vascular plants are flowering earlier, insects (especially butterflies) are appearing earlier in the year, some birds are starting to nest earlier in spring, amphibians are spawning earlier, and migratory birds are arriving earlier (see a review by Usher, 2002b). Some of these phenological observations are beginning to be used as indicators of the effects of climate change on biodiversity, although most studies are just recording data on the changes in species populations in the earlier part of the year (usually spring) and do not record data for the end-of-summer changes that could be affecting plant growth rates in the autumn or autumnal flight periods for species of insect. The important ecological impact of phenology concerns how changes will affect interactions between pairs of species. If one species changes its phenology more than another, will this then increase or decrease the effects of competition, herbivory, predation, parasitism, etc.? If synchrony occurs, and the organisms become less synchronous, this could have considerable effects on population sizes and biodiversity.

In the marine environment, seabirds show strong preferences for regions of particular sea surface temperatures (SSTs) (Schreiber, 2002). Some seabird populations have been found to respond to long-term climatic changes in the North Atlantic Ocean (Aebischer et al., 1990; Thompson P. and Ollason 2001), the North Pacific Ocean (Anderson and Piatt, 1999; Bertram et al., 2001; Jones I. et al., 2002; Sydeman et al., 2001; Veit et al.,

1997), and Antarctica. Although global SSTs are generally increasing, this long-term trend is superimposed on cyclical patterns created by climatic oscillations, such as the North Pacific, North Atlantic, and Arctic Oscillations (Francis et al., 1998; Hare and Mantua, 2000; Hurrell et al., 2003; Wilby et al., 1997). These oscillations cause periodic reversals in SST trends, two of which have occurred since 1970 in the Northern Hemisphere; from 1970 much information has been accumulated on seabird population trends in the circumpolar Arctic (Dragoo et al., 2001; Gaston and Hipfner, 2000).

To examine the effect of SST changes on seabird populations at a global scale, data on population changes throughout the distribution ranges of the common guillemot or murre *(Uria aalge)* and Brünnich's guillemot or thick-billed murre *(U. lomvia)* were examined to document how they changed in response to climate shifts, and potential relationships with SSTs (D.B. Irons, U.S. Fish and Wildlife Service, pers. comm., 2003). Both species breed throughout the circumpolar north from the high Arctic to temperate regions, although Brünnich's guillemots tend to be associated with colder water than common guillemots and are the dominant species in the Arctic (Gaston and Jones, 1998).

The analysis showed that positive population trends occurred at guillemot colonies where SST changes were small, while negative trends occurred where large increases or large decreases in SST occurred. Highest rates of increase for the southerly species, the common guillemot, occurred where SST changes were slightly negative, while increases for the arctic-adapted Brünnich's guillemot were most rapid where SST changes were slightly positive. These results demonstrate that most guillemot colonies perform best when temperatures are approximately stable, suggesting that each colony is adapted to local conditions (D.B. Irons, U.S. Fish and Wildlife Service, pers. comm., 2003). This study also demonstrates how seabirds respond to changes in climatic conditions in the Arctic over large temporal and spatial scales.

A study on the Atlantic puffin in the Lofoten Islands, northern Norway, has shown that sea temperatures from March through July (which is the first growth period for newly hatched Atlantic herring) and the size of herring in the food intake of adult puffin together explain about 84% of the annual variation in fledging success of puffin chicks (T. Anker-Nilssen, Norwegian Institute for Nature Research, pers. comm., 2003). Although there are relatively few data for the marine environment, what there are (especially for seabirds) indicate reduced population sizes for many of the marine wildlife species of the Arctic, and so conservation activity must aim to ameliorate such declines. Protected areas are an important aspect of such activity and are discussed further in section 10.4.7.

10.4.4. Changes in genetic diversity

Little attention had been paid to genetic diversity, despite it being one of the major themes in the Convention on

Biological Diversity. For example, Groombridge's (1992) book on biological diversity had 241 pages on species diversity, 80 pages on the diversity of habitats, but only 6 pages on genetic diversity. Similarly, Heywood's (1995) Global Biodiversity Assessment had only 32 pages on the subject of "genetic diversity as a component of biodiversity" of its total of 1140 pages.

The reason for this discrepancy is because species tend to be tangible entities and many are easily recognizable. The species concept does not work well, however, for the single-celled forms of life, which often live in soils or sediments under freshwater or the sea, where the genetic variability is often more important than the species itself. Habitats are also recognizable, often on the basis of their species, but present complications because they tend to merge into one another. Compared with these tangible entities, genetic variability is often not recognizable and can only be detected by sophisticated methods of analysis using molecular techniques. Of the millions of species that exist, very little is known about their genetic diversity except for a few species of economic importance, a few species that are parasites of people or their domestic stock, and a few other species that geneticists have favored for research (e.g., the *Drosophila* flies). As in all other parts of the world, relatively little is known about the genetic variability of species that occur in the Arctic.

What then can be done to conserve the Arctic's genetic diversity? On the basis that natural selection requires a genetic diversity to operate, conservation practice should aim to find a surrogate for the unknown, or almost unknown, genetic diversity. This is best done by conserving each species over as wide a distribution range as possible and in as many habitats as possible. This ensures maximum geographical and ecological variability, assuming that local adaptation of species represents different genotypes. Attempting to map population genetics to landscape processes is relatively new (Manel et al., 2003) and has been termed "landscape genetics". Manel et al. (2003) stated that it "promises to facilitate our understanding of how geographical and environmental features structure genetic variation at both the population and individual levels, and has implications for…conservation biology". At the moment it must be assumed that the geographical and environmental features have structured the genetic variation, and this assumption must be made before the links can be proved. How this variability has actually arisen is unclear.

Throughout continental Europe, a continuous postglacial range expansion is assumed for many terrestrial plant and animal species. This has often led to a population structure in which genetic diversity decreases with distance from the ancestral refugium population (Hewitt, 2000), and so northern populations are often genetically less diverse than their southern counterparts (Hewitt, 1999).

Among discontinuously distributed species, such as those living on remote islands, this pattern can be obscured by

differences in local effective population sizes. For example, considerable genetic diversity exists among populations of common eider ducks (*Somateria mollissima*) nesting throughout the circumpolar Arctic. Historical and current processes determining phylogeographic structure of common eiders have recently been reconstructed, based on maximum parsimony and nested clade analysis (A. Grapputo, Royal Ontario Museum, pers. comm., 2004; Tiedemann et al., 2004). Five major groups (or "clades") have been identified; the three most different include common eiders from Alaska, Svalbard, and Iceland. The remaining two include eider populations from the eastern Canadian Arctic and West Greenland, and from northwest Europe.

Nested clade analysis also suggests that the phylogeographic patterns observed have a strong historical pattern indicating past fragmentation of eider populations due to glacial events. Following the retreat of the glaciers, eiders surviving in refugia expanded to re-colonize their range, and populations apparently remixed. These refugial populations occurred across Arctic Canada and Greenland (A. Grapputo, Royal Ontario Museum, pers. comm., 2004), and apparently in a single refugium in northwest Europe (Tiedemann et al., 2004). The oldest population split was estimated between Pacific eiders and birds that colonized the western Canadian Arctic islands about 120 000 years ago after the retreat of ice sheets in the previous glacial maximum. In North America, this was likely to have been followed by a second expansion that began in warmer periods about 80 000 years ago from Alaska eastward across the Palearctic to establish populations in the eastern Canadian Arctic and West Greenland. In Europe, genetic analyses suggest that common eiders underwent a postglacial range expansion from a refugium in Finland, north and west to the Faroe Islands and subsequently to Iceland. Despite this relatively recent mixing of haplotypes, extant populations of common eider ducks are strongly structured matrilineally in the circumpolar Arctic. These results reflect the fact that current long-distance dispersal is limited and that there is considerable philopatry of female eiders to nesting and wintering areas (Tiedemann et al., 2004).

In contrast to common eider ducks, king eider ducks (*Somateria spectabilis*) show a distinct lack of spatial genetic structure across arctic North America (Pearce et al., 2004). In the western Palearctic, the king eider has been delineated into two broadly distributed breeding populations in North America, in the western and eastern Arctic, on the basis of banding (ringing) data (Lyngs, 2003) and of isotopic signatures of their diet while on wintering grounds (Mehl et al., 2004, in press). These studies indicated the use of widely separated Pacific and Atlantic wintering areas. Despite this, recent studies of microsatellite DNA loci and cytochrome *b* mitochondrial DNA show small and non-significant genetic differences based on samples from three wintering and four nesting areas in arctic North America, Russia, and Greenland (Pearce et al., 2004). Results from nested clade analysis and coalescent-based analyses suggest his-

torical population growth and gene flow that collectively may have homogenized gene frequencies. However, the presence of several unique mtDNA haplotypes among birds wintering in West Greenland suggested that gene flow may now be more limited between the western and eastern arctic populations than in the past (Pearce et al., 2004); this would be consistent with recent banding data from eastern Canada and West Greenland (Lyngs, 2003).

Collectively, these two examples of closely related duck species illustrate how climatic events can influence the genetic structure of arctic species over time. They also show how historical periods of isolation, combined with little gene flow currently (matrilineally, at least), have contributed to maintain genetic diversity. However, the fact that the common and king eider differ so markedly in their degree of genetic diversity throughout the circumpolar Arctic, despite sharing many ecological traits, suggests that the effects of more rapid climate change on genetic diversity may be difficult to predict.

There are at least three features of this genetic variability that need to be considered in the conservation of the Arctic's biodiversity. First, the genetic structure of a species at the edge of its range, where it is often fragmented into a number of small and relatively isolated populations, is often different from that at the center of the range, where populations can be more contiguous and gene flow is likely to be greater. It is these isolated, edge-of-range populations that are possibly undergoing speciation, and which might form the basis of an evolution toward different species with different ecologies in the future.

Second, hybridization can be both a threat and an opportunity. Although arctic examples are rare, it can be a threat where two species lose their distinctive identities, as is happening with the introduction of Sika deer (*Cervus nippon*) into areas where red deer (*C. elaphus*) naturally occur. This is one of the potential problems with the introduction into the Arctic of non-native species (section 10.4.6). Hybridization can also be an opportunity. The hybrid between the European and American *Spartina* grasses doubled its number of chromosomes and acts as a newly evolved species in its own right.

Third, there are suggestions (Luck et al., 2003) that the genetic variability of populations is important in maintaining the full range of ecosystem services. Although this concept is little understood, it is intuitively plausible because, as factors in the environment change, individuals of differing genetic structure may be more or less able to fulfill the functional role of that species in the ecosystem. Thus, with a variable environment, the ecosystem needs species whose individuals have a variable genetic makeup.

Although little is known about genetic variability, a geographically spread suite of protected areas, encompassing the full range of habitat types, is probably the best conservation prescription for the Arctic's biodiversity that can

currently be made. It should be appropriate for conserving the biodiversity of habitats and species, and is probably also appropriate for conserving genetic biodiversity.

10.4.5. Effects on migratory species and their management

Migration was briefly addressed in sections 10.2.6 and 10.3.2, and the eight major international flyways for shorebirds breeding in the Arctic are shown in Figure 10.4. Migration is a cold and ice avoidance strategy used by birds, marine mammals, and fish. Although some species of insect also migrate, it is uncommon for the milkweed butterfly (*Danaus plexippus*), well known for its migrations through North America, to migrate in the spring and early summer as far north as the Canadian Arctic.

The goose species of the western Palearctic region provide good examples of migratory species that have been the subject of considerable research and conservation action (Madsen et al., 1999). Of the 23 populations, five populations of greylag goose (*Anser anser anser* and *A. a. rubirostris*) do not nest in the Arctic; neither do the two populations of Canada goose (*Branta canadensis*) which are not native to the region. The remaining 16 populations of seven species (11 subspecies) are listed in Table 10.8. There are a variety of flyways, some moving southeast from the breeding grounds in northeast Canada, Greenland, and Iceland, and others moving southwest from the breeding grounds in the Russian Arctic, both into Western Europe. The three populations of barnacle goose (*Branta leucopsis*) can be used as an example (see Box 10.1).

The examples demonstrate a number of features of migratory populations and their conservation. The geese require sufficient food resources to make two long journeys each year. The summer feeding grounds in the Arctic and the winter feeding grounds in temperate Europe provide the majority of the food requirements. However, while on migration, the geese need to stage and replenish their energy reserves. In years when winter comes early and Bjørnøya is iced over before the geese arrive, it is known that many are unable to gain sufficient energy to fly on to Scotland and there can be very heavy mortality, especially of that year's young. Although the three populations appear from the brief descriptions in Box 10.1 to be geographically isolated from each other, there is a very small amount of mixing between these populations, and so gene flow is probably sufficient for this one species not to have sub-speciated.

The examples also demonstrate that conservation efforts need to be international. For each of the three populations, protection is required for parts of the year in the breeding grounds, in the wintering grounds, and in the staging areas. Conservation action needs to be taken wherever the geese land. The fact that there is some straying from the main flight paths implies that conservation is required all along these migration routes. In Europe, the Bonn Convention aims to provide such an instrument for the conservation of migratory species; this could form a model for all migratory species, including those that use the Arctic for part of their life cycle.

Climate change could affect these species through changes in their habitats. For the Greenland nesting population it would be possible for their breeding grounds to move northward because there is land north of the current breeding range. This could hardly happen for the populations breeding on Svalbard and in Russia because there is very little ground north of the current breeding areas (just the north coast of Svalbard and the north of Novaya Zemlya). Because many of the wintering

Table 10.8. The sixteen goose populations that nest in the Arctic and overwinter in the western Palearctic. The data were extracted from Madsen et al. (1999).

		Breeding area	Wintering area
Taiga bean goose	*Anser fabalis fabalis*	Scandinavia and Russia	Baltic
Tundra bean goose	*Anser fabalis rossicus*	Russia	Central and Western Europe
Pink-footed goose	*Anser brachyrhynchus*	Iceland and Greenland	Great Britain
Pink-footed goose	*Anser brachyrhynchus*	Svalbard	Northwest Europe
White-fronted goose	*Anser albifrons albifrons*	Russia	Western Europe
Greenland white-fronted goose	*Anser albifrons flavirostris*	West Greenland	British Isles
Lesser white-fronted goose	*Anser erythropus*	Scandinavia and Russia	Central and southeast Europe
Greylag goose	*Anser anser anser*	Iceland	Scotland
Greylag goose	*Anser anser anser*	Northwest Europe	Northwest and southwest Europe
Barnacle goose	*Branta leucopsis*	East Greenland	British Isles
Barnacle goose	*Branta leucopsis*	Svalbard	Scotland and northern England
Barnacle goose	*Branta leucopsis*	Russia and the Baltic	Northwest Europe
Dark-bellied brent goose	*Branta bernicla bernicla*	Russia	Western Europe
Light-bellied brent goose	*Branta bernicla hrota*	Northeast Canada	Ireland
Light-bellied brent goose	*Branta bernicla hrota*	Svalbard	Northwest Europe
Red-breasted goose	*Branta ruficollis*	Russia	Black Sea

Box 10.1. The three populations of barnacle goose in the western Palearctic

The western population of barnacle goose (*Branta leucopsis*) in the western Palearctic breeds near the coast along northeast Greenland from about 70° to 78° N. On the autumn migration the geese stage in Iceland, near the south coast, where they spend about a month feeding before they fly on to the wintering grounds along the west coast of Ireland and the west and north coasts of Scotland. In the spring the geese leave the British Isles in April and stage on the northwest coast of Iceland for three or four weeks before flying back to Greenland to recommence the annual cycle. These geese are legally protected in Greenland from 1 June to 31 August, although a few are legally hunted by local people. In Iceland the geese are protected in the spring, although it is considered that some are illegally killed, but few are thought to be killed in autumn. In the United Kingdom the geese are fully protected as a result of domestic legislation and of being listed in Annex I to Council Directive 79/409/EEC on the conservation of wild birds (also known as the Birds Directive).

A second (or central) population of about 25 000 birds breeds in Svalbard between about 77° and 80° N. After breeding, the geese leave Svalbard in August, and many arrive on Bjørnøya at the end of August staying until late September or early October when they fly on to the Solway Firth in southwest Scotland. They return north in the spring, staging in the Helgeland Archipelago off the coast of Norway (between 65° and 66° N) for two to three weeks before flying on to Svalbard. The geese are legally protected in Svalbard, Norway, and the United Kingdom, and it is thought that very few are illegally shot.

The eastern population breeds in northern Russia, from the Kola Peninsula in the west to Novaya Zemlya and the Yugor Peninsula in the east. In the autumn the birds fly southwest, along the Gulf of Bothnia and the southern part of the Baltic Sea, staging on the Estonian and Swedish Baltic islands. The majority of the birds winter on the North Sea coast of Denmark, Germany, and the Netherlands. The species is legally protected in Russia, although Madsen et al. (1999) reported that it appears that many are shot and that both the adults and the eggs are used as an important part of the diet of local people. Within the countries of the European Union, the geese are fully protected by the Birds Directive.

Barnacle geese from the Greenland population overwintering on the island of Islay, western Scotland

grounds are managed as grasslands for cattle and sheep grazing, it is possible that these may change less than the breeding grounds. The staging areas are also likely to change, and it is possible that the distance between breeding and wintering grounds might become longer, requiring more energy expenditure by the migrating birds. This leaves a series of unknowns, but at present these goose populations are increasing in size, are having an economic impact on the wintering grounds, and have raised what Usher (1998) has termed "the dilemma of conservation success". This is the problem of reconciling the interests of the local people with the need to conserve species that the people either depend upon harvesting or that damage their livelihoods.

10.4.6. Effects caused by non-native species and their management

Biological invasions have fascinated ecologists for well over 50 years (Elton, 1958). The many problems caused by non-native species are becoming more apparent, and the World Conservation Union (IUCN) identifies them as the second most important cause of loss in global biodiversity (the primary reason being loss and fragmen-

tation of habitats). A word of caution is, however, needed with language. Why a species is geographically where it is currently found cannot always be determined; if it is known to be there naturally, it is generally referred to as "native". If it has been brought in from another geographical area by human agency, either intentionally or unintentionally, it is referred to as "non-native" (Usher, 2000, discussed these distinctions and the gradations between them). The term "non-native" is essentially synonymous with "alien", "exotic", and "introduced", all of which occur in the literature. Williamson (1996) described the "10:10 rule", suggesting that 10% of species introduced to an area would establish themselves (i.e. they do not die out within a few years of introduction, and start to reproduce) and that 10% of these established species would become "pests". While this rule seems reasonably true for plants, it seems to underestimate the numbers of vertebrate animals that become problematic (Usher, 2002b). It is this 1% (10% of 10%) of species that are introduced, or rather more for vertebrate animal species, which can be termed "invasive".

To date, the Arctic has escaped the major problems that invasive species have caused in many other parts of the

world. During the 1980s there was a major international program on the ecology of biological invasions. The synthesis volume (Drake et al., 1989) does not mention the Arctic (or the Antarctic), although global patterns of invasion into protected areas indicated that the problems diminished with latitude north or south of the regions with a Mediterranean climate (Macdonald I. et al., 1989).

In terrestrial ecosystems, climate change is very likely to mean that more species will be able to survive in the Arctic. It is arguable whether new species arriving in the Arctic can be classified as "native" or "non-native" when the rapidly changing climate is anthropogenically driven. However, with a changing climate new species will very probably arrive in the Arctic, some of which will establish and form reproducing populations. Although there is no obvious candidate for a non-native species to be invasive in the Arctic, it needs to be remembered that at least 1% of species introduced into the Arctic are likely to become invasive. At present there are no means of determining the major risks, but the introduction of disease organisms, for wildlife and people, is a distinct possibility.

In the boreal forests, the insects, as a group, pose the most serious challenge because of their ability to increase rapidly in numbers and because of the scarcity of effective management tools. From past experience, it is probable that many forest-damaging insects have the potential to appear at outbreak levels under a warmer climate and increased tree stress levels, but this has not been observed to date. Two examples demonstrate the risks. First, the bronze birch borer (*Agrilus anxius*) has been identified as a species that can cause severe damage to paper birch (*Betula papyrifera*), and may be effective in limiting the birch along the southern margin of its distribution (Haak, 1996). It is currently present at relatively low levels in the middle and northern boreal region of North America. Second, an outbreak of the Siberian silkworm (*Dendrolimus sibiricus*) in west Siberia from 1954 to 1957 caused extensive tree death on three million hectares of forest. Movement of outbreak levels northward would considerably alter the dynamics of Siberian forests.

There are similar concerns in the freshwater environment. In much of northern Europe and northern America, it is the introduction of fish species that cause most problems. For example, in Loch Lomond in Scotland the invasive ruffe (*Gymnocephalus cernuus*) eats the eggs of an arctic relict species, the powan (*Coregonus lavaretus*), thereby threatening this species in one of its only British habitats (Doughty et al., 2002). Similarly, in North America the invasion of the Great Lakes by the lamprey (*Petromyzon marinus*), first seen in Lake Erie in 1921, led to the collapse of a number of fisheries following its establishment and first known breeding in the 1930s. For example, the trout fishery in Lake Michigan was landing about 2600 tonnes of fish each year between 1935 and 1945, but this dropped to 155 tonnes by 1949 when the fishery essentially ended (Watt, 1968). Although these examples are outside the Arctic, they highlight potential problems with non-native fish species

as arctic rivers and lakes become warmer. There are also potential problems with fish that escape from fish farms and enter the natural environment and breed with native fish stock. The genetic effects of this interbreeding can be profound, altering the behavior of the resulting fish stock, as has been found with Atlantic salmon (*Salmo salar*) in Norway.

In the marine environment one of the major potential problems is the discharge of ballast water. With thinning of the sea ice and the opening up of the Arctic Ocean to more shipping for more of the year, the possibility of the introduction of non-native species is greater and the environmental risks are increased. Analyses of ballast water have shown that it can contain a large number of different species of marine organisms, including marine algae and mollusks that are potentially invasive. Also, ballast water has occasionally been found to contain organisms that could be pathogenic to people. Regulating discharges of ballast water in not easy, nor is its enforcement always possible, but to prevent the threat of invasive marine organisms it is essential that international agreements regulate such discharges in coastal waters and on the high seas of the Arctic.

The effects of introduced Arctic foxes on seabird populations is an example that links the marine and terrestrial environments. Seabirds commonly nest on offshore islands, in part to avoid terrestrial predators to which they are vulnerable, both to the loss of eggs and chicks and to direct predation on adults. Several seabird populations have declined when mammalian predators were accidentally or intentionally introduced to nesting islands (Burger and Gochfeld, 1994). Arctic foxes were intentionally introduced for fur farming in the late 1800s and early 1900s on several of the Aleutian Islands of Alaska. Before these introductions, the islands supported large populations of breeding seabirds and had no terrestrial predators. Although most fox farming ended prior to the Second World War, the introduced animals persisted on many islands, preying on breeding seabirds at rates affecting their population sizes (Bailey, 1993). Evidence from southwestern Alaska (Jones R. and Byrd, 1979), and comparisons of islands with and without foxes in the Shumagin Islands (Bailey, 1993), suggest it is likely that foxes are responsible for the reduced seabird population sizes on islands supporting foxes. Those species nesting underground, in burrows or in rock crevices, were less affected (Byrd et al., 1997).

Foxes have recently been eradicated from several islands (Bailey, 1993) and the responses of seabird populations have been dramatic. Pigeon guillemot (*Cepphus columba*) populations began to increase within three to four years following fox removal at Kiska Island and 20-fold increases occurred in guillemot numbers at Niski-Alaid Island within 15 years of fox removal (Byrd et al., 1994). The introduction of Arctic foxes to the Aleutian Islands, and their influence on native seabird species, provides a dramatic example of how the intentional introduction or movement of species can influence arctic biodiversity.

The report by Rosentrater and Ogden (2003) contained the cautionary note "presently, the magnitude of the threat of invasive species on Arctic environments is unclear: however, the potential impacts of this threat warrant further investigation and precautionary action on species introductions, especially since climate change is expected to result in the migration of new species into the region". The risk to the environment and to biodiversity of intentionally introducing any non-native species into the Arctic must be established before the species is introduced. Experience worldwide indicates that it is often too late if the risk is assessed after the introduction; it might then also be too late to control the spread and effects of the invasive species. The precautionary action is to stop the arrival of the invasive species in the first place because its later eradication may be impossible, and even if possible worldwide experience shows that it is likely to be extremely expensive.

10.4.7. Effects on the management of protected areas

Establishment of protected areas has been a core activity of conservation legislation throughout the world. The concept is implemented in different ways by different national governments, with differing degrees of success, as is clear from reviews of international activities (e.g., IUCN, 1991). This section reviews the underlying ecological concepts related to the conservation of biodiversity and the potential effects of climate change.

Reviews by CAFF (2001, 2002a) showed that much progress has been made in designating protected areas in the Arctic, but that further progress is needed, especially in the marine environment. Halpern and Warner (2002) indicated that marine reserves are very effective at conserving biodiversity, and Halpern (2003) considered that marine protected areas need to be large in extent. In the terrestrial and freshwater environments, some of the largest protected areas worldwide occur in the Arctic. Few studies explore whether such protection is achieving its stated aims.

In general the establishment of protected areas has a scientific foundation. As Kingsland (2002) stated "its goal is to apply scientific ideas and methods to the selection and design of nature reserves and to related problems, such as deciding what kinds of buffer zones should surround reserves or how to establish corridors to link reserves and allow organisms to move from one area to another. As in other areas of conservation biology, designing nature reserves is a 'crisis' science, whose practitioners are driven by an acute sense of urgency over the need to stem the loss of species caused by human population growth". This to some extent misses a vital point: the social sciences are also involved with conservation. Why is it important to conserve biodiversity, why are particular species favored over others, or how do people fit into the conservation framework? Such questions are not addressed here, despite their importance to the local communities of the Arctic (section 10.2.7); this section focuses on the scientific bases of conservation.

Three main facets of ecological thinking have affected the design of potential protected areas. The concepts of island biogeography, of habitat fragmentation, and the establishment of metapopulations (and of corridors) are not unrelated and can all impact upon protected areas in a changing climate.

The concept of island biogeography (MacArthur and Wilson, 1967) includes the idea that the number of species on an island is dynamic, representing the equilibrium between the arrival of new species and the extinction of existing species. Larger islands would have greater immigration rates, and possibly smaller stochastic extinction rates, than small islands, and hence the equilibrium number of species would be greater. Similarly, distant islands would have smaller immigration rates than similarly sized islands nearer the source of immigrants, but would probably have similar extinction rates, and so would have fewer species. Using many sets of data for island biota, these concepts are formulated into the empirical relationship:

$$S = CA^z$$

where S is the number of species on the island, A is the area of the island, and C and z are constants (C represents the number of species per unit area, and z generally takes a value of about 0.3. This relationship implies that if the island area is increased ten-fold, the number of species will about double). Although there have been few island biogeographical studies in the Arctic, Deshaye and Morisset (1988, 1989) confirmed that larger islands in the subarctic (in the Richmond Gulf, northern Québec, Canada) contain more species than smaller islands.

Island biogeography has thus been used to justify larger rather than smaller protected areas. With climate change, and with arctic wildlife populations and their distribution ranges likely to diminish (sections 10.4.1 to 10.4.3), use of the precautionary principle would also suggest that larger rather than smaller protected areas should be established.

Fragmentation of ecosystems has been viewed as the "islandization" of habitats. Although fragments cannot be thought of as real islands, the use of island biogeographical concepts tends to apply relatively well (Harris, 1984). This has led to the formulation of "rules" for the design of protected areas, starting with Diamond (1975), but leading to more sophisticated designs as in Fig. 10.15. Size and shape are the key factors in the design of protected areas, but the inclusion of fragments of natural ecosystems is helpful for biodiversity conservation. Under a changing climate, fragmentation of arctic ecosystems should be avoided. Fragmentation always causes problems (Saunders et al., 1987), even if at some scales it might appear to increase biodiversity (Olff and Ritchie, 2002).

Fig. 10.15. A representation of the biodiversity conservation value of potential protected areas, based on a study of insects in farm woodlands but also applicable to other habitats and other taxonomic groups (Usher, 2002a). The scaling should change to reflect the larger areas prescribed for the Arctic. Habitats are in black and habitat fragments are small white circles. Linear features, such as small rivers, are represented by straight lines.

With fragmentation an integral part of modern development, corridors appear to be a useful concept. How does the landscape fit together such that individuals can move from habitat patch to habitat patch? As pointed out by Weber et al. (2002), land managers and wildlife biologists must collaborate to determine the patterns of protected areas within the landscape that will be of most benefit to wildlife. Some scientists advocate corridors: Saunders and Hobbs (1991) gave a number of examples where corridors appear to work. Others have argued that corridors allow invasive species entry into protected areas, while more recent research calls into question the whole value of corridors. Albeit a beguilingly simple concept, at present neither the value of corridors, nor their lack of value, has been proven. With climate change underway, it is thus best to avoid the necessity for corridors by focusing on larger protected areas and a reduction in the processes leading to habitat fragmentation. This will promote real connectivity, rather than an apparent connectivity, for species and habitats.

However, will the protected areas that exist today, even if they have been located in the best possible place to conserve biodiversity, still be effective in the future with climate change? The answer is probably "no". Designations have been widely used, but are based on assumptions of climatic and biogeographic stability and usually designated to ensure the maintenance of the *status quo*. Available evidence indicates that these assumptions will not be sustainable during the 21st century. So what can be done to make the network of protected areas more appropriate to the needs of the Arctic and its people?

First, today's protected areas should encompass land or water that will potentially be useful for biodiversity conservation in the future. This is where models of the changing distribution of species and habitats are useful and where their outputs should be included in the design

of protected areas (see the example of the Canadian national parks in section 10.4.1). This means that designation should reflect both the present value of the areas for biodiversity as well as the projected future value (the potential value).

Second, boundaries may need to be more flexible. In general, boundaries are lines on maps, and enshrined in legislation, and so are difficult to change. The present practices could be described as having "hard boundaries". An alternative could be that the boundaries change with changes in the distribution of the flora or fauna being protected. That is, over time (probably decades rather than years) the location of the protected areas would shift geographically (this could be described as the protected areas having "soft boundaries"). However, it is important that sociological and developmental pressures do not destroy the value of the protected areas in safeguarding the biodiversity that is their *raison d'etre* – nothing would be worse than in 50 years time having a network of sites that were protecting very little. More flexible systems of designation, adding areas which are or will become important, and dropping areas that are no longer important, would appear to be one way forward to conserve biodiversity within the Arctic. A system of designations with "soft boundaries" has not yet been tried anywhere in the world, but could become a policy option that is pioneered in the Arctic.

Protected area designations are a major policy and management system for the conservation of biodiversity, as well as for historical and cultural artifacts. Climate change might result in designated communities and species moving out of the designated area; communities and species new to the area will tend to colonize or visit, especially from the south; and assemblages of species without current analogues will form as individual species respond to climate change at different rates and in different ways. It will therefore be necessary to adjust such concepts as "representative communities" and "acceptable limits of change" that are part of the mandate of many national and international designations. The expected changes will include many surprises resulting from the complex interactions that characterize ecosystems and the non-linearity of many responses.

The scientific basis of biodiversity conservation planning in the era of climate change argues against procedures designed to maintain a steady state. There are four general policy options to respond to climate change that have been used in the Canadian national parks (summarized by Scott and Lemieux, 2003).

1. Static management. Continuing to manage and protect current ecological communities and species within current protected area boundaries, using current goals.
2. Passive management. Accepting the ecological response to climate change and allowing evolutionary processes to take place unhindered.
3. Adaptive management. Maximizing the capacity of species and ecological communities to adapt to cli-

mate change through active management (for example, by fire suppression, species translocation, or suppression of invasive species), either to slow the pace of ecological change or to facilitate ecological change to a new climate adapted state.

4. Hybrid management. A combination of the three previous policy options.

It is likely that adaptive management will be the most widely applied. This is likely to include actions to maintain, for as long as possible, the key features for which the original designation was made, for example by adjusting boundaries. Past experience indicates that intervention strategies tend to be species-specific, and to be strongly advocated, but this must not detract from the more scientific goal of conserving the Arctic's biodiversity in a holistic manner.

10.4.8. Conserving the Arctic's changing biodiversity

Preceding sections have addressed issues such as the effects of climate change on the size and spatial extent of species populations and the communities in which the species occur, the need to conserve genetic diversity, potential problems resulting from the arrival of non-native species, and problems faced by migrant species. This section addresses a few topics that cut across those already discussed. The two main topics discussed here are taxonomy and monitoring.

Biodiversity depends upon taxonomy. It is necessary to be able to name species and habitats, or to understand variation in DNA, to be able to start to think about biodiversity and its conservation, and to communicate thoughts. Taxonomy is therefore fundamental to the work on biodiversity (Blackmore, 2002). It is necessary to know the species being considered – knowledge of birds, mammals, and fish is certainly satisfactory, but is this true for all the insects in the Arctic and their roles in the arctic freshwater and terrestrial ecosystems? Knowledge of vascular plants (flowering plants and ferns) is probably satisfactory, but is this true for the mosses, liverworts, lichens, and algae that are responsible for much of the photosynthesis, in the sea, freshwaters, and on land? As in almost all parts of the world, is there knowledge about the species of protozoa or bacteria that are associated with the processes of decomposition in arctic soils and in the sediments under lakes or on the sea floor? There are many areas of arctic taxonomy that require exploration and research, and it is vital to the conservation of the Arctic's biodiversity that these taxonomic subjects are addressed.

Monitoring is important for understanding how the Arctic's biodiversity is changing and whether actions to conserve this are being successful. As Cairns (2002) pointed out, monitoring needs to occur at both the system level and the species level. Monitoring will help now, and in the future, to determine if current predictions are correct and to modify and improve the systems

of management. From a scientific perspective, monitoring will allow more data to be collected and, if coupled with research, will also allow a greater understanding of the mechanisms involved with change. In time, therefore, with increasing data and increasing understanding, the conservation of biodiversity would move in the plane shown in Figure 10.12 from the bottom left hand corner and, perhaps only slightly, toward the top right hand corner. With data and understanding it should be possible in the future to build better models and hence make better predictions.

Conservation of the Arctic's biodiversity at present relies upon two approaches. One is through the establishment of protected areas, and this was discussed in section 10.4.7. Greater knowledge of taxonomy and monitoring of what is happening within those protected areas are both important for their future management. The other approach is more educational, bringing biodiversity thinking into all aspects of life in the Arctic. Considerations of biodiversity need to be explicit in planning for developments at sea or on land. Biodiversity needs to be considered explicitly in the management of land, freshwater, and the sea. Links between biodiversity and the health of the local people need to be established. Biodiversity forms the basis of most tourism into the Arctic, but facilities for tourists need particular care so as not to damage the very reason for their existence (Rosentrater and Ogden, 2003). Biodiversity conservation as a concept therefore needs to permeate all aspects of life in the Arctic.

If it is accepted that protected areas are only ever going to cover a relatively small percentage of the land and sea area of the Arctic (possibly between 10 and 20%), then it is the land and sea outside the protected areas that will hold the majority of the Arctic's biodiversity. Just as within protected areas it is vital to have knowledge of taxonomy and programs of monitoring, there must also be taxonomic knowledge and monitoring throughout the Arctic. The majority of the biodiversity resource in the non-protected areas must not be sacrificed because a minority of that resource is within protected areas. Apart from the Antarctic, it is probably easier to achieve this balance between protected areas and the rest of the land and sea area in the Arctic than in other areas of the world, but it will require international effort if the Arctic's biodiversity is to be conserved for future generations to use and enjoy. All this, in the face of climate change, will need "building resilience" (the expression used by Rosentrater and Ogden, 2003) into all arctic ecosystems, whether or not they lie within protected areas.

10.5. Managing biodiversity conservation in a changing environment

To conclude this chapter on conserving the Arctic's biodiversity, it is appropriate to explore a number of topics that have been implicit in the various descriptions and discussions of sections 10.1 to 10.4. Four topics are addressed in this final section: documenting the current

biodiversity; predicting changes in that biodiversity resource over the next 50 or 100 years; determining how that biodiversity resource is actually changing; and managing the Arctic's biodiversity resource in a sustainable manner.

Each topic generates a number of questions, and their answers involve many concepts, most of which have already been introduced in this chapter. Sixteen recommendations are made in relation to the various discussions and conclusions in this section.

10.5.1. Documenting the current biodiversity

The Arctic nations have very good inventories of their mammals and birds (listed by Sage, 1986). Although it is possible that a few more species might have been recorded in the Arctic since the mid-1980s, it is unlikely that the numbers of 183 species of bird and 48 species of terrestrial mammal will have changed significantly.

It is notable that Sage (1986) was unable to provide similar lists for any other taxa of wildlife in the Arctic. From the literature on the Arctic it would probably now be possible to prepare reasonably good inventories of the marine mammals, freshwater and marine fish, and vascular plants. Although this is as much as most nations in the world can compile for national inventories, such lists omit the most species-rich taxa. Large numbers of species of bryophyte (mosses and liverworts), lichen (or lichenized fungi), fungi, and algae occur, as well as many species of invertebrate animals. Terrestrially, it is likely that the insects and arachnids (mites and spiders) will be the most species-rich, whereas in the sea it is likely to be the crustaceans and mollusks that are most species-rich. However, there are many other taxonomic groups, especially the nematodes and many marine taxa of worms, sponges, and hydroids, as well as single-celled organisms in which the "species" concept is more difficult to apply.

Inventories are important. They form the building blocks for biodiversity conservation because, unless the biodiversity is known, it is not possible to begin to conserve it or to recognize when it is changing. Documentation of the numbers and types of species living in the Arctic has focused mainly on terrestrial systems and is detailed in Chapter 7. The Arctic has around 1735 species of vascular plants, 600 bryophytes, 2000 lichens, 2500 fungi, 75 mammals, 240 birds, 3300 insects dominated by the Diptera (two-winged flies), 300 spiders, 5 earthworms, 70 enchytraeid worms, and 500 nematodes. This species diversity represents a small but variable percentage of the world's species, with some groups relatively strongly represented. Thus, there are about 0.4% of the world's insects but 6.0% of the Collembola; as well as 0.6% of the world's ferns but 11.0% of the lichens. There is currently no comparable documentation of numbers of species in the freshwater and marine environments of the Arctic, although there is significant environmental overlap for some taxa, for example, the birds.

An excellent example of an arctic inventory is the work done on Svalbard (Elvebakk and Prestrud, 1996; Prestrud et al., 2004). An overview is given in Table 10.9, giving Svalbard a species richness of about 5700 (terrestrial, freshwater, and marine environments combined). However, this total does not include many of the single-celled organisms, such as the protozoa, and so a full inventory would be substantially longer.

Many species, particularly vascular plants, are endemic to the Arctic. However, there are few endemic genera. This has been attributed to the youthfulness of the arctic flora and fauna, with insufficient time undisturbed to allow the evolution of endemic genera. The proportions in many taxa that are endemic to the Arctic, especially for the lower plants and invertebrates, is unknown, a feature that deserves more attention. The level of information varies widely between taxonomic groups, especially for the soil invertebrates and lower plants that have been examined at few sites. In contrast, information on vascular plants, birds, and mammals is detailed, both in terms of species identification, and in terms of population size and distribution.

In documenting current arctic biodiversity as a basis for conservation, a key feature is that many of the vertebrate

Table 10.9. Species richness in the terrestrial, freshwater, and marine environments of Svalbard (summarized from Elvebakk and Prestrud, 1996, and Prestrud et al., 2004). Detailed species lists are contained in the references quoted.

	Number of species
Plants	
Cyanobacteria[a]	73
Algae[a,b]	1049
Fungi and lichenised fungi[c]	1217
Mosses and liverworts[d]	373
Vascular plants[e]	173
Animals	
Marine crustacea[f]	467
Marine mollusks[f]	252
Other marine invertebrates[f]	924
Marine vertebrates (fish)[f]	70
Terrestrial and freshwater arachnids[g]	134
Terrestrial and freshwater insects[g]	289
Other terrestrial and freshwater invertebrates[g]	617
Birds[h,i]	53
Mammals[h,j]	9
Total	**5700**

[a]Skulberg (1996); Hansen J. and Jenneborg (1996); [b]Hasle and Hellum von Quillfeldt (1996) [c]Alstrup and Elvebakk (1996); Elvebakk and Hertel (1996); Elvebakk et al. (1996); Gulden and Torkelsen (1996); [d]Frisvoll and Elvebakk (1996); [e]Elven and Elvebakk (1996); [f]Palerud et al. (2004); [g]Coulson and Refseth (2004); [h]Strøm and Bangjord (2004); [i]202 species recorded, of which 53 are known to be breeding, to have bred in the past, or are probably breeding; [j]23 species recorded (plus another 8 species which are known to have been introduced), of which 9 are known to be breeding or to have bred in the past.

species spend only a small proportion of their time in the Arctic. This adaptive behavior is found in most birds, some marine mammals, and some freshwater and marine fish. As a result, documentation of their status and conservation action for them is dependent on international cooperation. It is also probable that the main threats to these migratory species occur during their migrations or during their winter period outside the Arctic. Current threats include changes in land- and water-use, human exploitation of resources upon which the animals depend, direct cropping of the animals for food or sport, accidental killing (as in the by-catch resulting from other fisheries), or pollution. A particular benefit of detailed and long-term observations, particularly for migratory birds that cover all continents (Figure 10.4), is that they provide a highly sensitive indicator of global environmental change.

After drawing up biodiversity inventories, individual items (species or habitats) can be assessed for their ability to survive into the future. For example, the IUCN has established criteria for assessing the degree of threat to the continued existence of species (IUCN, 1994). Many nations have used these IUCN criteria as the basis for compiling their national "Red Lists". Species are allocated to the various threat groups on the basis of criteria (Table 10.10). These criteria are grouped into four sets, which are briefly outlined here (see IUCN, 1994 for the various nuances).

First, there is a criterion of the known or suspected reduction in a species' population size. If this is known to have declined by at least 80% over the last ten years or three generations, then the species might be categorized as "critically endangered". Similarly, if the reduction in population size is more than 50% or more than 20% over the last ten years or three generations, then the species could be categorized as "endangered" or "vul-

nerable" respectively. Good data are necessary for such changes in population size to be known or estimated.

Second, there is a criterion relating to the known or estimated decline in the range of the species. Again somewhat arbitrary thresholds are set where the extent of occurrence is estimated to be less than 100 km^2, 5000 km^2, and 20 000 km^2, or the area of occupancy is estimated to be less than 10 km^2, 500 km^2, and 2000 km^2, for the "critically endangered", "endangered", and "vulnerable" categories respectively. For these, the populations must be severely fragmented or located in a single place and either declining or demonstrating extreme fluctuations, in order to be categorized as "critically endangered". There are similar weaker criteria for the "endangered" and "vulnerable" categories (for example, populations must be at no more than 5 or 10 places respectively).

Third, the total population size can be used. The thresholds are less than 250 mature individuals and declining, or less than 50 mature individuals, for the "critically endangered" category. These thresholds are raised to 2500 and 250 for the "endangered" category and 10 000 and 1000 for the "vulnerable" category. At these small total population sizes it is feared that inbreeding could occur, thus reducing the genetic variability within the species. Consequently, conservation action is needed, encouraging all of the mature individuals to contribute to future generations so that the present genetic diversity is not lost.

Finally, assessments can be on the basis of quantitative analyses estimating the risk of extinction in the wild over a period of either a number of years or over a number of generations, whichever is the longer. For the "critically endangered" category, the risk of extinction in the wild would have to be greater than 50% over 10 years or three generations. For the "endangered" category, the risk would have to be at least 20% within 20 years or

Table 10.10. The categories proposed by the IUCN for assessing the vulnerability, and hence the conservation priority, of species (abstracted from IUCN, 1994).

Species evaluated	Data adequate	IUCN category and code	Notes
Yes	Yes	Extinct (EX)	There is no reasonable doubt that the last individual of the species has died
Yes	Yes	Extinct in the wild (EW)	As above, but the species survives in cultivation, in captivity, or in at least one naturalized population outside its native distribution range
Yes	Yes	Critically endangered (CR)	The species is facing an extremely large risk of extinction in the wild in the immediate future
Yes	Yes	Endangered (EN)	The species is facing a large risk of extinction (but not as large as the category above) in the wild in the near future
Yes	Yes	Vulnerable (VU)	The species is facing a large risk of extinction in the wild in the medium-term future
Yes	Yes	Lower risk (LRcd, LRnt, LRlc)	The species does not fit into the above categories, but this category can be divided into three. *Conservation dependent* taxa are those that have a conservation program, cessation of which is likely to result in the species being moved into one of the above categories within five years. *Near threatened* taxa are those that are close to being vulnerable. *Least concern* taxa are those that do not fit into either of the above categories
Yes	No	Data deficient (DD)	There are insufficient data for a decision to be made about allocating the species to any of the above categories
No	No	Not evaluated (NE)	The species has not been assessed for sufficiency of data and hence does not fit into any of the above categories

Box 10.2. Five examples of the causes and possible consequences of genetic variability

1. Low levels of genetic variation in arctic plants, especially in the high Arctic, have been considered to result from widespread vegetative propagation and low sexual recruitment. The Swedish-Russian Tundra Ecology Expedition in 1994 provided the opportunity to sample 16 sites in a coastal transect from the Kola Peninsula to eastern Russia and up to 77° N. Four sedge species, *Carex bigelowii*, *C. ensifolia*, *C. lugens*, and *C. stans*, all showed a relatively high degree of genetic variation within most populations. Those populations with the lowest variation were associated with sites that were recently glaciated (10000 years ago) rather than populations from refugia which were already deglaciated 60000 to 70000 years ago (Stenstrom et al., 2001). Thus, although individual species may be geographically widespread, their genetic makeup and ecotypic variation, and hence their capacity to react to change, can be variable.

2. In Sweden, the rare wood-inhabiting polyporous fungus, *Fomitopsis rosea*, illustrates the limitation of genetic variability resulting from isolation of populations. Populations in isolated forest stands in Sweden had much narrower genetic structure than populations within the continuous taiga forests of Russia (Seppola, 2001). This suggests that habitat fragmentation can restrict genetic differentiation and potentially limit responses to environmental change.

3. Survival of reciprocal transplants of *Dryas octopetala* between snowbed and fellfield sites was followed for 15 years. Non-native genotypes have shown variable mortality rates after experiencing the rapid environmental change of transplanting. Some non-native transplants have survived, with variable rates between sources, but were far fewer than native transplants within their own environment. McGraw (1995) concluded that the existence of ecotypes adapted to different environments improves the probability that the species as a whole will survive rapid environmental change.

4. Musk oxen (*Ovibos moschatus*), despite a circumpolar distribution, have extremely low genetic variability and it is uncertain how they will respond to environmental change or to new parasites and diseases. However, since 1930, reintroduction following local extinction has proved successful from Greenland to Alaska, from Alaska to Wrangel Island, and from Alaska to the Taymir Peninsula. Reintroductions in Norway have been less successful (Gunn, 2001).

5. The genetic composition of plant populations, for example the purple saxifrage (*Saxifraga oppositifolia*) and the moss campion (*Silene acaulis*), determines their capacity to respond to short- or long-term environmental change. Species and populations also respond to the contrasting wet and dry micro-environments within high-arctic habitats. Evidence indicates that current populations in the high Arctic are derived from survivors in refugia during the last glaciation and from migrants that colonized more recently. It is likely that heterogeneity of sites and populations, combined with the history of climate variation, has provided the present flora with the resilience to accommodate substantial and even rapid changes in climate without loss of species (Crawford 1995; Crawford and Abbott 1994).

five generations, whereas for the "vulnerable" category it would have to be at least 10% within 100 years. Such an assessment depends on good data as well as on a suitable model that can be used to assess the risks.

The IUCN criteria are predicated upon species conservation. However, genetic diversity is also a part of the Convention on Biological Diversity. Many species have widespread distributions within the Arctic and occur in different habitats, landforms, and communities. This is a feature of the low species diversity, providing the opportunity for species to exploit resources and environments with little or no competition. Under the conditions of low species diversity, it is thought that the width of the ecological niche of the remaining species is wide. Measures of species richness underestimate the genetic diversity and there is a need to increase documentation of genetic variation within species, especially for those of conservation concern. Ecotypic differentiation is likely to be an important attribute in species response to climate change and is recognized as a key characteristic of arctic biodiversity. Five examples that illustrate genetic variability, its causes, and possible consequences emphasize the importance of both understanding and maintaining genetic variation within species by conserving diverse populations as a basis for conservation – an application of the precautionary principle (see Box 10.2).

This poses a number of questions for nations with arctic territory and for nations interested in the Arctic's biodiversity. Can inventories be prepared for more taxa than just the mammals and birds, which already exist? Are there data of sufficient quality and quantity to allocate the species to the IUCN categories? Are the data good enough and are there suitable models that can be used to estimate the risks of extinction? Are there sufficient taxonomists to be able to recognize, identify, and list the Arctic's species? Although the work of the IUCN is aimed at species, it is also important to have an inventory of habitats. Initially, however, on a circumpolar basis there needs to be agreement on the classification of habitats in the marine environment, the freshwater environment, and the terrestrial environment. This will require ecological expertise and international agreement, but is

a requisite first step in drawing up an inventory of the Arctic's habitats, and then assessing which habitats are priorities for conservation action.

These considerations lead to the first four recommendations. These are made without attempting to allocate responsibility for undertaking the work involved.

1. There needs to be a supply of trained ecologists who can devise appropriate circumpolar classifications of habitats and then survey these so as to measure their extent and quality and to establish their dynamics.

2. There needs to be a supply of trained taxonomists who can draw up inventories of the Arctic's species. There are already good data on which species of vertebrate animals and vascular plants are to be found in the Arctic, so particular attention needs to be given to the training of taxonomists who can work with non-vascular plants, invertebrate animals, fungi, and microorganisms (protozoa, bacteria, etc.).

3. Inventories need to be generated for the Arctic's biodiversity (both species and habitats), indicating for each entry in the inventory where it occurs and either the size of the overall species population or the extent of the habitat. Such inventories need to be on a circumpolar basis rather than on a national basis as nations with arctic territory also have territory south of the Arctic.

4. The genetic diversity of many of the Arctic's species is presently poorly known or unknown. Much research is needed to explore this aspect of the Arctic's biodiversity and conservation management will need to ensure that genetic diversity is not lost.

10.5.2. Identifying changes in the Arctic's biodiversity

In section 10.4, seven series of changes were explored, focusing on the distribution range of species and habitats, on the total size of species populations and the extent of habitats, and on genetic variability within populations. Each of these interacts with the success and failure of non-native species to establish themselves in the Arctic, with the migration routes and timing of migration of migratory species, and with the selection and management of protected areas. Change is expected, and each species is likely to respond in an individualistic way so that novel assemblages of species are very likely to occur in the future. Sources of information on changes to biodiversity are many and varied and analyses of past changes can provide insights into the future (Box 10.3).

Change in ecological communities is often referred to as "ecological succession". A distinction is drawn between "primary succession", which occurs on new substrates such as when a glacier recedes (Miles and Walton, 1993), and "secondary succession", which occurs following a disturbance or perturbation. A preservationist atti-

tude might be to maintain what occurs today and so manage a habitat in such a way as to oppose ecological succession. A conservationist attitude would be to work with ecological succession. This dichotomy of thinking is highlighted by Rhind (2003), who said "we have become fixated with the idea of preventing natural succession and, in most cases, would not dream of allowing a grassland or heathland to develop into woodland". In the Arctic, climate change will drive primary and secondary successional changes and, in the interests of conserving the Arctic's biodiversity, management should work with these changes rather than opposing them.

Species might adapt to new environmental conditions if they have a sufficient genetic diversity and sufficient time. This is outlined in Chapter 7 where it is stated that a key role of biodiversity is to provide the adaptive basis for accommodating the extreme levels of environmental variability that characterize much of the Arctic. The genetic level of biodiversity allows populations to meet the challenges of an extremely variable arctic environment and this ensures persistence of the populations, at least in the short to medium term. Over the longer term, such genetic diversity is the basis for evolutionary change leading to the emergence of new subspecies and species. With projections of a rapidly changing climate, genetic diversity is important as a kind of insurance that the species will be able to successfully meet the environmental challenges that they will face.

As stated by Walls and Vieno (1999) in their review of Finnish biodiversity "…mere biological information is not enough for successful biodiversity conservation. Conservation decisions and the design of biodiversity management are primarily questions of social and economic policy…Biodiversity conservation requires, in fact, the whole spectrum of sociological, economic and policy analyses to complement the basic biological information". Traditional knowledge was addressed in section 10.2.7, but the implications of Walls and Vieno's (1999) comment are that the knowledge gained in the past is insufficient since the aspirations of today's people for the future also need to be considered. This highlights one of the central divisions of thought about biodiversity conservation. Is it "nature-centric", because it is believed that nature has an inherent right to exist? Or, is biodiversity conservation "human-centric", because it is believed that the biological world must be molded to suit the needs of people, now and in the future? The problem with the former approach is that it can neglect the fact that humans (*Homo sapiens*) are an integral part of the ecosystem and the food web. The problem with the latter is that it places *H. sapiens* as the only species that really matters, and hence it is of limited concern if other species become extinct. A middle way needs to be found.

In the Arctic, people have been part of the food web more or less since the end of the last ice age when ecological succession began with the northward movement of plants and animals, in the sea and on land, as the ice retreated. As well as the obvious changes in distribution,

Box 10.3. Some sources of information on changes in the Arctic's biodiversity

Paleo-ecological evidence

Probably the most dramatic ecological event in arctic prehistory was the conversion of a vegetation mosaic dominated by semi-arid grass–steppe with dry soils and a well developed grazing megafauna to a mosaic dominated by wet-moss tundra without a large grazing fauna. There are three main hypotheses to explain the changes.

- The "pleistocene overkill hypothesis". This suggests that Beringia was colonized by people with hunting skills who developed spears with stone micro-blades which enabled them to drive the megafauna to extinction and that it was this loss of grazing that caused the vegetation change. Corroborative evidence for intensive killing comes from paleolithic sites where large quantities of bones have been unearthed. At Mezhirich in the Ukraine, bones of 95 individual mammoths (*Mammuthis primigenius*) were found.
- The "climate hypothesis". This assumes that an arid, continental climate prevailed in Beringia during the Pleistocene giving low summer precipitation and dry soils, promoting productive steppe vegetation which supported the populations of large grazers (mammoths, bison, and horses). As the climate became wetter during the Holocene, snow depth increased, the moss–lichen cover developed, and herbaceous vegetation reduced. This vegetation change is shown in the Pleistocene pollen and plant macrofossil record and it is hypothesized that the vegetation change resulted in the decline and eventual extinction of the megafauna.
- The "keystone-herbivore hypothesis". This hypothesis combines the overkill and climate hypotheses with a more detailed understanding of vegetation changes that results from current knowledge of changes in both grazing and climate (Zimov et al., 1995).

Evidence from refugia such as Beringia, which remained without ice cover during past glaciations as a result of local climate conditions, and changes in sea level have been important in documenting long-term development of species and genetic diversity. Documentation of past ecological changes through analyses of plant and animal remains in stratified terrestrial, freshwater, and marine sediments has contributed much to the analysis of climate change.

Historical documentation

Historical records show that Greenland was first colonized by Norsemen around AD 986. The population rose to about 3000 based on up to 280 farms and enhanced by fishing and trading in walrus skins and ivory. The colony became extinct in the 15th century, probably due to climatic deterioration and possibly disease. Analysis of the vegetation in the vicinity of the farms and habitations indicates that about 50 vascular plants were probably introduced by the Norsemen and have survived to the present day – an ecological footprint detected and quantified through historical documentation (Fogg, 1998). It is the historical records of fishing, whaling, and sealing in the arctic seas that provide some of the most detailed documentation of the distribution and population changes of marine fauna. These are extensively detailed in Chapters 11 and 13. The data reflect the impacts of variation in climate and exploitation often over the past 50 to 100 years or more.

number, extent, etc., there are likely to be many more subtle changes in the functions of ecosystems and in the physiology of individuals, but prediction of what these changes might be is largely elusive. Predictions are based on models. The concept of modeling biodiversity conservation has already been addressed (see Fig. 10.12) and has been shown to be within the domain of statistical models rather than precise models that give a definitive result. However, despite such limitations, models are useful in attempting to explore the likely changes to the Arctic's biodiversity and their effects on the human population.

For example, in Finland models have been used to project the likely changes in the distribution of the major forest trees – pine (*Pinus sylvestris*), spruce (*Picea abies*) and birch (*Betula* spp.) – predicting the movement north of the two coniferous species (Kuusisto et al., 1996). At the same time, the models have projected that whereas at present only the southern fifth of Finland is

thermally suitable for cultivating spring wheat, by 2050 it is likely that this crop could be grown throughout the southern half of Finland. Herein lies the social problems. Finland currently is a country with an economy largely based on forestry and it has a biodiversity rich in forest species. If the economy were to change to one more agriculturally based, how would this affect the social structure of the human population? Would the loss of the forest biodiversity and the loss of the social aspects of its use (e.g., collecting berries and mushrooms, hiking, and other leisure activities in the forest) be acceptable?

These considerations of change lead to two further recommendations.

5. Management of the Arctic's biodiversity must work with ecological succession and not against it. This thinking needs to be incorporated into all aspects

Indigenous knowledge

Insights into environmental and ecological change that are based on indigenous knowledge are now fully recognized and increasingly documented (see Chapters 3 and 12). The documentation includes insights into changes in biodiversity over recent decades, particularly regarding species of importance to hunters. The knowledge is specific to local areas but can be accumulated and compared across regions. For example, maps of migration routes indicate species-specific changes around Hudson Bay (McDonald et al., 1997), whereas recent changes in fish and wildlife, described by Inuvialuit hunters in Sachs Harbour, illustrate specific evidence of other responses to climate changes (Krupnik and Jolly, 2002):

Two species of Pacific salmon caught near the community.
Increased numbers of Coregonus sardinella (least cisco).
Fewer polar bears in area because of less ice.
Increasing occurrence of "skinny" seal pups at spring break-up.
Observation of robins; previously unknown small birds.
Increased forage availability for caribou and muskox.
Changes to timing of intra-island caribou migration
Identification of current and future changes

Documentation of changes in many mammals, birds, and fish is already well developed in national programs of individual arctic nations and internationally for migratory species. Monitoring is particularly strong where international agreements and commercial interests are involved and where individual species are classified as "endangered" on the national or international "Red Lists" drawn up using IUCN criteria (see section 10.5.1). There are, however, other aspects of biodiversity where documentation of change is seriously lacking. Documentation of changes in various aspects of plant diversity is very weak. There are only two programs that approximate to systematic, circumpolar observations of plants. (1) One is the International Tundra Experiment (ITEX), which has routinely recorded changes in vegetation cover and plant performance at about 30 sites (including some alpine and antarctic sites). Experimental passive warming of about 1 to 2 °C is achieved by installing replicated open-topped chambers, with adjacent plots without experimental warming as controls. ITEX has been in operation for a decade, but initial data synthesis has already begun (Arft et al., 1999). The serious limitation in ITEX as a monitoring program is that individual sites are largely dependent on short-term research funding. (2) The other, on a totally different spatial scale and level of resolution, is the use of satellite measurements to detect changes in vegetation greenness (Myneni et al., 1997). This assessment of change in greenness between 1981 and 1991 cannot be validated owing to the total lack of systematic ground observations at a compatible spatial scale.

of the management of biodiversity in the sea, in freshwater, and on the land.

6. Models need to be further developed to explore changes in biodiversity under the various scenarios of climate change. Again, these models will need to explore biodiversity change in the sea, in freshwater, and on land.

10.5.3. Recording the Arctic's changing biodiversity

There are two aspects to recording the Arctic's changing biodiversity that need to be addressed: monitoring (or surveillance) and indicators. Monitoring involves the periodic recording of data so that trends can be detected. Usually, it also involves assessing progress toward some target, but often it only involves determining if the resource being monitored still exists and how the

amount of that resource is changing (and this is often referred to as surveillance). Indicators are regularly monitored measures of the current state of the environment, the pressures on the environment, and the human responses to changes in that state. This three-point set of indicators is often referred to as the "pressure-state-response model" (Wilson et al., 2003). It is often easier to find indicators of state than indicators of either pressures or responses.

Monitoring of wildlife has a long history. There have been attempts to coordinate monitoring, as outlined for the Nordic Nations by From and Söderman (1997). The aim in these nations was "to monitor the biodiversity and its change over time with appropriate and applicable mechanisms, and to monitor the cause-effect relationship between pressure and response on biodiversity by using specific biological indicators". There were five implications of these objectives: (1) the program would

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Box 10.4. The seven long-term objectives for CAFF's biodiversity monitoring (CAFF, 2002c)

Overall objective

To provide an information basis for sound decision-making regarding conservation and sustainable use of arctic flora and fauna.

Detailed objectives

1. To detect change and its causes amongst flora and fauna of the circumpolar Arctic.
2. To strengthen the infrastructure for and harmonization of long-term monitoring of arctic flora and fauna.
3. To provide an early warning system and strengthen the capacity of arctic countries to respond to environmental events.
4. To ensure the participation of arctic residents, including indigenous peoples, and to incorporate their knowledge into monitoring.
5. To establish a circumpolar database of biodiversity monitoring information and contribute to existing European and global database systems.
6. To contribute to national, circumpolar, European, and global policies concerned with conservation of biodiversity and related environmental change.
7. To integrate circumpolar biodiversity monitoring information with physical and chemical monitoring information of the Arctic Monitoring and Assessment Programme and others.

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exclude chemical and physical aspects of environmental monitoring; (2) the focus would be on ecosystems and species and the data would be analyzed in the simplest manner to provide appropriate, qualitative, and quantitative information; (3) another focus would be anthropogenic changes, although the analyses would need to distinguish these from natural changes; (4) monitoring would include, among others, threatened habitats and species, and hence their disappearance or extinction would become known; and (5) the monitoring would not directly focus on administrative performance indicators, although it might provide important information for understanding these. The main problem with this Nordic monitoring program is that it relates only to the terrestrial environment, although this does include wetland and coastal habitats. More attention needs to be paid to the marine environment.

Progress is being made in relation to monitoring biodiversity in the Arctic (CAFF, 2002c) with the Circumpolar Biodiversity Monitoring Program. Its goal is "to improve understanding of biodiversity through harmonization and/or expansion of existing programs and networks. The proposed approach focuses on three large ecosystems (terrestrial, freshwater, marine) and selected criteria include ecological importance, socio-economic importance, and feasibility". CAFF (2002c) then continued with accounts of a number of monitoring programs, covering Arctic char, caribou and reindeer, polar bear, ringed seal, shorebirds (also known as waders), seabirds, geese, and work in relation to the International Tundra Experiment. The strengths of this proposal are that the connections between the marine, freshwater, and terrestrial environments are recognized and that the monitoring would be on a circumpolar basis; the weakness is that so few actual species are being monitored, although the aspirations are more ambitious. At present there is no explicit botanical monitoring, and the invertebrate

animals have been overlooked. For example, a program focused on the many species of fritillary butterfly of the genus *Clossiana* (although taxonomically this has now been divided into a number of genera), which occur in northern Asia, northern Europe, and North America, would indicate much about the effects of climate change on insects and their food plants, and on the interrelationships between plants and specialized herbivores. For the future, the Circumpolar Arctic Biodiversity Monitoring Network project is challenging, having the twin goals to "develop the infrastructure, strengthen ecological representation, and create data management systems for circumpolar Arctic species biodiversity monitoring networks", and to "establish functional links between these arctic networks and European and global biodiversity observation systems and programs". The long-term objectives of CAFF's biodiversity monitoring are listed in Box 10.4.

Monitoring is widely advocated. For example, BirdLife (2000) indicated that it wished to "monitor and report on progress in conserving the world's birds, sites and habitats", but also that it wished to monitor the effectiveness of its work in achieving the objectives set out in its strategy. Usher (1991) posed five questions about monitoring. These related to the *purpose* (what are the objectives?), the *methods* to be used (how can the objectives be achieved?), the form of *analysis* (how are the data, which will be collected periodically, to be analyzed statistically and stored for future use?), the *interpretation* (what might the data mean and can they be interpreted in an unbiased manner?), and *fulfillment* (when will the objectives have been achieved?). It is vital that all five questions are asked and answered before a monitoring scheme begins. All too frequently *ad hoc* monitoring programs provide data that cannot be analyzed statistically and so the confidence that can be placed in resulting trends is minimal.

The basic need is for the establishment of a circumpolar network of sites where large-scale (hectares or square kilometers) replicated plots can be distributed where vegetation cover and composition can be documented. Following scientific principles, the network could be spatially located to test the hypotheses of vegetation change that have been generated during the ACIA process. Establishment of some sites within the CPAN could further test the performance of this approach to conservation. Further, fine-scale observations, for example of species performance, could be nested within the landscape-scale plots. Such a hierarchy of spatial scales would be similar to that defined in the Global Terrestrial Observing System (GTOS) led by the FAO. 171 arctic sites and a number of arctic site networks are currently registered on the Terrestrial Ecosystem Monitoring Sites of the GTOS, and they could provide the basis for an appropriate monitoring network. The GTOS has developed a Biodiversity Module with seven core variables to guide development in the program (threatened species, species richness, pollinator species, indicator species, habitat fragmentation, habitat conversion, and colonization by invasive species). The relationship with the sister programs, the Global Ocean Observing System (GOOS) and the Global Climate Observing System (GCOS), needs to be clarified. This would correspond with the recommendations in Chapters 7, 8, and 9. Each chapter identifies the need for improved systematic, long-term observation and monitoring programs.

Based on the aspects of the conservation of biodiversity identified in this chapter, further attention should be given to the five subsidiary aspects of monitoring outlined in Box 10.5. It would be too resource intensive to

Box 10.5. Five other aspects of monitoring that relate to the principles of biodiversity conservation outlined in this chapter

Phenology monitoring

This has a long tradition, especially in Russia, but has not been developed to meet future needs. Observation of the timing of specific phenomena, for example leaf and flower emergence, arrival and departure of migratory birds, and timing of emergence and feeding of specific insects, can be directly related to climatic conditions if repeated annually. Such observations are particularly suited to remote rural communities where other monitoring is not feasible. It also has a strong educational potential.

Genetic diversity

This is generally poorly and unsystematically documented. The establishment of a baseline for future detection of change is a priority. Selection of a limited number of distinct taxonomic and functional groups, with particular conservation concern, should allow establishment of an initial circumpolar baseline, including storage of appropriate material.

Invertebrate fauna

Both the diversity and distribution of invertebrates, especially in soils and freshwater sediments, are poorly documented, despite their importance as a basis for food webs and in the decomposition of organic matter and nutrient cycling. Establishment of basic survey information is best developed through a short-term targeted program at a limited number of existing research bases and field sites, supplemented where necessary so as to obtain a representative coverage of broad habitat types.

Integrated monitoring

Potential cause and effect variables would be recorded; this is seen to be increasingly important as the complexity of the systems is recognized. The ACIA has provided the best available understanding of the complex system responses to climate change. The next critical step is to express these as system models and test these through existing and expanded data at a limited number of selected field sites, so as to test and refine the hypotheses and to assess the potential establishment of long-term integrated monitoring.
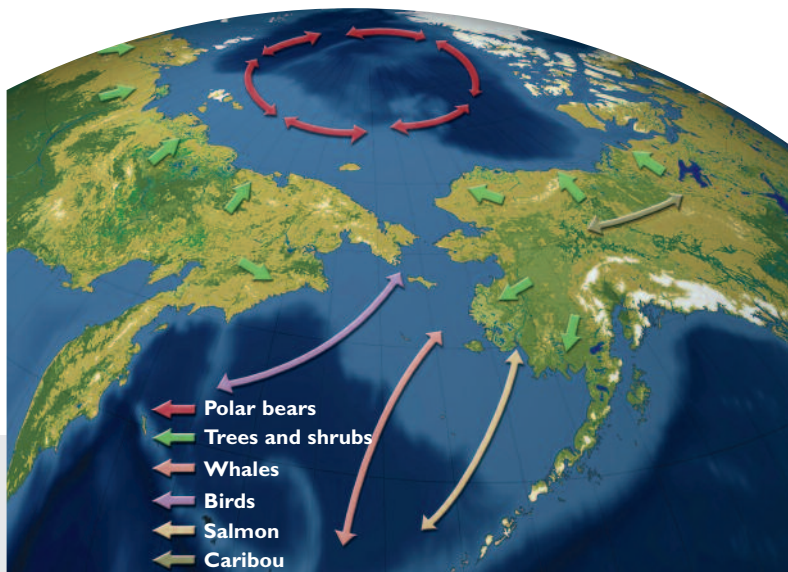
A rapid response network

The ACIA has highlighted the probability of increased frequency and intensity of climatic events, increased outbreaks of pests and diseases, increased pollution, and other environmental accidents. The timing and location of such events are currently unpredictable. Yet the need for rapid initial documentation of impacts on biodiversity as a basis for longer-term observations is regularly required. The use of existing distributed field stations to provide an initial, international rapid response network is a logical development that would benefit from a feasibility study.
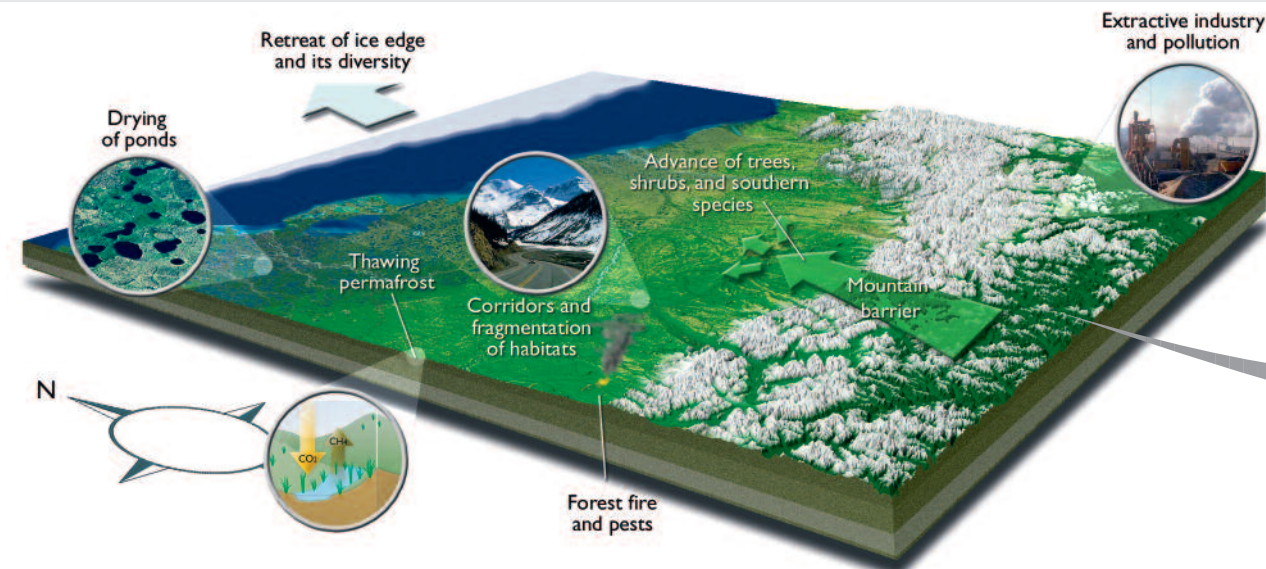
(a) Global level
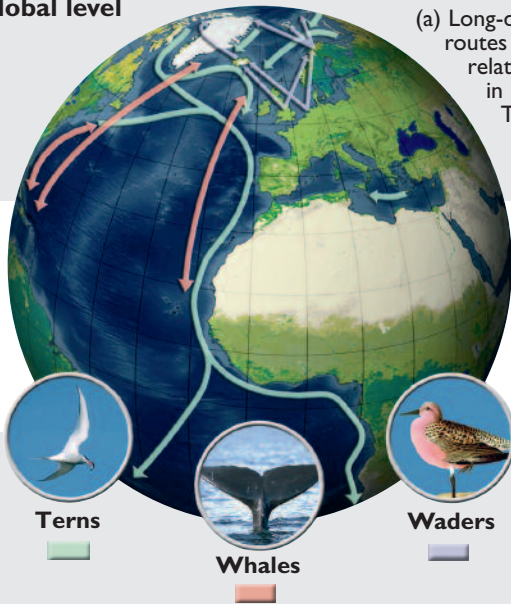
(a) Long-distance animal migration routes are sensitive to climate-related changes such as alterations in habitat and food availability. The amplification of warming in the Arctic thus has global implications for wildlife.

Terns

Whales

Waders

attempt to monitor all aspects of the Arctic's biodiversity. So in order to reduce the amount of work required indicators are often advocated. For indicators to be valuable they should ideally fulfill the following four criteria (modified from Wilson et al., 2003). First, they should reflect the state of the wider ecosystems of which they are a part. Second, indicators should have the potential to be responsive to the implementation of biodiversity conservation policies. Third, indicators should be capa-

(b) Regional level

(b) At the regional level, vegetation and the animals associated with it will shift in response to warming, thawing permafrost, and changes in soil moisture and land use. Range shifts will be limited by geographical barriers such as mountains and bodies of water. Shifts in plankton, fish, and marine mammals and seabirds, particularly those associated with the retreating ice edge, will result from changes in air and ocean temperatures and winds.

Polar bears
Trees and shrubs
Whales
Birds
Salmon
Caribou

ble of being measured reliably on a regular (not necessarily annual) basis, and should be comparable with similar measures at greater spatial scales. Fourth, they should have, or have the potential for, strong public resonance. Such a set of criteria for indicators fits well with the set of seven long-term objectives of CAFF's Circumpolar Arctic Biodiversity Monitoring Network proposal, outlined in Box 10.4.

(c) At the landscape level, shifts in the mosaic of soils and related plant and animal communities will be associated with warming-driven drying of shallow ponds, creation of new wet areas, land use change, habitat fragmentation, and pests and diseases. These changes will affect animals' success in reproduction, dispersal, and survival, leading to losses of northern species and range extensions of southern species.

(c) Landscape level

Retreat of ice edge and its diversity

Extractive industry and pollution

Drying of ponds

Advance of trees, shrubs, and southern species

Thawing permafrost

Corridors and fragmentation of habitats

Mountain barrier

N

Forest fire and pests

Fig. 10.16. A representation of the effects of climate change on biodiversity at different spatial scales. The text focuses on species diversity and to some extent on habitat diversity, but genetic diversity is not included.

These discussions lead to three further recommendations.

7. Circumpolar monitoring networks need to be fully implemented throughout the Arctic. The proposals are challenging, but data on the state of the Arctic's biodiversity, on the drivers of change in that biodiversity, and on the effectiveness of responses to those changes, needs to be collected, analyzed, and used in the development of future arctic biodiversity policy.

8. Attention needs to be given to establishing the kinds of subsidiary aspects of monitoring, examples of which are outlined in Box 10.5. These are vital if a holistic view is to be taken of the Arctic's biodiversity, its conservation in the face of a changing climate, and the management of the biodiversity resource for future generations of people to use and enjoy.

9. A suite of indicators needs to be devised and agreed, monitoring for them undertaken, and the results made publicly available in a format (or formats) so as to inform public opinion, educators, decision-makers, and policy-makers.

10.5.4. Managing the Arctic's biodiversity

"The Arctic is a distinct and significant component of the diversity of life on Earth" was a statement made at a meeting in 2001 to celebrate ten years of arctic environmental cooperation (Vanamo, 2001). This probably encapsulates why the conservation of the Arctic's biodiversity is not only essential to the peoples of the Arctic but also why the Arctic is important globally. It sets the imperative to do something to conserve the biodiversity of one of the more pristine geographical parts of the

(d) PLOT LEVEL
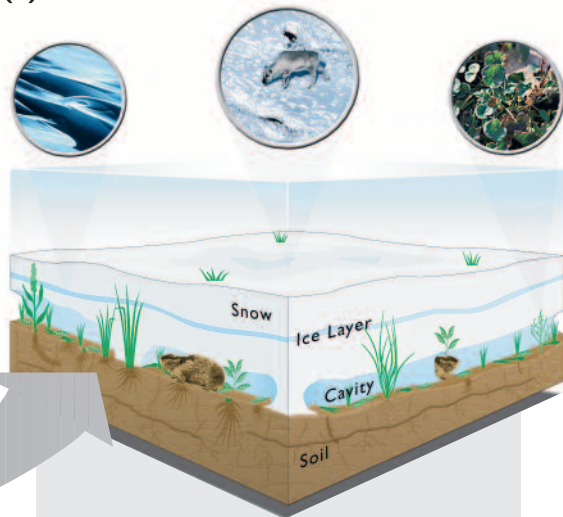
(d) Changes in snow conditions, ice layers, the cavity beneath the snow, summer temperatures, and nutrient cycling act on individual plants, animals, and soil microorganisms leading to changes in populations. It is at the level of the individual animal and plant where responses to the climate take place leading to global-scale vegetation shifts.

world, but nevertheless a geographical area that is threatened with a series of human-induced changes due to developments and over-exploitation within the Arctic, and to long-range pollution and climate change, which are both global problems.

One of the first requirements is to collate information about the best way to manage the Arctic's biodiversity in a changing climate. This will be based on knowledge held by local people together with knowledge that has been gained by scientists, either through observation or experiment. There have been a number of attempts to bring together guidelines for best practice, usually either in a nation or for a particular area. An example would be the proposals developed in Finland for practical forest management (Korhonen et al., 1998). These guidelines integrate concern for the environment with the needs of production forestry, and the use of forests for recreation, protection of the quality of soil and water, and the management of game species. They provide an example of what can be done when all the interest groups work together for a common goal. Such an approach would also be useful on a circumpolar basis for the conservation and sustainable use of the Arctic's biodiversity. This leads to a further recommendation.

10. Best practice guidelines need to be prepared for managing all aspects of the Arctic's biodiversity. These need to be prepared on a circumpolar basis and with the involvement of all interested parties.

The value of protected areas has been discussed (section 10.4.7), as well as the plans for developing a comprehensive network of these areas throughout the Arctic. Such a start is excellent, setting aside areas of land, freshwater, and sea where nature has primacy over any other forms of land- and water-use. The three questions that need to be asked are how quickly can this network of protected areas be completed, how will they need to change as the climate is changing, and are they doing what they were designed to do? First, the reviews by CAFF (2001, 2002a) indicated that there were some of the Arctic's habitats, especially in the marine environment, that were not adequately covered by the CPAN. It is important that work on establishing a comprehensive CPAN is undertaken so that protection can be afforded to the breadth of the Arctic's biodiversity before any is lost. Second, work on understanding how climate change will affect each protected area will allow management to have a greater chance of protecting the biodiversity in that area, or of adopting the "soft boundary" approach outlined in section 10.4.7. Work needs to be undertaken, and made widely available in management guidelines, on the management of these protected areas; an example for the protected areas in Finland is as in Anon (1999). Work also needs to analyze how climate change is likely to affect each of the protected areas. Such work has been carried out for the Canadian national parks (Scott and Suffling, 2000), stressing the importance of sea-level rise for the many national parks that are located on the

coast. These considerations give rise to two further recommendations.

11. The CPAN needs to be completed and then reviewed so as to ensure that it does actually cover the full range of the Arctic's present biodiversity.
12. An assessment needs to be made for each protected area of the likely effects of climate change, and in the light of this assessment the management methods and any revisions of the area's boundary need to be reviewed.

In undertaking these reviews, one of the important questions is whether or not the protected area is conserving what it was designed to conserve. This is not always a simple task, especially with year-to-year variation in population sizes and with longer term changes in habitat quality, but such assessments are becoming more commonplace (e.g., Parrish et al., 2003).

Protected areas are just one method for attempting to conserve the Arctic's biodiversity. Although biodiversity conservation is the primary focus of management within the protected areas, they will only ever cover a relatively small proportion of the land and water area of the Arctic, and thus will only contain a small proportion of the Arctic's biodiversity resource. Hence, it is imperative that biodiversity is also considered in the land and water outside protected areas. Forms of integrated management need to be adopted whereby biodiversity is not forgotten among all the other competing claims for space on land or at sea. The kind of approach proposed for the Canadian Arctic, with forms of integrated management of coastal and marine areas (M.A.K. Muir, Arctic Institute of North America and CAFF, pers. comm., 2003), is just one example of practical applications of a biodiversity approach to the wider environment. The need is to incorporate biodiversity thinking into all forms of policy development, not just environmental policies, but also policies on education, health, development, tourism, and transport. This is clearly a part of this wider environmental approach for biodiversity conservation. In this way more of the Arctic's biodiversity is likely to be protected in the face of a changing climate than by relying solely on the protected areas. These considerations give rise to two further recommendations.

13. Integrated forms of management, incorporating the requirement for biodiversity conservation, need to be explored for all uses of the land, freshwater, and sea in the Arctic.
14. Biodiversity conservation needs to be incorporated into all policy development, whether regional, national, or circumpolar.

In order to assist in these processes, the "ecosystem approach", sometimes also referred to as the "ecosystem-based approach", has been advocated (Hadley, 2000). This sets out a series of 12 principles, some of which are science-oriented, but all of which form an essentially socio-economic context for conservation. In relation to

climate change in the Arctic, two of the 12 principles are particularly relevant. Principle 5 focuses on ecosystems services, and is that "conservation of ecosystem structure and function, in order to maintain ecosystem services, should be a priority target for the ecosystem approach". Principle 10 states that "the ecosystem approach should seek the appropriate balance between, and integration of, conservation and use of biological diversity". An example of the possible application of this approach for the marine environment in the Arctic is as reported by CAFF et al. (2000, the summary of the presentation by K. Sherman) and Muir et al. (2003). Since this approach is still comparatively new, its details have as yet been worked out in very few situations. Hence, a further recommendation.

15. The ecosystem approach (or ecosystem-based approach) should be trialed for a number of situations in the Arctic, so as to assess its ability to harmonize the management of land and water both for the benefit of the local people and for the benefit of wildlife.

In all this work, it should be remembered that the conservation of the Arctic's biodiversity is necessary for itself, for the peoples of the Arctic, and more generally for this planet. These concepts were implicitly enshrined in the Convention on Biological Diversity, the final text of which was agreed at a conference in Nairobi, Kenya, in May 1992. Within a year, the Convention had received 168 signatures. As a result, the Convention entered into force on 29 December 1993, and there is now considerable international activity to implement the Convention in the majority of nations globally. This gives rise to a final recommendation.

16. All nations with arctic territory should be working toward full implementation of the Convention on Biological Diversity, coordinating their work on a circumpolar basis, and reporting both individually and jointly to the regular Conferences of the Parties.

10.5.5. Concluding remarks

Biodiversity is not the easiest of concepts to grasp. On the biological side, biodiversity needs to be considered at three scales – variation within species (genetic diversity), variation between species (species diversity), and variation among assemblages of species (habitat diversity). Whereas habitat diversity in the Arctic's land, freshwater, and sea would probably be measured in hundreds of habitats, species diversity would be measured in thousands or tens of thousands of species, and genetic diversity in millions of genes. These are all influenced by a changing climate. On the geographical side, biodiversity can be considered at many different scales, from the individual plant or animal and its immediate surroundings, to the whole world. Again, a changing climate can affect each of these scales, and indeed the effects at one scale may be different to the effects at another.

This chapter has shown that the Arctic's biodiversity is important in relation to the biodiversity of the world at the largest extreme and to local people at the smallest extreme. The types of impacts that climate change might have are illustrated in Fig. 10.16, which endeavors to highlight the importance of four of the spatial scales. Each of the ecological processes is affected by climate change, whether the migrations at the global scale or decomposition of dead plant and animal material at the plot level. A small shift in a climatic variable can have very different effects at these scales, and a small change at one scale can cause other changes in scales both above and below. Cause and effect are often difficult to determine, and so models to project changes as a result of climate change are still problematic.

Herein lies the difficulty in conserving the Arctic's biodiversity. Among this multitude of scales, what are the priorities? Should the primary focus be on habitats, species, or genes? Which of the many spatial scales is the most important? It is clear that not every aspect of the Arctic's biodiversity can be conserved, so priorities have to be attached to actions that can conserve the greatest amount of biodiversity or, in some situations, the greatest amount of useful biodiversity. But to set these priorities, information is required about the present state of biodiversity and about how it is changing. With such information, models of a more or less sophisticated type can be used to project what might happen in the future. It is within this context that the 16 recommendations have been made, and their acceptance should assist the peoples of the Arctic in conserving their biodiversity into the future.

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