Chapter 25

Polar Systems

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FIGURES

TABLES

*This appears in Appendix A at the end of this volume.

Main Messages

Changes in polar community composition and biodiversity are affecting human well-being (*high certainty*). Important changes include the reduction of top predators in Antarctic marine food webs, altering food resources; increased shrub dominance in Arctic wetlands, which contributes to summer warming trends and alters forage available to caribou; changes in insect abundance that alter food availability to wetland birds, energy budgets of reindeer and caribou, or productivity of forests; increased abundance of snow geese, which are degrading Arctic wetlands; overgrazing by domestic reindeer in parts of Fennoscandia, Russia, and sub-Antarctic islands; and a rapid increase in the occurrence and impact of invasive alien species, particularly in previously isolated sub-Antarctic islands.

Climate change has substantially affected ecosystem services and human well-being in polar regions (*high certainty*). Warming has been regionally variable but, on average, temperatures are warmer now than at any time in the past 400 years. Warming-induced thaw of permafrost is becoming more widespread, causing threshold changes in ecosystem services, including subsistence resources, climate feedbacks (energy and trace gas fluxes), and support for industrial infrastructure. International conventions have established mechanisms to reverse human impacts on UV-B, but international efforts to reverse human impacts on climate change have been less successful.

Regional changes in atmospheric temperatures and sea-ice extent and duration are changing the functioning of Antarctic marine ecosystems (*high certainty*). The Antarctic Peninsula, with its neighboring oceanic sectors, is one of the most rapidly warming regions on the planet (*high certainty*). It is also the area where populations of higher predators are concentrated as a result of high primary and secondary production and where the majority of exploitation of living resources has been concentrated. Changes in ecosystem structure are already occurring.

Most changes in feedback processes that occur in polar regions magnify trace-gas-induced global warming trends and reduce the capacity of polar regions to act as a cooling system for planet Earth. These climate feedbacks result from changes in the physical system (increased moisture transport to the poles, declines in the areal extent of sea ice and glaciers, and earlier snowmelt) (*high certainty*). In addition, within the Arctic, most changes in vegetation (expansion of shrubs in North America) and trace gas fluxes (release of soil carbon to the atmosphere as carbon dioxide and methane) are amplifying regional warming, although the retreat of the tree line in Russia is leading to cooling (*medium certainty*).

In the Arctic, regional warming interacts with socioeconomic change to reduce subsistence activities by indigenous and other rural people, the segments of society with the greatest cultural and economic dependence on these resources. Warming has reduced access to marine mammals (less sea ice) and made the physical and biotic environment less predictable. Industrial development has reduced the capacity of ecosystems to support subsistence activities in some locations. Other animals, such as moose (*Alces alces*) in North America, have moved northward in response to warming.

There is *high certainty* that reductions in the summer extent of sea ice will increase shipping access along northern sea routes, fostering northern development, and—together with rising sea level—will increase coastal erosion that currently threatens many coastal villages. The net effect is generally to increase the economic disparity between rural subsistence users and urban residents.

Increases in persistent organic pollutants and radionuclides in subsistence foods have increased health risks in some regions, but diet changes associated with the decline in harvest of these foods are usually a greater health risk.

Mitigation of impacts (rather than reversing changes in drivers) is the most feasible short-term strategy for protecting polar ecosystem services and human well-being because the major causes of polar change are globally distributed. Direct impacts of human activities on polar regions have been modest, and nations with Arctic lands or Antarctic obligations have the economic resources to mitigate many current and expected problems if appropriate policies are applied. Consequently, many parts of polar regions have a high potential to continue providing key ecosystem services, particularly in polar oceans and wetlands where biodiversity and resource harvest are concentrated. However, the sensitivity of polar ecosystems to disturbances associated with resource extraction makes them vulnerable to future global increases in resource demand.

25.1 Introduction

The polar systems treated in this chapter are treeless lands at high latitudes. These systems merge in the north with boreal forest (see Chapter 21) and in the south with the Southern Ocean (see Chapter 18). This chapter emphasizes the ecological processes that most directly influence human well-being within and outside polar regions. The physical processes in polar regions that influence human well-being (such as ozone effects on UV-B and changes in glaciers and sea ice) are described briefly in this chapter and more fully in the Arctic Climate Impact Assessment and in assessments of the Intergovernmental Panel on Climate Change (Anisimov et al. 2001). Because of its greater area of ice-free land and larger human population, the Arctic figures more prominently than the Antarctic in this chapter, although both are equally important when physical processes and marine ecosystems are integrated with terrestrial ecological processes.

25.1.1 The Arctic

The basic characteristics of Arctic terrestrial ecosystems were recently summarized by the Arctic Climate Impact Assessment (Callaghan et al. in press). It is a 12-million-square-kilometer treeless zone between closed boreal forests and the ice-covered Arctic Ocean. Within the Arctic, there are northward gradients of shorter snow-free seasons (from three months to one month), lower temperatures (from 10–12° Celsius to 2° Celsius in July), and less precipitation (generally from about 250 to 45 millimeters per year) (Jonasson et al. 2000). Permafrost (permanently frozen ground) is nearly continuous in most of the Arctic but becomes less continuous to the south and in maritime regions such as Scandinavia. Regional variation in Arctic climate reflects the nature of adjacent oceans. Cold waters in ocean currents flowing southwards from the Arctic depress the temperatures in Greenland and the eastern Canadian Arctic, whereas the northeasterly flowing North Atlantic Current warms the northern landmasses of Europe.

The land cover of the Arctic includes ice, barrens (which in this chapter includes polar desert and prostrate shrub tundra with less than 50% plant cover), and tundra (which in this chapter includes treeless vegetation with nearly continuous plant cover). Tundra constitutes the largest natural wetland in the world (5 million square kilometers). (See Table 25.1.) The distribution of these major Arctic land cover types is well known, although their areal extent differs substantially among authors, depending on vegeta-

Table 25.1. Polar Subtypes and Their Areas. The area of the major subtypes of Arctic and Antarctic ecosystems was estimated from the maps in Figure 25.1. The Arctic includes only areas north of 55°N and excludes forests and woodlands in that zone. Barrens are lands with less than 50% vascular plant cover, and arctic tundra has >50% plant cover. Barrens include polar desert and prostrate shrub tundra; Arctic tundra includes graminoid tundra, erect shrub tundra, and wetlands. All Arctic tundra is classified as wetlands under the Ramsar Convention. (CAVM Team 2003)

Ecosystem type	Total	Canada	United States	Greenland	Eurasia
			(mill. sq. km.)		
Arctic	10.57	3.29	1.01	2.14	4.13
Ice	2.50	0.25	0.10	1.95	0.20
Barrens	3.01	1.90	0.11	0.12	0.88
Artic tundra	5.06	1.14	0.80	0.07	3.05
Antarctic ice	12.44				

tion classification (McGuire et al. 2002; CAVM Team 2003). (See Figure 25.1 in Appendix A.)

Only 3% of the global flora and 2% of the global fauna occur in the Arctic, and their numbers decrease toward the North (Chernov 1995; Matveyeva and Chernov 2000). However, the Arctic is an important global pool of some groups, such as mosses, lichens, and springtails. The proportions of species that occur in the Arctic differ among major groups—spiders at 1.2%, for instance, insects at 0.3%, fishes at 1.8%, reptiles at <0.1%, mammals at 2.8%, and birds at 2.8%. In general, primitive groups (such as springtails, up to 12%) are better represented in the Arctic than are advanced groups such as beetles (0.1%). Exceptions to the general gradient of declining terrestrial diversity at higher latitudes include sawflies and shorebirds (Kouki 1999; CAFF 2001).

Animal species decline with increasing latitude more strongly than do vascular plants (frequently by a factor of 2.5) (Callaghan et al. in press). There are about 1,800 species of vascular plant, 4,000 species of cryptogam, 75 species of terrestrial mammal, 240 species of terrestrial bird, 2,500 species of fungus, and 3,200 species of insect (Matveyeva and Chernov 2000). Because of the low species diversity, some ecologically important species—such as the sedge *Eriophorum vaginatum,* lemmings, reindeer and caribou, and mosquitoes—have large populations with broad geographic, often circumpolar, distributions. Terrestrial food webs are often simple, with few species at a particular level in the web. Consequently, changes in abundance of one species can have many direct and indirect ecosystem consequences (Blomqvist et al. 2002). A significant attribute of Arctic biodiversity is the importance of migratory species, including most birds and marine mammals, caribou, and many key fish species such as salmon. Many of these species are important subsistence foods for local residents, and their population dynamics can be strongly affected by processes outside the Arctic.

Terrestrial net primary production and decomposition rates are low and decrease from south to north. The stocks of soil carbon are high in boreal woodlands and Arctic tundra but low in barrens. (See Table 25.2.) Because of low productivity, revegetation after human disturbance can take centuries (Forbes et al. 2001).

The Arctic has been populated throughout the Holocene. Of the 3.8 million people who live there, about 8% (300,000) are indigenous. Population density ranges from near 8 persons per square kilometer in the Murmansk Region of Russia to fewer than 0.1 person per square kilometer in the Canadian Arctic (Knapp 2000). Most people in the Arctic live in urban areas, so population densities in rural areas are extremely low (typically fewer than 0.1 person per square kilometer). The percentage of indigenous peoples is greatest in Greenland and North America, intermediate in Scandinavia, and lowest in Russia.

25.1.2 The Antarctic

The Antarctic (12.4 million square kilometers) is similar in size to the Arctic but differs in being a largely ice-covered continent surrounded by a ring of sea ice and extensive cold oceans. It has no indigenous peoples, and use of the area for harvest of marine mammals, birds, and fish began less than 200 years ago. The northern boundary of the Antarctic region is the Antarctic Polar Frontal Zone linked with the Antarctic Circumpolar Current, where the southern cold surface waters sink below warmer southern temperate waters at about 58° S (Anisimov et al. 2001). The combination of the oceanic frontal zone and the circumpolar current and westerly atmospheric circulation provides a strong barrier to the movement of both terrestrial and marine biota into or out of the region (Clarke and Crame 1989; Barnes et al. submitted). Within the Antarctic region, three zones are frequently recognized (Smith 1984; Longton 1988): the sub-Antarctic (oceanic islands close to the Polar Frontal Zone), maritime Antarctic (Scotia Arc archipelagoes and west coast of Antarctic Peninsula to about 72° S), and continental Antarctic (the remainder of the peninsula and main continental mass).

The Antarctic and Arctic experience parallel latitudinal influences on seasonal climate (day length and insolation) but otherwise have quite different environmental patterns and extremes (Convey 1996; Danks 1999), largely driven by the contrasting geography of the two regions. Several sub-Antarctic islands encircle Antarctica close to the Polar Frontal Zone. These have cold, relatively stable temperatures, with thermal variation buffered by the surrounding ocean and with high precipitation and cloud cover. Mean monthly air temperatures for most islands are positive year-round (Doran et al. 2002a; Thost and Allison in press).

The maritime Antarctic also experiences a strong oceanic influence, effectively acting as a physical barrier to the circulation of moist air from the Pacific component of the Southern Ocean. Mean monthly air temperatures in the maritime Antarctic are positive (but less than 2° Celsius) for two to four months in summer and negative for the remainder of the year, although positive air temperature may occur in any month (Walton 1984; Smith et al. 2003).

Inland, the climate of the Antarctic continent is colder than the Arctic, with average annual temperatures of −20° Celsius or lower (Hempel 1994; Doran et al. 2002b). Large parts of continental Antarctica are classified as frigid or polar deserts, with extremely low precipitation. This, combined with low humidity and strong katabatic winds, can lead to rapid ablation and extensive ice-free areas (Doran et al. 2002a; Nylen et al. 2004). The largest of these, the McMurdo Dry Valleys (about 4,800 square kilometers), contains a mosaic of perennially ice-covered lakes, ephemeral streams, and arid soils (Fountain et al. 1999). Plant and animal biomass of these valleys is low, and microbes dominate biological productivity (Doran et al. 2002b).

The Southern Ocean is covered by an expanse of sea ice that varies seasonally from 3 million to 20 million square kilometers: about the size of North America. Sea ice contains within its matrix a microbial community of algae, bacteria, and small consum-

Table 25.2. Comparisons of Carbon Pools in Arctic-Alpine Tundra with the Boreal Zone and World Total. The soil pools do not include the most recalcitrant humic fractions. (McGuire et al. 1997)

	Area	Soil	Vegetation	Soil:Veg. ratio	Total carbon		
					Soil	Veg.	Soil+Veg.
	(mill. sq. km.)	*(grams per sq. meter)*			*(trillion kilograms)*		
Arctic and Alpine tundra	10.5	9,200	550	17.0	96	5.7	102
Boreal woodlands	6.5	11,750	4,150	2.8	76	27	103
Boreal forest	12.5	11,000	9,450	1.2	138	118	256
Terrestrial Total	130.3	5,900	7,150	0.8	772	930	1,702

ers (Arrigo et al. 1997; Brierley and Thomas 2002). It also serves as a refuge for juvenile krill that browse on the microbial community (Siegel et al. 1990) and as a feeding platform for penguins and seals (Fraser and Hofmann 2003). There are marked regional interannual variations in the extent and duration of sea ice that generate changes in the functioning of the whole ecosystem (Murphy et al. 1995, 1998; Loeb et al. 1997; Fraser and Hofmann 2003). The entire Antarctic marine ecosystem, from primary producers to whales, therefore depends on the extent and duration of sea-ice cover (Quetin and Ross 2001; Smith et al. 2003; Atkinson et al. in press).

The terrestrial biodiversity of Antarctica is much lower than that in the Arctic because of its geographic isolation, the relative youth of most terrestrial habitats (formed after the retreat of Pleistocene glaciers), and the extreme environmental conditions (Convey 2001b). There are no native terrestrial vertebrates, but large populations of marine birds (penguins, petrels, gulls, terns, skuas) and seals take advantage of the absence of land-based predators, relying on terrestrial sites to breed, molt, and rest. These provide considerable nutrient input to terrestrial habitats while also imposing physical damage through trampling and manuring.

Less than 1% of the continent is seasonally ice- or snow-free, providing rock and soil habitats for life (Block 1994). Vascular plants and higher insects are poorly represented on the Antarctic continent (two native species of each, both restricted to the maritime Antarctic). Mosses, liverworts, and lichens are frequent in coastal low-altitude areas but rapidly decrease with progression into the interior or the ice-free dry valley deserts. Likewise, the more primitive or lower groups of invertebrates (such as mites, springtails, nematodes, and other soil mesofauna) assume a dominant role in food webs rarely seen elsewhere. The simplest faunal assemblages found worldwide occur in the Dry Valleys and inland continental nunataks (Freckman and Virginia 1997; Convey and McInnes in press). Many of these groups show high levels of endemism. Biodiversity on the sub-Antarctic islands is considerably higher than on the continent, though lower than at comparable latitudes in the Arctic, and rates of endemism are again extremely high (Chown et al. 1998; Bergstrom and Chown 1999).

The only permanent human residents in Antarctica are scientists and support staff who live in 37 research stations and many temporary camps. They number about 4,000 in the three- to four-month summer and 1,000 in winter (Frenot et al. in press). Their research examines processes and patterns that can only be explored in extreme conditions, such as the record of Earth's climate history preserved in ice cores, physiology and organism adaptation in extreme conditions, and the functioning of highly simplified ecosystems (Weller et al. 1987). There is a rapidly growing tourist trade, with 14,000 people visiting the Antarctic in 1999–2000 (Frenot et al. in press). Tourists predominantly visit coastal areas to view marine birds and seals and to see historic huts and sites used by Antarctic explorers of the early twentieth century, spending most of their time on ships. Increased tourism has global causes. Economic prosperity provides individuals with the financial means to participate, while events such as the economic downturn in Russia resulted in the release of ice-strengthened research ships to support tourism.

25.2 Condition and Trends in Polar Ecosystem Services

The dramatic changes in many of the drivers that shape polar processes are having profound effects on ecosystems and the services they provide to society. This section describes the current condition and major trends in ecosystem services that are important to society, both within and beyond polar regions.

25.2.1 Climate Regulation

25.2.1.1 Physical Feedbacks

Polar regions play a key role in the global climate system and therefore influence human activities and well-being throughout the world. (See Chapter 13.) They act as an important cooling system for Earth by reflecting incoming radiation from ice, snow, and clouds and by radiating back to space the heat that is transported poleward by the atmosphere and oceans. The heat loss from polar regions (180 W m^{-2} annually), for example, is greater than solar input (80 W m^{-2}), with the imbalance (100 watts per square meter) coming from lower latitudes (Nakamura and Oort 1988).

The latitudinal temperature gradient is a major driving force for atmospheric and ocean circulation and therefore for heat transport from the equator to the poles. Ocean heat transport is driven both by surface winds and by the movement of cold saline surface water to depths around Antarctica and in the North Atlantic (Anisimov et al. 2001). Recent increases in Antarctic precipitation have caused a freshening of surface layers that weakens bottom-water formation (Anisimov et al. 2001). This bottom-water formation is sensitive to climate effects on sea-ice formation and decay and, in the Arctic, on freshwater discharge to the ocean. Polar ice sheets account for 68% of the fresh water on Earth, so changes in the mass balance of these ice sheets could alter sea level and the input of fresh water to zones of deepwater formation. Past variation in the strength of bottom-water formation has contributed substantially to Earth's long-term climate variation (Anisimov et al. 2001).

Until recently, the warming trend at high latitudes had little detectable effect on the mass balance of the Greenland and Antarctic ice sheets, because of measurement inaccuracy and because warming simultaneously increased inputs of snow (because the warmer atmosphere holds more water) and the melting of ice sheets (Anisimov et al. 2001). Since 1990, however, increased melting and water infiltration at the base have increased ice flows to the ocean (Krabill et al. 2000; Thomas 2004). The mass wastage in 1991–2000 was 80 cubic kilometers per year (Box et al. 2004). Mountain and subpolar glaciers have exhibited a negative mass balance of similar magnitude (90–120 cubic kilometers per year) for the past 40 years (see Figure 25.2), particularly in Alaska, Canada, high-mountain Asia, and Patagonia (Dowdeswell et al. 1997; Dyurgerov and Meier 1997; Arendt et al. 2002; Rignot et al. 2004). In contrast, the Antarctic ice sheet shows regional and temporal variation in mass balance but no overall directional trend (Rignot and Thomas 2002; Bentley 2004). Warming has been most pronounced on the Antarctic Peninsula, causing a 10,000-square-kilometer retreat of adjacent ice shelves (Anisimov et al. 2001).

There is enough ice on the Antarctic Peninsula to raise global sea level by 0.5 meters, but the time course of its melting is *speculative*. The rapid disintegration and collapse of the Larsen-B ice shelf in 2002 was unprecedented; grounded ice sheets serve as brakes on the glaciers behind them, and the glacier behind the (now absent) Larsen-B sheet has accelerated its seaward flow (Scambos et al. 2004). The total freshwater input from these ice sheets and glaciers has, however, had less effect on sea level than the thermal expansion of oceans resulting from recent climate warming has. Nonetheless, freshwater input from glacial melt has substantially increased since 1990.

The Southern Ocean has warmed faster than the global ocean at mid-depths (700–1,100 meters) has over the past 50 years (Gille 2002). In addition, the surface and shelf waters in the Ross Sea have warmed and become less saline over the past 40 years (Jacobs et al. 2002), owing to a combination of increased precipitation, a reduction of sea-ice production, and increased melting of the West Antarctic ice sheet (Jacobs et al. 2002). Ice dynamics are also sensitive to fluctuations in the Antarctic Circumpolar Current, regional warming, and ENSO-related variation in Southern Hemisphere atmospheric and oceanic conditions (Liu et al. 2002). The apparent precession around the Antarctic of anomalies in sea-ice conditions and the ocean temperatures associated with the Antarctic Circumpolar Current (termed the Antarctic Circumpolar Wave) (Murphy et al. 1995; White and Peterson 1996) are also related to ENSO and contribute to regional and interannual variation in ocean temperatures and ice conditions. Whaling records suggest a possible circumpolar retreat in Antarctic sea ice by 2.8 latitude between the mid-1950s and early 1970s, although this interpretation is debated (Anisimov et al. 2001). The sea ice then became more extensive from 1979 to 2002, but with high regional variability (Liu et al. 2004) and large impacts on ecosystem processes (Smith et al. 1998).

In contrast, Arctic sea ice continues to decrease in extent by 2.9% per decade (see Figure 25.3) and has become thinner over the past 40 years (Maslanik et al. 1996; Anisimov et al. 2001). The reductions in areal extent of sea ice, glaciers, and seasonal snow cover reduce high-latitude albedo (the reflectance of incoming solar radiation) and act as a positive feedback that has *medium certainty* of amplifying the rate of high-latitude warming at both poles (Serreze et al. 2000; Mitchell et al. 2001). Increases in clouds, as sea ice retreats, could dampen this polar amplification, however (Wang and Key 2003). The reduction in summer ice cover has a *high certainty* of making commercial shipping feasible in the Northern Sea Route, likely by 2020. The reduction in sea ice over the past 40 years has reduced available habitat and hunter access to many marine mammals, which are an important subsistence and cultural resource for many coastal indigenous peoples of the Arctic (Krupnik 2002). The modest sea level rise that has occurred to date, combined with reduction in sea ice and greater storm surges, has caused considerable coastal erosion, which endangers coastal communities and increases organic carbon input to coastal oceans.

25.2.1.2 Ecosystem Feedbacks

Ecosystem processes at high latitudes influence the climate system when they cause these regions to become net sources or sinks of greenhouse gases such as carbon dioxide and methane. In the Antarctic, oceans have the strongest influence on carbon flux through both physical processes that are driven by ocean circulation and biotic processes driven by photosynthesis and respiration. Photosynthesis (carbon uptake) by marine phytoplankton converts inorganic carbon into organic matter. When algae are eaten or die, some of this carbon is respired and returns to the atmosphere and some sinks to depth as dead cells or fecal pellets of their grazers, a biological pump that sequesters carbon in the deep ocean (Ducklow et al. 2001).

Many factors interact to control the productivity of phytoplankton, as described later in this section, and therefore the carbon export to depth in the oceans around Antarctica. Spatial variability in productivity and carbon export depends on vertical mixing, mixed layer depth, krill grazing, and micronutrient (iron, for example) limitation (Arrigo et al. 1999; Prezelin et al. 2000). Temporal variation correlates with sea-ice extent and timing, with

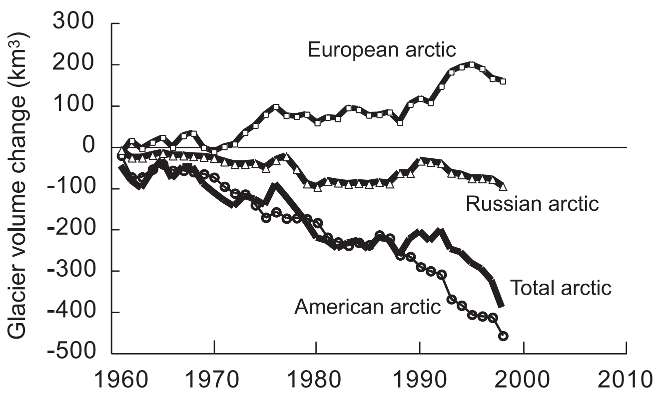

Figure 25.2. Trends in Glacier Volume for Different Arctic Regions, 1961–98 (Hinzman et al. in press)

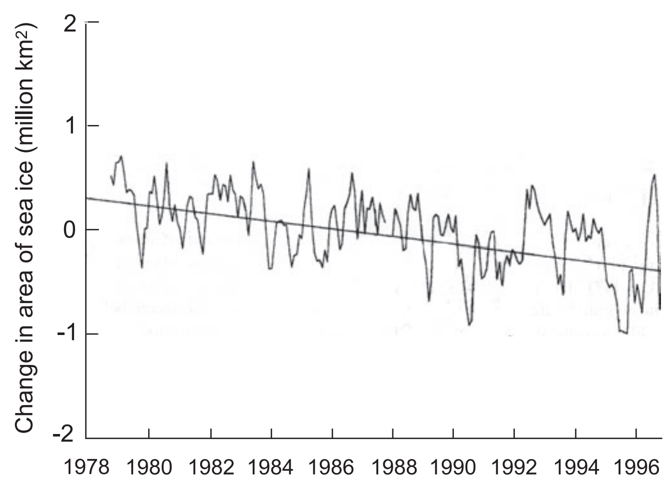

Figure 25.3. Trend in Arctic Sea Ice Extent, 1978–97 (Serreze et al. 2000)

extensive or late-melting ice favoring high productivity. Ice margins are highly productive because of high nutrient availability, whereas the productivity of the open ocean appears limited by iron availability (Boyd et al. 2000).

Warming has two counterbalancing effects on productivity and therefore on carbon export to depth. The more highly developed freshwater lens beneath melting ice enhances productivity, whereas the decreasing extent of sea ice reduces the areal extent of productive ocean. The Southern Ocean below 50°S is a net carbon sink, taking up about 0.5 petagrams of carbon annually, or about 20% of the total oceanic uptake, in 10% of its area (Takahashi et al. 2002). The intensity of uptake in the Southern Ocean highlights its role in the global carbon cycle. How it will respond to climate change remains *highly uncertain* (Sarmiento and Le Quere 1996; Sarmiento et al. 1998).

In the Arctic, terrestrial ecosystems are the major site of greenhouse gas exchange. Under current conditions, both direct measurements and global carbon models suggest that the circumpolar Arctic is neither a large source nor a large sink of carbon dioxide. Measurements suggest a modest source, whereas models suggest a small sink of 17 ± 40 grams of carbon per square meter per year (mean ± SD, spatial variance) (McGuire et al. 2000; Sitch et al. 2003; Callaghan et al. in press). Both estimates overlap zero, owing to *low certainty* and large interannual and regional variation.

Areas that have warmed and dried, such as Alaska and Eastern European Arctic, are generally a carbon source. For example, after a pattern of net carbon accumulation during most of the Holocene, Alaska became a net carbon source when regional warming began in the 1970s (Oechel et al. 1994). The strength of this source then declined as plant- and ecosystem-scale negative feedbacks increased carbon uptake by plants (Oechel et al. 2000). (See Figure 25.4.) This may reflect warming-induced nutrient release, which tends to enhance photosynthesis and net primary production (Shaver et al. 2000). Scandinavian and Siberian peatlands, which have become warmer and wetter, are a net carbon sink of 15–25 grams of carbon per square meter per year (Aurela et al. 2002; Smith et al. 2004). In Greenland, where there has been little warming (Chapman and Walsh 1993), net carbon exchange is close to zero, with sinks in wet fens balanced by carbon losses in dry heath (Christensen et al. 2000; Soegaard et al. 2000; Nordstrøm et al. 2001). Carbon fluxes in the high Arctic are extremely low—a net sink of about 1 gram of carbon per square meter per year (Lloyd 2001).

Taken together, Arctic flux measurements suggest that warming has substantially altered Arctic carbon balance but that the direction of this effect varies regionally, depending on hydrology, with wet areas tending to gain carbon and dry areas tending to lose carbon with warming. Remote sensing and indigenous observations suggest that drying trends predominate in the North American Arctic (Hinzman et al. in press). The greatest uncertainties in estimating recent and future trends in carbon exchange relate to changes in hydrology, nutrient dynamics associated with decomposition, and disturbance effects on vegetation (Chapin et al. 2000a; Oechel et al. 2000; Callaghan et al. in press). These processes have not yet been adequately incorporated into global carbon models. In summary, the short time period of record and the incomplete inclusion of key processes in global models result in *low certainty* of long-term trends, but the balance of evidence suggests a small trend toward carbon release in the short term, with long-term trends depending on the balance between increased production and uncertain trends in respiration.

High-latitude wetlands are one of the largest natural sources of atmospheric methane, about 70 teragrams per year (Cicerone and Oremland 1988; Schlesinger 1997). Methane fluxes are highly variable, both temporally and spatially. However, methane efflux responds positively to soil moisture, summer soil temperature, and the presence of oxygen-transporting vascular plants such as wetland sedges (Christensen et al. 2003). Warming and thawing of permafrost (see Figure 25.5) increase the area of wetlands and thaw lakes, further increasing methane efflux from the Arctic (Zimov et al. 1997; Christensen et al. 2004). There is *medium certainty* that warming enhances methane release, creating a positive feedback to climate change (Christensen et al. 2003).

Recent increases in length of the snow-free season (2.6 days per decade and similar increases in other northern regions) (Keyser et al. 2000; Walther et al. 2002) and the reduced albedo (reflectance) associated with shrub expansion (Eugster et al. 2000) both tend to increase annual energy absorption. This acts as a positive feedback to high-latitude warming (Betts and Ball 1997; Chapin et al. 2000b), but the magnitude of these effects has *low certainty*. Conversion of tundra to forest creates an even larger climate feedback by replacing a snow-covered surface with a dark, more absorptive surface. (See Chapter 13.) Model simulations suggest that conversion of tundra to forest accounted for half of the high-latitude mid-Holocene warming (Foley et al. 1994). Forest expansion generally lags behind regional warming because tree establishment is slow near the climatic limit of trees (Huntley 1996; Lloyd et al. 2003b).

Russian rivers have increased their discharge to the Arctic Ocean by 7% over the past 70 years, primarily due to increases in winter discharge (Peterson et al. 2002; Yang et al. 2002). (See Figure 25.6.) Changes in permafrost distribution associated with

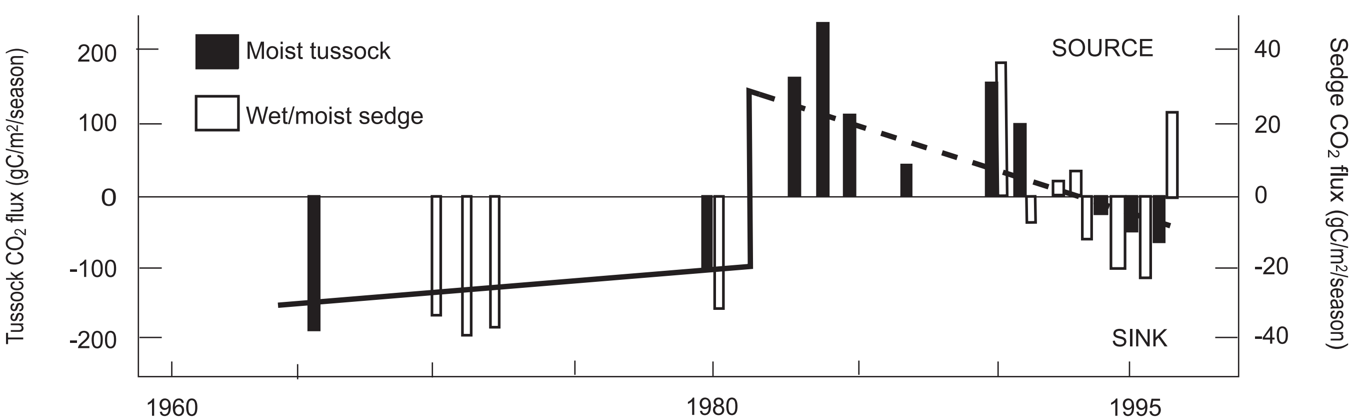

Figure 25.4. Trend in Net Annual Carbon Flux from Alaskan Arctic Tundra, 1960–95 (Oechel et al. 2000)

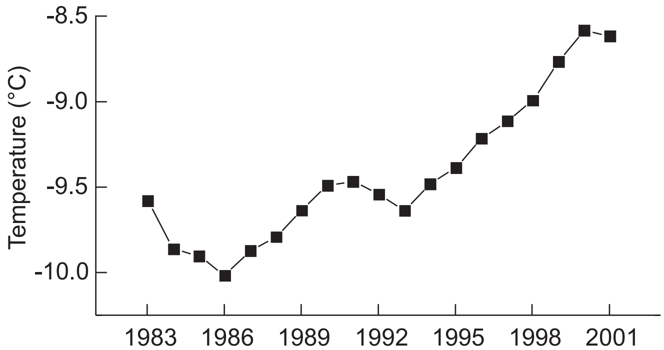

Figure 25.5. Trend in Permafrost Temperature at 20 m Depth at West Dock on the Coastal Plain of Northern Alaska, 1983–2001 (Osterkamp and Romanovsky 1999)

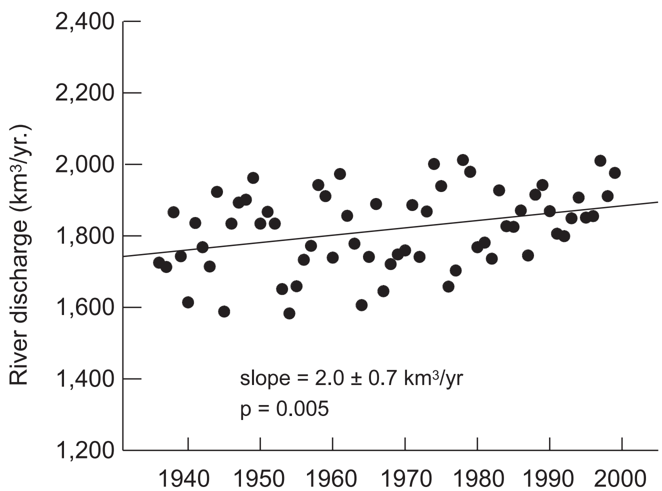

Figure 25.6. Trend in Discharge of the Six Largest Eurasian Arctic Rivers, 1935–2000 (Peterson et al. 2002)

wildfire or human-induced vegetation changes may have contributed to the increase in winter discharge (Serreze et al. 2003), although the causes are *speculative.* The discharge records for North American rivers are too short to detect long-term discharge trends. The Arctic Ocean is extremely sensitive to changes in discharge because it receives more discharge per unit ocean volume than any other ocean. Most river discharge into the Arctic Ocean eventually exits in the North Atlantic. Continued increase in the input of low-density fresh water could reduce North Atlantic bottom-water formation by the end of the twenty-first century if the discharge of Arctic rivers continues to increase at its current rate (Peterson et al. 2002). This potential change is *speculative,* but the climatic implications for Europe and the North Atlantic Region are enormous.

In the Southern Ocean, physical processes are entirely responsible for variation in bottom-water formation. Dense saline water is produced when sea ice forms beneath ice shelves and when polynyas (open water) or thin ice transfer heat rapidly from the ocean to the atmosphere. Antarctic surface waters have warmed since 1970 (Wong et al. 1999), a trend that would tend to reduce rates of bottom-water formation and thermohaline circulation. In summary, different processes at the two poles both tend to weaken bottom-water formation.

Less is known about carbon cycling in Antarctic terrestrial systems. Rates of CO_2 flux in Antarctic dry valley soils are exceedingly low, and the total volume of soil in the Antarctic is tiny in comparison with that of the Arctic (Parsons et al. 2004). The soil organic matter in some dry valleys appears to be a legacy of past climates when paleo-lake production enriched soils in carbon and nutrients (Burkins et al. 2001). It is not known whether these systems are net sources or sinks of carbon because interactions between abiotic and biological controls of CO_2 flux vary with soil environment and climate (Parsons et al. 2004).

25.2.2 Fresh Water

Antarctica is the driest continent on Earth, with nearly all water locked up in ice. Dependence on fuel to melt ice for usable water limits potential for human habitation, and low water availability limits many physical and biological processes across the continent (Kennedy 1993).

In contrast to Antarctica and much of the rest of the world, inhabited portions of the Arctic generally have abundant fresh water despite low precipitation. Water is important to Arctic residents as a source of hydropower and as a transportation corridor. (See Chapter 20.) Water quality in the Arctic is generally good except in areas of industrial development.

The net transport of contaminants (persistent organic pollutants, heavy metals, and radionuclides) to polar regions, however, produces a dilute source of pollutants that often become concentrated as they move through food webs and are a potential health risk to people, as described later in this chapter. Changes in water availability in the Arctic (for example, regional drying) are important primarily through effects on ecosystem services (such as habitat for fish and water birds, or trace gas emissions).

Arctic fresh water continues to receive attention from water-deficient regions of the world as a potential freshwater supply. Russian newspapers, for example, recently reported the reactivation of 1970s plans to divert the Ob and other northbound rivers toward water-starved regions in the south.

25.2.3 Biodiversity and Species Composition

25.2.3.1 Changes in Vegetation

Polar regions have historically experienced fewer invasions of exotic plant species than most biomes because climate is a severe physiological filter (Walther et al. 2002). However, recent climate warming has facilitated invasion of new species (Robinson et al. 2003; Frenot et al. in press). On some sub-Antarctic islands exotic species account for more than 50% of vascular plant diversity, and exotic grasses may outcompete native species (Smith 1994; Chown et al. 1998; Gremmen et al. 1998; Bergstrom and Chown 1999; Gremmen and Smith 1999; Frenot et al. in press). Exotic species also occur in maritime regions of the Arctic (such as Iceland) (Wiedema 2000) and inland areas with road and rail connections (in Canada and Russia, for example) (Forbes 1995), but the frequency of invasion is known with *low certainty.* Twenty species of Arctic plants are considered globally threatened—vulnerable, endangered, or critically endangered, according to IUCN Red List criteria (CAFF 2001).

Polar plant species have also changed in their relative abundance (Walther et al. 2002; Callaghan et al. in press). On the Antarctic continent, mosses have colonized previously bare ground, and the only two native vascular plant species have expanded their ranges (Smith 1994; Convey 2001a). Repeat aerial photography demonstrates that shrubs have increased in dominance in 70% of 200 sample locations in Arctic Alaska (Sturm et al. 2001), a change confirmed by indigenous observations across much of the North American Arctic (Nickels et al. 2002; Thorpe et al. 2002). NDVI, an index of vegetation greenness, has increased by 15% since 1981 in Arctic Alaska (Jia et al. 2003) (see Figure 25.7) and to a more variable extent in the circumpolar Arctic as a whole (Myneni et al. 1997).

In Alaska, the latitudinal tree line has moved northward, converting about 2% of tundra to forest in the past 50 years (Lloyd et al. 2003a), whereas in Russia the tree line has retreated southward as a result of forest harvest and anthropogenic burning, creating about 500,000 square kilometers of wetlands superficially resembling the tundra (Callaghan et al. 2002; Vlassova 2002). Thawing of permafrost has also converted large areas of well-drained lands to wetlands (Crawford et al. 2003; Hinzman et al. in press).

Experimental manipulations of climate, nutrients, and UV-B radiation in numerous studies throughout the Arctic suggest that mosses and lichens could become less abundant when vascular plants increase their growth (Van Wijk et al. 2004). Mosses and lichens are a large component of polar plant diversity and controllers of ecosystem processes: lichens are a key winter food for caribou and reindeer, and mosses insulate the soil. Similar manipulations on the Antarctic Peninsula indicate complex responses that could include a decline in density and diversity of soil invertebrates in response to warming (Convey et al. 2002) and a decline in nematodes in response to cooling in the McMurdo Dry Valleys (Doran et al. 2002b).

25.2.3.2 Changes in Caribou and Reindeer

Many of the North American barren-ground wild caribou (*Rangifer tarandus*) herds were at historic high levels at the end of the 1980s; several herds are currently in decline (Russell et al. 2002). Interannual variation in caribou calving success of several North American herds correlates with the rate of spring vegetation growth in calving grounds, as measured by satellite-derived NDVI (Griffith et al. 2002), although regional heterogeneity in other ecological conditions also affects reproductive success (Russell et al. 2002). The Peary caribou herd that occupies polar barrens in the Canadian Arctic islands has, in contrast to other North American herds, decreased to critically low levels and is currently on Canada's endangered species list. Potential causes of the decline include the impact of climate change on extreme weather events (such as autumnal ice storms), vegetation composition, insect harassment, animal energy demands, animal behavior, and shifts in animal distribution relative to human users' access.

In Fennoscandia, reindeer are intensively managed for meat, as a cultural resource, and for recreational harvest. Here reindeer herding is the subject of political conflicts owing to the degradation of pastures, protection of predators, and indigenous people's efforts to assert their access rights to traditional herding areas (covered later in this chapter).

In the Russian North, the collapse of the former state-supported supply and marketing system has led to a decline in domesticated reindeer stock over the past 10 years from 2 million to 1 million animals (Baskin 2000). This decrease was accompanied by increases in several large wild reindeer populations of Taimyr, Yakutia, and Chukotka, leading to serious impacts on pasturelands. Wild and domesticated reindeer are typically seen as ecological antagonists, because wild reindeer lead domesticated animals away, compete for (or damage) pastures, and are a reservoir of infectious diseases. On the Yamal Peninsula, in contrast, the population of semi-domesticated reindeer increased steadily in the post-Soviet period, in part because of the cultural role of reindeer herding among the Nenets people of that region.

Oil development has contributed to trends in caribou and reindeer populations in some areas. Caribou and reindeer are sensitive to disturbance during calving (Vistnes and Nellemann 2001; Griffith et al. 2002). In Alaska, for example, concentrated calving was displaced from industrialized areas to areas of lower forage richness, with caribou returning to industrialized areas during the post-calving period (Griffith et al. 2002). The effects on population dynamics of this herd displacement during calving are debated (NRC 2003). Development conflicts associated with potential habitat loss have been resolved in some areas through "calving group protection measures" (in the Northwest Territories of Canada, for instance), whereas in other areas (such as Alaska and Russia) calving grounds hold no special policy status.

Onshore oil and gas activities also impede access to traditional hunting and herding areas and thus disrupt community activities and traditional practices (Golovnev and Osherenko 1999). Pipelines and facilities create obstacles to free movement of reindeer herds. In the intensively developed Yamal Peninsula in Western Siberia, destruction of vegetation due to construction of facilities, roads, and pipelines and to off-road vehicle traffic exceeds 2,500 square kilometers and could more than double under current development plans. The resulting concentration of reindeer herds into an ever-decreasing undeveloped area has led to overgrazing,

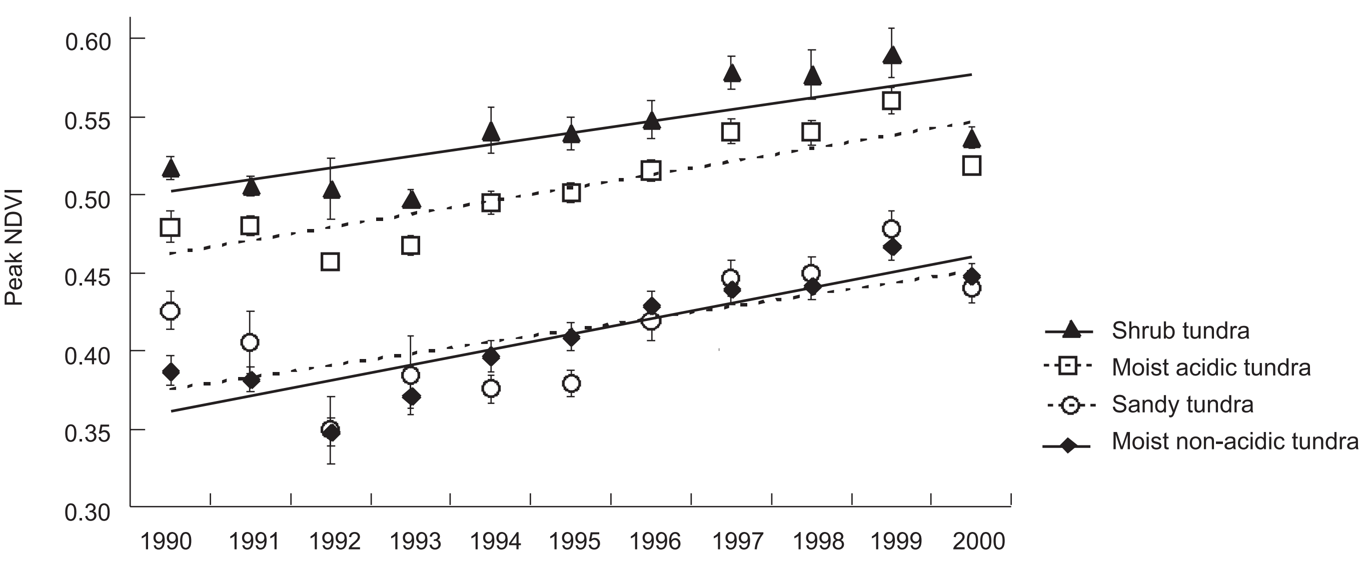

Figure 25.7. Trend in Normalized Difference Vegetation Index in Alaskan Arctic Tundra, 1990–2000 (Jia et al. 2003)

with potential long-term adverse effects on ecosystem productivity and local economies (Forbes 1999).

25.2.3.3 Changes in Other Terrestrial Mammals

Twenty-one species of Arctic mammal are considered globally threatened (CAFF 2001). However, it is difficult to assess recent population trends of polar mammals as a whole, because quantitative data are available for only a few species, mostly animals of economic importance or high conservation profile. (See Table 25.3.) Possibly in response to changes in climate or prey abundances, red fox (*Vulpes vulpes*) has expanded northward into habitats of the smaller Arctic fox (*Alopex lagopus*) in Fennoscandia and Canada, where it is thought to exploit the most productive habitats by interference competition (Hersteinsson and MacDonald 1992; Elmhagen et al. 2002). The observed expansion of shrubs favors the range expansion from adjacent biomes of some herbivore species with wide dietary flexibility (Klein 1999). Moose (*Alces alces*), for example, have expanded from the boreal forest to Arctic tundra in Alaska and eastern Canada but have declined in Siberia owing to increased hunting.

Deliberate introductions are modifying animal distributions. Musk oxen (*Ovibos moschatus*) have been introduced to new areas and to portions of their former ranges, after dramatic reductions in their numbers in the nineteenth century from many of these areas; they are expanding in population sizes and ranges in Alaska, Russia, west Greenland, Quebec, and Norway (CAFF 2001). Wood bison (*Bison bison athabascae*), the closest relative of the extinct Pleistocene bison, have also been reintroduced in several areas of Arctic Canada. Bison, like many animals, substantially disturb their habitat, so their reintroduction could lead to ecosystem changes that alter many species abundances and ecosystem processes (Zimov et al. 1995).

Fennoscandian lemmings and voles are changing in seasonal dynamics and losing the synchronous cyclic population fluctuations that characterize these species (Hanski et al. 2001), as occurred earlier in Alaska (Batzli et al. 1980). In Scandinavia, but not in Greenland, declines in lemming populations cause increased predation on water birds as an alternative prey, although changes in weather may contribute to these population changes (Summers and Underhill 1987; Soloviev et al. 1998; Yoccoz and

Table 25.3. Population Numbers and Trends of Some Key Arctic Animals. Population trends indicate moderate to high certainty that populations exhibit a directional trend. Where the trends differ regionally, the nature of these trends (increasing, decreasing, stable) is indicated. (Modified from CAFF 2001 with marine mammals from Marine Mammal Commission 2002)

Species	Total Arctic Population	Population Trend	Major Driver of Change
Birds			
Eiders (4 spp)	>3 million	declining/stable/increasing	unknown
Common murre/guillemot (*Uria aalge*)	8–11 million	declining/stable/increasing	unknown
Thick-billed murre (*U. lomvia*)	14 million	unknown	unknown
Gulls		increasing	garbage ??
Geese (15 spp)	11 million	40% of populations increasing 28% stable 18% declining 14% trend unknown	winter habitat, overharvesting
Shorebirds			
North America (21 spp)	14 million	decreasing	unknown
Eurasia (16 spp)	8 million	no clear trend; some declines	unknown
Terrestrial mammals			
Caribou/reindeer (*Rangifer tarandus*)	4.5 million	many herds increased until 1980s; Peary caribou declining	forage, weather
Muskoxen (*Ovibos moschatus*)	150,000	increasing/stable	reintroductions, weather
Brown bear (*Ursus arctos*)	170,000	declining/stable/increasing	habitat loss, poaching
Wolverine (*Gulo gulo*)	30,000	unknown/stable/increasing	unknown
Wolf (*Canis lupus*)	50,000	declining/stable/increasing	hunting, habitat loss
Marine mammals			
Right whale (*Eubalaena glacialis*)	<1,000	stable/uncertain	19th century harvest
Humpback whale (Megaptera novaeanglie)	thousands	increasing	19th century harvest
Gray whale (*Eschrichtius robustus*)	27,000	stable; near optimal	19th/20th century harvest
Killer whale (*Orcinus orca*)	few thousand	stable, not endangered	not widely harvested
Steller sea lion (*Eumatopius jubatus*)	30–40,000	declined 85% since 1970s	uncertain
Pacific walrus (*Odobaenus rosmarus divergens*)	230,000	trend uncertain	uncertain
Harbor seal (*Phoca vitulina richardsi*)	100,000	some populations declining	human and natural factors
Polar bear (*Ursus maritimus*)	25,000	unknown	sea ice decline
Sea otter (*Enhydra lutirs*)	100,000	decline since 1995	unknown

Ims 1999). Trends in mammalian predators (such as wolves (*Canis lupus*), bears (*Ursus* spp.), and wolverines (*Gulo gulo*)) have been regionally variable. In general, species interactions are complex and regionally variable (Blomqvist et al. 2002; Gilg 2002), making broad generalizations uncertain.

25.2.3.4 Changes in Marine Mammals

Hunting for marine mammals, especially whales, seals, and sea otters (*Enhydra lutris*), in the nineteenth century radically reduced many populations (Marine Mammal Commission 2002). The Steller sea cow (*Hydrodamalis gigas*) was hunted to extinction. The Southern right whale (*Eubalaena glacialis australis*) and Antarctic fur seal (*Arctocephalus gazella*) were almost extinct by 1830. Whaling proliferated in the nineteenth and first half of the twentieth centuries. Overexploitation led to the formation of the International Whaling Commission in 1949. There is now a moratorium on commercial whaling, although Iceland and Japan continue to harvest whales for research, and Norway, which objected to the moratorium on commercial whaling, continues commercial whaling, leading to an annual harvest of 400 ± 40 minke whales (*Balaenoptera acutorostrata*). Indigenous whaling in Greenland and North America has had no detectable effect on whale populations (Caulfield 1997).

Antarctic fur seal populations are growing as a result of decreased whale predation and are expanding their range to the south. In contrast, many whale populations have not fully recovered. The causes of recent declines in populations of southern elephant seal, Steller sea lion (*Eumatopius jubatus*), harbor seal (*Phoca vitulina richardsi*), sea otter (*E. lutris*), and other marine mammals are *speculative,* but in some cases appear to involve commercial fishing (of the southern elephant seal and sea otters, for example), reduced sea ice (for polar bears (*U. maritimus*) and walrus (*Odobaenus rosmarus divergens*)), or other changes in marine ecosystems (Estes et al. 1998).

Northern oil and gas development may also influence marine mammals. Noise from offshore oil exploration in the Beaufort Sea disturbs bowhead whales (*Balaena mysticetus*) and could deflect them from migration routes, making them less accessible to hunters. Autumn-migrating bowheads, for example, stay 20 kilometers from seismic vessels (NRC 2003). Oil spills from marine transportation or offshore oil platforms have the potential for widespread ecological damage, particularly in ice-covered Arctic waters. Spills from pipelines in temperate-zone oil basins in the headwaters of Arctic rivers such as the Ob, Pechora, and McKenzie could also contaminate Arctic waters.

25.2.3.5 Changes in Birds

There is extensive evidence of environmentally related changes in Antarctic seabird populations, although long-term exploitation of living resources may also be a contributing factor (Fraser et al. 1992). Among the most dramatic Antarctic changes have been local declines in Adélie penguins (*Pygoscelis adeliae*) combined with a southward reduction in range (Fraser et al. 1992). Chicks that fledge at a body mass of less than 2,850 grams have low survivorship. Most available penguin rookery habitat occurs in landscapes where snow deposition is enhanced during late winter and early spring storms. This causes chicks to hatch later and delays their key growth period until early February, when local krill (*Euphasia superba*) is less abundant and adults must forage greater distances for food. Adélie penguins have become locally extinct on some islands along the Antarctic Peninsula and are declining rapidly on other islands (Ainley et al. 2003). As the Adélie penguins decline, they are being replaced by a southward shift in distributions of chinstrap and gentoo penguins (*P. antarctica* and *P. papua*).

Adélie penguin populations in the Ross Sea sector appear to oscillate with a five-year lag to sea-ice extent, which in turn is related to ENSO conditions (Wilson et al. 2001). In the longer term, the southern limit to distribution of Adélie penguin breeding colonies is determined by changes in the pattern of year-round sea-ice presence (Baroni and Orombelli 1994; Emslie et al. 2003) Extensive sea ice during winter months appears to reduce sub-adult survival. Similarly, emperor penguins (*Aptenodytes forsteri*) decline with warmer temperatures and reduced sea-ice extent (Barbraud and Weimerskirch 2001), although they hatched fewer eggs when winter sea ice was extended (Barbraud and Weimerskirch 2001). These data indicate that penguins may be quite susceptible to climatic changes. In addition, there have been serious population declines in 16 of 24 species of albatrosses, primarily as a result of incidental catches in longline fishing (Crawford and Cooper 2003).

The Arctic is a breeding ground for many migratory wetland birds that overwinter throughout the world. Several hundred million birds, including swans, geese, and ducks, migrate from southern overwintering grounds to the Arctic to breed. These birds are indirectly affected by climate changes, habitat loss, and altered food abundance throughout their range (Lindström and Agrell 1999; Zöckler and Lysenko 2000). Critical coastal stopover sites are also threatened by human activities. The increases in Arctic plant biomass, height, and density caused by recent warming and eutrophication affect wetland birds negatively (Callaghan et al. in press). Twelve Arctic bird species are globally threatened (CAFF 2001). Climate change also fosters northern migration of more southerly bird species, including the common snipe (*Gallinago gallinago*), black-tailed godwit (*Limosa limosa*), and northern lapwing (*Vanellus vanellus*) in Russia (Lebedeva 1998; Morozov 1998), as well as American robins (*Turdus migratorius*) in the polar barrens of North America (Jolly et al. 2002). Ravens (*Corvus corax*) and some gulls have become more abundant near human settlements, acting as nest predators on other birds.

The greater snow goose (*Chen caerulescens atlantica*) increased twenty-five-fold, from 28,000 birds in 1965 to 700,000 in 1998 (CAFF 2001). The overall populations of "white" geese (greater and lesser snow goose and Ross's goose) increased from about 1 million to about 8.5 million over the same time period (Batt 1997). Changes in agricultural practices, which increased food availability, are probably the most important cause of these changes. The population increase has exceeded the threshold for persistence of salt-marsh vegetation, leading to catastrophic vegetation change and salinization of many coastal wetlands (Hik et al. 1992; Srivastava and Jefferies 1995).

25.2.3.6 Changes in Fish

The most dramatic changes in fish populations have occurred in Antarctic waters, where overfishing rapidly depleted stocks of marbled notothenia (*Notothenia rossii*), mackerel icefish (*Champsocephalus gunnari*), gray notothenia (*Lepidonotothen squamifrons*), and Patagonian toothfish (*Dissostichus eleginoides*). Some stocks recovered when conservation measures were instituted by the Convention on the Conservation of Antarctic Marine Living Resources, but others remain depressed by illegal, unregulated, and unreported fishing (CCAMLR 2002). (See Chapter 18.)

Overharvesting of whales and seals may have led to population increases of krill (*E. superba*), their major food source. Subsequent reductions in krill reflect some combination of commercial fishing, recent increases in fur seal and penguin populations, changes in sea-ice duration and extent, and, perhaps, increases in UV-B associated with ozone depletion (Naganobu et al. 2000). Krill are long-lived animals whose variation in growth and reproduction are sensitive to oceanic and sea-ice conditions; they comprise the main food source for fish in Antarctic waters (Murphy et al. 1998; Quetin and Ross 2001; Fraser and Hofmann 2003). Under conditions of increased sea-ice melt, cryptomonads expand at the expense of the diatoms, which are preferred by krill, potentially resulting in krill decline (Moline et al. 2000). This tight but complex linkage of krill population dynamics to sea ice suggests that any future changes in timing, duration, or extent of sea ice will strongly affect the community composition of phytoplankton, krill, and their predators. Because advection of biological material is important in maintaining Southern Ocean ecosystems, the potential impacts of regional changes may extend well to the north of the main sea-ice-covered regions.

In the Arctic, regional warming may have contributed to recent northward range extensions of anadromous fish such as salmon (*Oncorhynchus* spp and *Salmo* spp.) (Babaluk et al. 2000; Jolly et al. 2002) and to increased abundance of salmonid parasites in Alaskan rivers. Human activities have also altered fish distributions. For example, the salmonid parasite *Gyrodactylus salari* that is native in Central Asia spread naturally to the Baltic and then further to Scandinavia with the help of humans (Johnsen and Jensen 1991; CAFF 2001). This parasite feeds on young salmonids and causes major damages in Norwegian fish farms and rivers. Another example of human impacts on fish production involves introduction of the shrimp *Mysis relicta* to high-elevation Norwegian and Swedish lakes and rivers that are regulated for hydroelectric purposes. Initially the shrimp introduction had positive effects but over time feeding by *Mysis* on zooplankton reduced this food resource, leading to a decline in fish growth (Nesler and Bergersen 1991).

25.2.3.7 Changes in Insects

The introduction of alien insects on sub-Antarctic islands is threatening some native species and vegetation communities (Ernsting et al. 1995; Hanel and Chown 1998), and introduced flora is affecting soil faunal composition (Gremmen et al. 1998). The northern limit of Arctic insect species is usually determined by climatic factors (Strathdee and Bale 1998). For example, food plants probably determine distributions in less than 3% of the macrolepidopteran (butterfly) species of Finland (Virtanen and Neuvonen 1999). Species richness decreases by 65 species for each degree of latitude northward—that is, 93 species (12% of the total) per degree of mean summer temperature.

Lepidopteran species are usually good dispersers, so climate warming will likely promote increases in their richness as species move poleward. Conversely, the distribution of northern species (11% of the Finnish species) such as sawflies may shrink in a warmer climate (Kouki et al. 1994). Among bark beetles, *Ips amitinus* and *Xylechinus pilosus* have expanded their ranges in Fennoscandia (Heliövaara and Peltonen 1999), whereas other species (such as *Tomicus minor*) are retracting southwards.

A rise in winter temperature would favor species overwintering as eggs and may increase the frequency of insect outbreaks of those species (such as *Epirrita autumnata,* a geometrid defoliator of birch) (Nilsson and Tenow 1990; Neuvonen et al. 1999; Niemelä et al. 2001). Species overwintering as pupae will likely increase the number of generations per year (Virtanen and Neuvonen 1999). Summer warming will also increase the number of generations completed; this increase has been found in experimental field manipulations to increase the overwintering population of aphids on Svalbard by an order of magnitude (Strathdee et al. 1993).

In boreal Canada, pest-caused timber losses may be as much as 1.3–2.0 times the mean annual depletions due to fires (Volney and Fleming 2000). Global change will likely increase the frequency and intensity of outbreaks, particularly at the margins of host ranges. Changes in mosquito abundance in response to altered hydrology could strongly affect fish and waterfowl, for which they are an important food source, as well as caribou and reindeer, whose energy budgets are sensitive to insect harassment (Chernov 1985).

25.2.4 Food, Fuel, and Fiber

Documented changes in biodiversity have had negligible effects on the food supply of people in Antarctica, who bring their food, fuel, and fiber from lower latitudes. Marine harvests in Antarctic waters, however, provide food that is used globally. Fish and krill are now primary targets of human exploitation in the Southern Ocean. From 1970, when recordkeeping began, to 1998 a total of 8.7 million tons of krill and fish were harvested (CCAMLR 2000).

In contrast, indigenous peoples throughout the Arctic (and many nonindigenous residents as well) maintain strong social, cultural, and economic connections to the environment through traditional hunting, herding, fishing, trapping, and gathering of renewable resources. Local mixed economies of cash and subsistence depend strongly on household production involving harvest of local resources, food preparation and storage, distribution, consumption, and intergenerational transmission of knowledge and skills (Nuttall 1992; Caulfield 2000; Dahl 2000; Freese 2000; Nuttall et al. in press). Per capita consumption by rural Alaskans (indigenous and nonindigenous), for example, is 170 kilograms per year of wild foods (60% fish, 16% land mammals, 14% marine mammals, 10% plant products), valued at about $200 million. Urban Alaskans, in contrast, consume 22 kilograms of wild foods per capita per year. Cultivated crops are a smaller source of food except in maritime regions (such as Iceland and coastal Norway). Wood, sod, peat, and coal are used locally as fuels.

The subsistence resources used by Arctic peoples vary regionally. In the barrens, where terrestrial productivity is low, most communities are coastal and people depend primarily on fish and marine mammals (such as polar bears, seals, walrus, narwhals (*Monodon monoceros*), and beluga (*Delphinapterus leucas*), fin, and minke whales), although terrestrial mammals (such as caribou, reindeer, and musk ox), migratory birds and their eggs (such as ducks, geese, terns, and gulls), and plants and berries are seasonally important. In tundra, in contrast, people rely more heavily on fish—including salmon, Arctic char (*Salvelinus alpinus*), whitefish, and northern pike (*Esox lucius*)—migratory and sedentary birds, terrestrial mammals, and berries.

Caribou and reindeer, which include wild and domestic populations of North American barren-ground wild caribou, are arguably the most important terrestrial subsistence resource for Arctic indigenous peoples (Klein 1989; Paine 1994; Kofinas et al. 2000; Jernsletten and Klokov 2002). Many Arctic and sub-Arctic indigenous cultures co-evolved with reindeer or caribou, which provide food, shelter, clothing, tools, transportation, and other marketable goods. In North America, where indigenous subsistence hunting constitutes the primary use of caribou, there are approximately 3.2 million barren ground caribou and an estimated annual harvest of over 160,000 animals, equivalent to more than $30 million annually. In Russia, large-scale commercial hunting of wild reindeer, which began on the Taimyr in the

1970s, produced more meat than all reindeer husbandry of both Central Siberia and Yakutia but has not fulfilled the cultural role that reindeer play in reindeer-herding societies. The change from a migratory existence to permanent communities with schools, stores, and jobs alters traditional lifestyles.

25.2.5 Cultural Benefits

The numerous cultural groups in the Arctic (more than 50) reflect a diversity of historical roots and local ecological conditions provided by ecosystems. Subsistence activities, such as hunting, herding, fishing, trapping, and gathering, remain important for maintaining social relationships and cultural identity in these indigenous societies (Brody 1983; Nuttall 1992). These activities link people inextricably to their histories and their contemporary cultural settings and provide a context for thinking about sustainable livelihoods in the future (Nuttall et al. in press).

The Antarctic and Arctic provide important cultural benefits to non-Arctic residents as well. Some of these benefits are mediated by polar species that migrate to lower latitudes. In addition, non-polar residents value the near-pristine conditions of polar regions, motivating them to visit these lands (tourism) and to support legislation and lobbying efforts for their protection.

25.3 Drivers of Change in Polar Systems

The relative importance of drivers of change varies across the polar regions and depends on the stakeholders involved. For polar residents, the most important changes (in order of decreasing importance) are often climate change, industrial development, contaminants, marine fishing, and UV-B. For non-polar residents, the most important changes—again in order of importance—are often climate change, marine fishing, increased UV-B, industrial development, and introduction of exotic species. The shared concern by both polar and non-polar residents about many of the same drivers of change provides opportunities to develop agendas that enhance the well-being of residents both within and outside polar regions.

25.3.1 Climate and Hydrologic Change

Climate has warmed more dramatically in portions of the Arctic and Antarctic than in any other region on Earth, with substantial impacts on ecosystems, their services, and human well-being. The magnitude and global pattern of Arctic warming are known with *high certainty.* These warming trends are most pronounced in western North American Arctic and central Siberia (Kozhevnikov 2000; Serreze et al. 2000; Smith 2002; Convey et al. 2003). Warming has been negligible in parts of Scandinavia. (See Figure 25.8 in Appendix A.) Arctic warming results both from a general northern hemisphere warming and from a regime shift in hemispheric circulation (such as more-frequent positive phases of the North Atlantic and Arctic Oscillations) (Overland et al. 2004). Temperate air masses penetrate more frequently into the Arctic, causing increased climate variability (Overland et al. 2004) and conditions that are unfamiliar to local residents (Krupnik and Jolly 2002). Regions that previously exhibited a cooling trend (such as eastern North American Arctic and Chukotka from 1950 until 1990) are now warming.

Increases in precipitation during this time period are approximately balanced by increased evapotranspiration, suggesting only minor changes in terrestrial water balance (Serreze et al. 2000). Nonetheless, terrestrial studies suggest that changes in water balance are occurring but are regionally variable. These include increasing river runoff in Russia (Peterson et al. 2002) (as mentioned earlier), bog expansion in western Russia (Crawford et al. 2003), and drier soils in North America (Hinzman et al. in press) (perhaps explaining recent increases in area burned (Murphy et al. 2000)). The spatial pattern and magnitude of these changes in soil moisture are known with only a *low certainty.*

The Antarctic shows complex temporal and spatial patterns of both warming and cooling. Over the past 15–20 years, 60% of continental Antarctica has been thermally stable or cooling slightly (Doran et al. 2002b; Kwok and Comiso 2002; Thompson and Solomon 2002), although this trend is debated (Turner et al. 2002). In contrast, the McMurdo Dry Valleys show general twentieth-century warming but cooling since 1985 (Bomblies et al. 2001); the sub- and maritime Antarctic islands show consistent warming (Bergstrom and Chown 1999; Quayle et al. 2002; Convey submitted); and the Antarctic Peninsula has warmed as rapidly as any place on Earth (King et al. 2003; Smith et al. 2003; Vaughan et al. 2003). Increases and decreases in precipitation have also both been reported (Turner et al. 1997; Smith 2002; Quayle et al. 2003).

Temperature and precipitation changes show teleconnections with El Niño/Southern Oscillation events in the southern Pacific Ocean (Cullather et al. 1996; Harangozo 2000). Reported Antarctic cooling may result from increased strength of the Southern Hemispheric Annular Mode, which would cause the strong westerly winds around Antarctica to spend more time in the strong-wind phase (Thompson and Solomon 2002). Such an effect could also contribute to the warming seen along the Antarctic Peninsula, as fewer cold-air outbreaks would be seen with increased advection of warm moist air from the Southern Ocean.

25.3.2 Development of Extractive Industries

Extractive industries in the Antarctic are prohibited by the Protocol on Environmental Protection (the Madrid Protocol) to the Antarctic Treaty of 1959, which set aside Antarctica for peaceful purposes and international collaboration in science. In contrast, extractive industries have been a significant driving force for ecological and socioeconomic change in the Arctic for over a century. Gold mining has contaminated streams with mercury used to amalgamate gold dust and with increased sediment loads that damage downstream aquatic ecosystems. Industrial coal and base-metal mines have caused local surface contamination. However, the greatest local effects on ecosystem services derive from smelting non-ferrous metals. Emissions from smelters on the Kola Peninsula and in Norilsk, Russia have produced local concentrations of atmospheric heavy metals among the highest in the world, resulting in areas that are entirely devoid of vegetation from the combined effects of sulfur fumigation and acid and heavy-metal deposition (Doiban et al. 1992).

As petroleum and military development spread in the latter half of the twentieth century, transportation infrastructure (roads, pipelines, airstrips, ports) contributed significantly to surface disturbance and habitat fragmentation. Between 1900 and 1950, less than 5% of the Arctic was affected by infrastructure development (Nellemann et al. 2001; Ogden in press). By 2050, some 50–80% of the Arctic is projected to be disturbed, although this level of disturbance may occur by 2020 in Fennoscandia and some areas of Russia.

Changes in world energy markets and technology have led to a rapid expansion of oil and gas development in several regions of the Arctic during the past 30 years. Most activity to date involves oil onshore along the North Slope of Alaska and in western Siberia, and offshore in the Barents and Beaufort Seas. However, the Alaskan North Slope, the McKenzie Delta of Canada, the Yamal

Peninsula of Russia, and their adjacent offshore areas hold enormous natural gas deposits that are projected to be developed during the next decade (Forbes 2004a). These developments will likely continue expansion as reductions in sea ice open new sea and river routes and reduce development and transportation costs. In addition to direct effects on vegetation and hydrology, oil and gas developments have many cumulative effects on subsistence resources and on the economies and well-being of local peoples, including increased wages to local residents, the fragmentation of habitat, and increased access by nonresidents (Walker et al. 1987; NRC 2003).Global changes in politics, corporate structure, and resource demand strongly influence the patterns and rates of resource extraction at high latitudes (Whiteman et al. 2004).

25.3.3 Contaminants

Many environmental contaminants that are produced and released to the environment at low latitudes tend to accumulate in polar regions. Persistent organic pollutants, for example, are stable, fat-soluble, carbon-based compounds that volatilize at warm temperatures and are transported poleward by wind, water, and wildlife. Old and current research stations in the Antarctic and Distant Early Warning stations in the Arctic often constitute additional local sources of contaminants (MacDonald et al. 2002). Atmospheric transport is the most rapid pathway by which persistent organic pollutants, especially volatile or semi-volatile compounds, reach the poles. Once in polar regions, POPs are deposited on particles or exchanged with water, both processes that are enhanced by low temperature. Oceanic transport occurs more slowly but is an equally or more important pathway for compounds such as hexachlorocyclohexane or toxaphene that partition strongly into water (MacDonald et al. 2002).

Fish and migratory waterfowl, which winter in more-polluted regions of the world and come to polar regions to reproduce, constitute a third pathway for polar transport. Anadromous fish also transport POPs from the ocean to high-latitude lakes and streams (Ewald et al. 1998). Animals are particularly important vectors for highly fat-soluble compounds. Marine mammals, seabirds, top carnivores, and predatory fish accumulate the largest amounts of fat-soluble contaminants because of their high trophic position in complex marine food webs (AMAP 2003). These general contaminant patterns are known with *high certainty,* but the regional variation in contaminants is not well documented. Persistant organic pollutant concentrations in Antarctic pelagic food webs (Corsolini et al. 2003) and in the air (Kallenborn et al. 1998) are much lower than those found in the Arctic, but some forms may be increasing owing to greater usage of POPs in the Southern Hemisphere (Weber and Goerke 2003).

Limited evidence suggests a current decline in polar concentrations of POPs, such as dichlorodiphenyl-trichloroethane, or DDT, the use of which has declined globally. POPs that are increasing in their global use continue to accumulate in polar regions (AMAP 2003; Chiuchiolo et al. 2004), and brominated diphenyl ethers—flame retardants whose use is not banned—occur in high concentrations in Antarctic sea ice and juvenile krill (Chiuchiolo et al. 2004). Antarctic sea ice serves as a collector and focusing mechanism that injects accumulated POPs into the plankton system at its period of maximum biological activity. The effects of climate warming on persistant organic pollutant transport to polar regions have *low certainty.* Sources of uncertainty include the dynamics of adsorption to snow and the extent to which POPs currently trapped in sea and glacial ice will be released with warming.

Heavy metals, like POPs, are persistent compounds that can be globally transported, especially by wind. They differ from POPs, however, in that they occur naturally within and outside polar regions and exhibit areas of naturally high and low concentrations. Heavy metals bind to proteins, accumulate in organs (liver, kidney, brain), and are slowly excreted in hair, feathers, nails, and claws. With the exception of mercury, heavy metals tend not to biomagnify (concentrate as they move through food webs). Global sources of mercury pose the greatest threat in polar regions because the global combustion of coal, which is its major source, is expected to continue rising throughout the next century. There are trends of increasing mercury in some Arctic species (AMAP 2003).

In East Greenland, 100% of the human population has concentrations of mercury that are unacceptable, and health advisories have recommended reduced consumption of some locally harvested resources. Heavy metal pollution inputs have declined in those portions of the Russian North where cessation of subsidies caused many extractive operations to close. Even in these areas, however, pollutants released previously remain in high concentrations in ecosystems. In the Antarctic region, burning of fossil fuels (involving NO_x emissions) at research stations might affect local systems at decadal time scales (Lyons et al. 2000).

Radionuclides such as cesium-137 and strontium-90 are stable enough to be transported globally in the atmosphere and oceans. Radionuclide concentrations increased during atmospheric testing of nuclear weapons in the 1950s and, like other forms of air pollution, drifted to polar regions. Background levels of atmospheric fallout have declined markedly since the end of atmospheric testing in 1963, but a more recent release occurred during the Chernobyl accident in 1986. Anthropogenic radionuclides are locally abundant in sediments near sites of weapons testing, storage, and nuclear-powered electricity generation facilities. Lichens, which derive most of their mineral nutrition from the air, are particularly effective in accumulating radionuclides. Caribou and reindeer, which eat lichens in winter, are an avenue by which any future nuclear contamination might affect human health (Section 25.5.4).

25.3.4 Marine Fishing

Both climate variability and commercial fishing have caused significant variations in marine mammals and fish available for commercial and subsistence harvest (Finney et al. 2002; AHDR 2004). (See also Chapter 18.) For example, over half of the Northeast Atlantic regional stocks of cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), whiting (*Merluccius bilinearis*), and saithe (*Pollachius virens*) are depleted below safe biological limits and are therefore threatened with collapse. In Greenland, the collapse of the cod fishery occurred when overfishing coincided with climatic deterioration (Hamilton et al. 2000). In the North Pacific, the decline in bottom fish has contributed to drops in populations of Steller sea lions, causing killer whales to shift to sea otters for food and reducing the availability of marine mammals for human harvest (Estes et al. 1998). Commercial fishing has reduced fish runs in major rivers such as the Yukon in North America, reducing their availability as a subsistence resource. As sea ice continues to decline, commercial fishing may expand northward, reducing stocks that have previously had limited human harvest. These changes have, in many cases, had dramatic socioeconomic effects, as small Arctic communities adapt to the combined effects of climate change, changing fish stocks, and emergent markets (Hamilton et al. 2000).

In Antarctica, exploitation in the nineteenth and early twentieth centuries reduced seal and whale populations almost to extinction, but the consequences have *low certainty* (May et al. 1979; Murphy et al. 1995). Stocks of krill, the major food source of whales, may have increased, but this assumes that their abundance was under top-down control by predator demand. Fishing for krill has occurred over the past 20 years, but the fishery has operated at very low levels relative to the estimated stock sizes, and there is no evidence that fishing has significantly affected local abundance and availability to predators.

Fishing in Antarctic waters, particularly by Russia, expanded rapidly in the 1960s, leading to depletion of several fin-fish stocks by the 1990s. (See Chapter 18.) The Convention on the Conservation of Antarctic Marine Living Resources limits catch sizes, but continued illegal, unregulated, and unreported high-seas fishing threatens major fish stocks and makes effective monitoring and management difficult.

25.3.5 Increased UV-B

Anthropogenic destruction of Earth's protective stratospheric ozone layer gives rise to an ''ozone hole'' that allows UV-B radiation to penetrate to the surface (Farman et al. 1985). The boundaries of the ozone hole that forms over Antarctica each austral spring are dynamic and can extend to southern South America, New Zealand, and southern Australia. Although the Montreal Protocol curbs emissions of the causal chlorofluorocarbons, there is still no reduction in intensity of the annual ozone hole, although recovery is predicted within about a century (Shindell et al. 1998).

The most intensively studied biological impacts of UV-B are the effects on human health (described later in the chapter) and the reduction of phytoplankton production and plankton biodiversity (Smith et al. 1992; Quartino et al. 2001; Vernet and Kozlowski 2001). On land, UV-B reduces plant height and shoot mass (Day et al. 2001; Robinson et al. 2003) and induces the formation of protective pigments (Newsham et al. 2002; Newsham 2003) that may also alter palatability to herbivores (Hessen 2002). The impacts of UV-B in the Arctic are less dramatic than in the Antarctic and potentially include decreased marine primary production, increased mortality of fish larvae of some species, increased mortality of freshwater invertebrates, reduced growth of some plant species, and changes in microbial biodiversity and biogeochemical cycling (Vernet and Kozlowski 2001; Callaghan et al. in press). The net impact of increased polar UV-B on the ecological determinants of human well-being has *low certainty,* but its effects on Antarctic marine plankton assemblages and production have *high certainty* (Weiler and Penhale 1994; Meador et al. 2002).

25.3.6 Introduction of Exotic Species

Despite Annex II of the Protocol on Environmental Protection to the Antarctic Treaty, which prohibits introduction of exotic species to Antarctica, human introductions of exotic species (including rats, slugs, reindeer, cats, temperate grasses, and other plants) are problematic on most sub-Antarctic islands, although they have not yet significantly affected the Antarctic continent (Chown et al. 1998; Vidal et al. 2003; Frenot et al. in press). The combination of increased human activity in the region and the lowering of barriers to the transfer and establishment of biota through climate change leads to predictions of further increases in rates of exotic introduction and consequential impacts on native biota and biodiversity (Frenot et al. in press).

Weedy plant species from temperate and Mediterranean ecosystems have a long history of establishment in northern boreal and Arctic regions (Forbes 1995). Their migration north of the Arctic tree line is most common along road and railway corridors with connections to the south, but numerous incidental introductions have also occurred in places such as Baffin Island, Greenland, Svalbard, and remote portions of the Russian Arctic. Many of the introductions establish first on disturbed ground. Many persist for decades or even centuries without additional anthropogenic or zoogenic influence, although an ongoing disturbance regime favors the maintenance and spread of new populations.

Introductions of exotic mammals have had substantial impacts on many polar ecosystems. Until the advent of human influence, sub-Antarctic islands and many islands in the Bering Sea had no indigenous terrestrial mammals, so seabirds nested safely on the ground or in burrows (CAFF 2001). Arctic foxes (*A. lagopus*) were deliberately introduced to many Bering Sea islands as a fur resource, and cats, sheep, rabbits, reindeer, and cattle were introduced to some sub-Antarctic islands. At the same time, rodents (rats and mice) were inadvertently introduced to many islands.

As seen elsewhere when predators or competitors were introduced to previously isolated communities, these animals generally reduced, and in some cases drove to extinction, populations of marine birds, waterfowl, and other ground-nesting birds, through either habitat alteration or direct predation (Frenot et al. in press). Exotic plants have frequently been introduced as a by-product of animal introductions, typically accidentally in forage material or as resistant stages transported within the animal's digestive system. Introduced mammals have been successfully eliminated from some islands, resulting in recovery of bird nesting success. On Svalbard in Scandinavia, the introduction of the rodent *Microtus rossiaemeridionalis* led to the introduction of a tapeworm and associated disease problems (Henttonen et al. 2001). Muskrat (*Ondatra zibethica*) was introduced in 1905 into central Europe from North America and later to Finland and several places over the Soviet Union because of its valuable pelt (Hoffmann 1958). It has spread widely beyond the areas of introduction. Sable (*Martes zibellina*) has also been introduced to the Siberian Arctic.

One of the largest crab species in the world, the king crab (*Paralithodes camtschaticus*), was transferred by the Russians from the Bering Sea to the Barents Sea beginning in about 1960. Since it was first observed in Norwegian waters in about 1980, the species has spread eastward and southward along the coast (Sundet 1998). Although this species is a valuable catch, it causes problems to fishing gear and has reduced sea urchin populations in the Barents Sea. Marine introductions have to date been of very limited impact in Antarctic seas, although this perception may derive in part from a lack of monitoring.

25.4 Trade-offs, Synergies, and Management Interventions

Given the complex web of changes in ecosystem services in polar regions and their sensitivity to changes in global and regional drivers, changes in some ecosystem services inevitably affect others, either positively or negatively. (See Figure 25.9.) Identification of these interactions, whether they are trade-offs or synergies, facilitates the design of policies that enhance a broad array of services and reduce the likelihood that policies focused on a specific service will inadvertently damage others.

25.4.1 Synergies between Climate Regulation, Subsistence, and Cultural Resources

The most pervasive synergy among ecosystem services in polar regions links climate regulation, subsistence use, and cultural re-

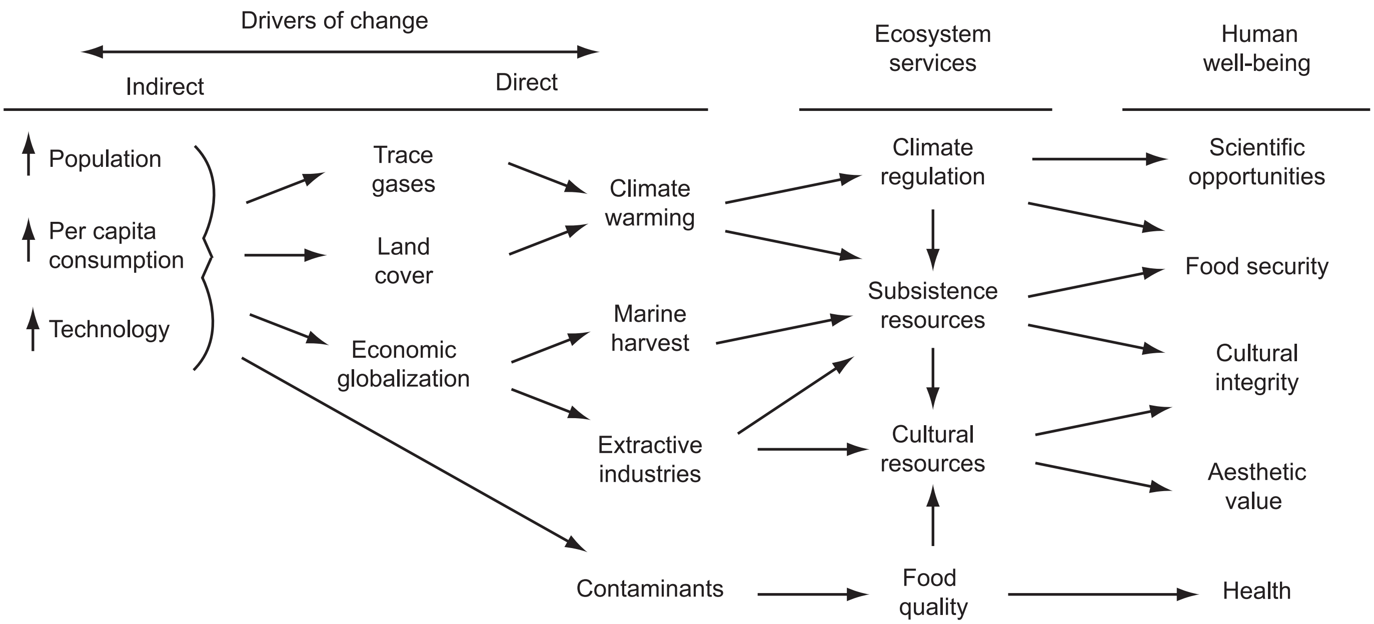

Figure 25.9. Links between Drivers of Change, Ecosystem Services, and Human Well-being in Polar Regions

sources. (See also Chapter 5.) Until recently, the magnitude of land use change in polar regions has been modest, allowing Arctic residents to maintain a substantial dependence on subsistence resources for food and clothing and for their cultural ties to the land. These same attributes make polar regions important to non-Arctic residents for existence and aesthetic values.

Fortunately, management strategies that foster the sustainability of these cultural resources have a *high certainty* of maximizing the retention of biodiversity, particularly in wetlands, and of maintaining the capacity of polar regions to serve as the planet's cooling system by maintaining current large stocks of soil carbon and preventing thaw of permafrost that would enhance methane emissions (as described earlier). Conversely, industrial development or pollution that seriously alters these ecosystems detracts from the aesthetic values that are important to both polar and non-polar residents, reduces ecosystem capacity to sustain biodiversity and subsistence resources, and increases methane and carbon emissions, a positive feedback to climate warming.

Policies that recognize these synergies sustain all these services simultaneously. For example, policies that allow local people to pursue traditional subsistence activities within protected areas contribute to biodiversity and cultural integrity while meeting the aesthetic needs of both Arctic and non-Arctic residents (Watson et al. 2003). Alternatively, policies that exclude subsistence use from protected areas create trade-offs between the subsistence needs of local residents and the aesthetic and recreational interests of non-Arctic residents. Current national regulations permit subsistence use in protected areas of the North American Arctic. In Russia, indigenous peoples are often excluded from protected areas, even though laws may permit subsistence uses (Fondahl and Poelzer 2003). Subsistence use in protected areas is generally prohibited in Fennoscandia.

25.4.2 Synergies and Trade-offs between Subsistence and Cash Economies

Residents of all Arctic nations participate in a mixed economy in which individuals and communities depend on both subsistence harvest from the land and sea and imports of food, fuel, and other products from outside the Arctic. Among many Arctic indigenous peoples, participation in a mixed cash-subsistence economy has been a way of life for more than a hundred years, with fur trading being the original base of the cash economy. This economy has both positive and negative impacts on subsistence activities; in recent years, participation in the cash economy has increased dramatically (AHDR 2004).

On the one hand, this reduces the necessity and time available to acquire food from the land, thereby reducing the transmission of cultural traditions to younger generations. Substance abuse, television, fast foods, and other attributes of a cash economy have also detracted from the central role of subsistence in the lives of rural Arctic people. On the other hand, cash income provides access to new harvesting technologies (Chance 1987) and other material benefits. Motorboats and vehicles (such as snow machines, off-road vehicles, and in some places aircraft) give people continued access to lands for hunting, herding, fishing, and gathering.

In all Arctic nations, government policies consolidated semi-nomadic indigenous peoples into permanent settlements by the mid-twentieth century in order to provide schools and other services. If residents of these communities had not had a cash income to help them purchase motorized transport, they would have been less able to reach the large areas typically required for subsistence. However, reliance on these technologies make industrial commodities a necessity, not just a supplement to the traditional economy (Kirkvliet and Nebesky 1997). These technologies also alter the balance between hunters and the hunted, raising new challenges for conservation and game management.

The intertwining of subsistence and market economies creates winners and losers in what was, until recently, a fairly egalitarian society and introduces new challenges of balancing time and money in household production. Gender roles change in areas where women obtain wage-earning jobs more frequently than men. Continued viability of a community may require increased specialization. Some individuals who work full-time for pay, for example, have insufficient time to participate in traditional activities, whereas others who are unable to obtain jobs serve as full-time hunters to meet the overall subsistence needs of their communities (Stabler 1990; Kruse 1991; Chabot 2003). These groups are linked through a traditional system of reciprocity that redistributes market and subsistence products.

All Arctic nations recognize the potential lack of viability of market economies in northern regions when semi-nomadic indigenous peoples are consolidated in permanent settlements and have subsidized northern communities heavily (Duerden 1992). The consequence, however, is that Arctic mixed economies are now vulnerable to withdrawal of government support, as witnessed in Russia after the collapse of the Soviet Union or in cases of reduced support in Alaska (Knapp and Morehouse 1991). Products derived from locally available fish and wildlife resources often offer important sources of cash that supplement wages and transfer payments from governments.

However, subsistence economies are vulnerable to declines in global markets for these commodities, which include seal or muskrat pelts (as changes in cultural values reduce global demand for furs), salmon (as fish farming increases alternative supplies), and reindeer antler (as cultural change in Asia reduces demand) (Myers 2000). When world market prices are high, regional resource management institutions may be unable to respond to the increased incentives for unregulated or illegal harvest (such as for Kamchatka salmon or Greenland cod) (Hamilton et al. 2000) or overgrazing by reindeer (Forbes 1999). On the other hand, government policies to conserve stocks may prevent Arctic people from taking advantage of the only viable commercial activities available (as with the International Whaling Commission ban on commercial whaling).

Specialization on one or two products also increases the vulnerability to ecological change. In Greenland, for example, northward movement of warm currents in the 1930s reduced seal harvests by 60%, but local residents switched to fishing for cod, with financial assistance from the Danish government (Hamilton et al. 2000). When the cod fishery collapsed in the 1980s in response to a combination of overfishing and colder currents, those communities that had boats large enough to fish for offshore shrimp continued to prosper, whereas those communities that had only small boats and therefore no access to the offshore shrimp fishery declined in income and population (Hamilton et al. 2000)

25.4.3 Synergies and Trade-offs between Industrial Development and Cultural Resources

There is a fundamental trade-off between the bundle of services associated with environmental protection (aesthetic resources for Arctic and non-Arctic residents and the capacity of ecosystems to provide subsistence resources and to store soil carbon that contributes to climate regulation) and the services provided by industrial development that provides cash income. Most Arctic regions are ruled by nations with a non-Arctic population majority and have governments housed outside the Arctic. Therefore non-Arctic strategic and economic considerations often weigh heavily in decisions about Arctic development. Political decisions by the United States and Russia, for example, have strong effects on polar regions because of the nations' large demands for resources and strong influence on polar development (AHDR 2004).

An ongoing challenge for the governments of Arctic nations is to create options that maximize the economic benefits of industrial development, including wages and services for local residents, without seriously compromising the integrity of ecosystem services. This challenge may become more complex if warming leads to increased development and further immigration of nonindigenous people (Whiteman et al. 2004).

New technologies provide opportunities to minimize the impact of industrial development on ecosystem services of Arctic wetlands, including ice roads that minimize the areal extent of transportation infrastructure, improved pipeline designs that reduce the probability of oil spills, and lateral drilling that maximizes access to oil reservoirs from a limited number of surface installations. However, these advances are relatively ineffective in preserving the aesthetic qualities of wilderness, and some of these options are threatened by climatic warming. As winter temperatures rise, permanent roads and bridges will increasingly replace ice roads for overland access, augmenting the disturbed area for a given development. In Alaska, the number of days on which the oil industry is permitted by the state to use off-road vehicles has decreased by 50% since 1970 because of both warmer autumn conditions and increased environmental awareness by managers. (See Figure 25.10.) In Yamal in northern Russia, melting of ice-rich permafrost exacerbates deterioration of forage from trampling and overgrazing by reindeer (Forbes 1999).

Where Arctic residents have opportunities to capture some of the economic benefits from industrial development through both employment and corporate investments, benefits in the form of improved public infrastructure, educational services, and health care can be significant (as in North Slope Borough, Alaska, for instance). Trade-offs can be decreased where communities of resource users are afforded adequate authority in development planning and operation policies to ensure that community concerns are adequately addressed.

Other opportunities for synergies between conservation and development involve compromises that concentrate development in certain areas, leaving other areas protected for the subsistence, cultural, and climate-regulating services that they provide.

25.4.4 Institutional Trade-offs in Managing Ecosystems and Their Services

In the Antarctic, international conventions form the framework for decisions about resource management. The Antarctic Treaty was ratified in 1961, with additional instruments added in subsequent years. Comprehensive protection of the environment was

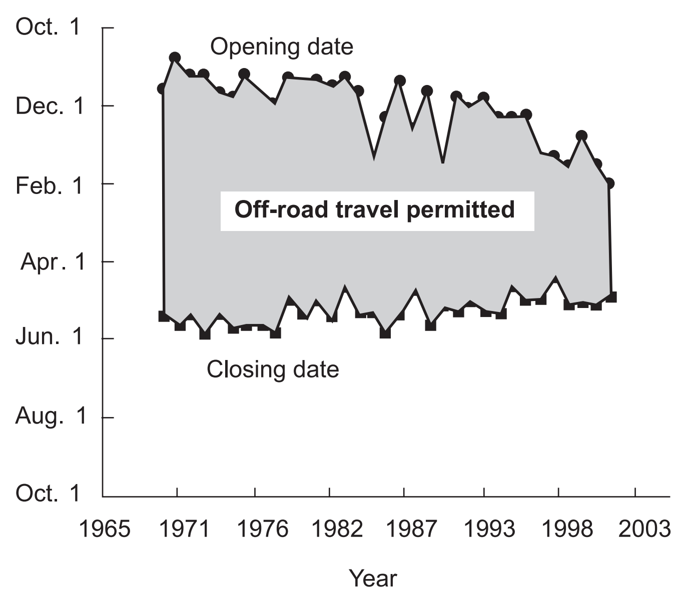

Figure 25.10. Trend in Dates Allowed for Travel by Seismic Vehicles on Alaskan Arctic Tundra, 1970–2000 (Alaska Department of Natural Resources)

achieved with the ratification of the Protocol on Environmental Protection, known as the Madrid Protocol, in 1998, which prohibited any activity relating to mineral resources, with exception for scientific research. Environmental assessment of all activities was required by the Madrid Protocol, ensuring that cumulative as well as immediate impacts are prevented. The Convention on the Conservation of Antarctic Marine Living Resources of 1980 permits fishing in the waters surrounding Antarctica, but only under the guidance of ecosystem management. This convention takes account not just of the dynamics of the exploited stocks but also their interactions in the ecosystem and the links to the physical environment.

Under these and other conventions, Antarctica now has the most stringent restrictions on use rights and the most advanced system of protected areas of any major region of the world. Nonetheless, Antarctica remains vulnerable to indirect human impacts such as pollution, stratospheric ozone destruction, and greenhouse-gas-induced climate change.

In contrast to Antarctica, institutions of the Arctic have evolved most actively at local and regional levels (AHDR 2004). Local stakeholders have asserted rights to develop their own rules and regulations governing use of natural resources and the right of their traditional institutions to be recognized by external parties. Both the outcomes of these efforts and the forms of local control differ regionally. In Alaska, Native corporations own about 12% of the land, and the federal government recognizes a rural subsistence preference regarding the use of living resources located on the 60% of the land remaining under federal jurisdiction. The U.S. federal government defends indigenous rights to use marine mammals and has established community development quotas to ensure that local groups have a stake in the region's marine fisheries.

The 1982 Canadian constitution acknowledges the validity of existing aboriginal rights, and the settlement of a number of comprehensive claims there has transferred to indigenous peoples both cash payments and title to large landholdings, along with recognized use and management rights in even larger traditional-use areas. In Greenland, there is no system of private property or well-defined use rights to land and natural resources, but the indigenous-controlled Greenland Home Rule has authority to make most decisions about the use of terrestrial and marine living resources. Devolution of authority to regional or local governments with good systems of accountability increases responsiveness of governments to the concerns of local stakeholders.

In Fennoscandia and Russia, national institutions have traditionally regulated natural resources, and local stakeholders have had greater difficulty establishing their rights. In Scandinavian countries, an ongoing struggle to secure Saami rights to land and natural resources has met with limited success. The state provides various forms of assistance to reindeer and coastal Saami. However, secure use rights have proved elusive, especially in Sweden, where the courts have generally denied claims to indigenous rights despite state recognition of these rights a century ago (Hahn 2000).

Recent federal laws in Russia theoretically allow indigenous peoples to establish long-term rights to land through the creation of both extensive Territories of Traditional Nature Use and smaller ''commune lands'' for pursuit of traditional activities (Kryazhkov 2000), although laws are difficult to implement in some areas and are not always enforced (Fondahl and Poelzer 2003). Recent outmigration of Russian and other nonindigenous residents may reduce pressures arising from competition over land and resource use. Efforts to devise a comprehensive system of rights and rules governing the use of land and natural resources in the region have repeatedly failed in the Duma.

A particularly significant innovation in governance in the circumpolar north—especially in the North American Arctic—has been the creation of co-management arrangements designed to forge partnerships between state governments holding formal authority to manage living resources and local user communities (such as the Porcupine caribou herd in Canada) (Osherenko 1988; Berkes et al. 1991). Co-management implies a sharing of power between resource users and state governments in various functions of resource management (monitoring, planning, enforcement, policy-making, and so on). These arrangements continue to evolve and are proving beneficial in regions where government agencies and resource users are together tracking the trends of climate change and monitoring the impacts of industrial development while exploring options for human adaptation.

In Fennoscandia, where traditional migration pathways conflict with complex patterns of private and Crown ownership, easement rights provide secure access (Hahn 2000). However, the amount of accessible, high-quality pasture available has decreased in many areas as a result of extensive forestry, tourism, hydropower, mining, and border fences and the concomitant increases in heavy trampling and grazing on the remaining lands (Forbes 2004b).

Oil, gas, and mineral developments have generally provided few long-term jobs for local residents. In North America, however, where local governments and land claims organizations provide an institutional framework for mitigation and compensation, extractive industries have provided substantial cash infusions to communities. Nevertheless, anxiety persists among Arctic residents about the cumulative effects of historical and proposed activities on resources and cultures (NRC 2003; AHDR 2004). In Russia's Yamal, where local residents have little influence over resource extraction, change has hit a crisis point, challenging the ability of local residents to adapt to the pace of oil and gas development (Krupnik 2000).

In the Arctic, the early development of international arrangements (the 1920 Svalbard Treaty guaranteeing signatories access to coal reserves, for example, or the 1973 Polar Bear Agreement committing signatories to the implementation of conservation measures) involved little input from local stakeholders. More recently, the Arctic Council and its forerunner, the Arctic Environmental Protection Strategy, have provided an important forum for the indigenous peoples of the Arctic to advance their agendas, including matters relating to the use of living resources. These international conventions then provide a basis for groups to go back to their home countries and demand the rights specified by these conventions. The Arctic Council has also devised and promoted an initiative designed to create and enlarge a Circumpolar Protected Areas Network.

25.5 Polar Systems and Human Well-being

25.5.1 Human Population Changes in the Arctic

Population in the circumpolar Arctic increased rapidly after 1960 as a result of immigration associated with expanded resource development and government activities in the north (AHDR 2004). However, change has been uneven, with much slower growth in Fennoscandia than in Russia or North America. (See Table 25.4.) Most of the population growth occurred in urban centers tied to industrial activities or public administration, so population density remains very low in rural areas across the Arctic. This pattern of growth has changed markedly since 1990. Growth has slowed in

Table 25.4. Population of Arctic Regions, 1960–2000 (Knapp 2000 for 1960–90; 2000 data from national census data and other sources as noted)

Region	1960	1970	1980	1990	2000
			(thousand)		
United States					
Arctic Alaska	81.9	96.1	112.2	151.0	158.7[a]
Canada					
Yukon Territory	14.6	18.4	23.2	27.8	30.9
Northwest Territories[b]	23.0	34.8	45.7	57.7	40.8
Nunavut[b]					26.7
Total, Arctic Canada	37.6	53.2	68.9	85.5	98.4[c]
Greenland	33.1	46.5	49.8	55.6	56.5[d]
Fennoscandia					
Norway	437.4	454.1	469.6	460.8	464.7[e]
Sweden (Norrbotten)	261.8	255.4	267.1	263.7	256.2[f]
Finland (Lappland)	205.1	197.1	194.9	200.7	187.7[g]
Total, Arctic Fennoscandia	904.3	906.6	931.6	925.2	908.6
Russia[h]					
European Arctic (Murmansk and Nenets)	613.2	838.6	1,025.0	1,201.0	934.0
Other European North	2,687.8	3,040.5	3,261.4	3,570.0	3,071.5
Asian Arctic, excluding Sakha[i]	468.2	637.5	895.6	1,298.0	951.0
Sakha Republic (Yakutia)	487.3	664.1	851.8	1,081.0	949.3
Other Asian North[j]	327.4	540.6	935.5	1,720.0	1,801.3
Total, Russian North	4,583.9	5,721.3	6,969.3	8,870.0	7,715.1
Arctic Russia (excluding Sakha)	1,081.4	1,476.1	1,920.6	2,499.0	1,885.0

[a] U.S. Census Bureau, Census 2000. Arctic Alaska includes all lands north of the Alaska Range.

[b] In 1999 Nunavut became a territory, separated from the Northwest Territories.

[c] Statistics Canada, 2001 Census, http://www.statcan.ca/.

[d] Statistics Greenland, 2001 Census, http://www.statgreen.gl/english/publ/figures/grfig-02.pdf.

[e] Statistics Norway. Arctic Norway includes provinces of Nordland, Troms and Finnmark.

[f] Population of Norrbotten: http://www.regionfakta.com/norrbotten_eng/Kapitel_09/e_a01_2500.htm.

[g] Statistics Finland: population of Lappland.

[h] Goskomstat of Russia, 2002 All-Russia Population Census, vol. 1.

[i] Yamalo-Nenets, Taimyr, Norilsk, Magadan, Chukotka, Koryak Oblasts

[j] Khanty-Mansi, Evenk, Kamchatka Oblasts

North America and Greenland, and population has declined in Arctic Fennoscandia and particularly in Russia. Although the indigenous population has grown at a rate of about 1.5% annually, its share of total population has declined. Indigenous peoples have become ethnic minorities in all Arctic regional government jurisdictions except Greenland and portions of Canada (Nunavut and the Northwest Territories). (See Table 25.5.) Nonindigenous population growth in the latter could make indigenous peoples a minority there, too, within a decade.

Drivers of population change differ significantly for indigenous and nonindigenous residents. For the nonindigenous, most of whom are of European ancestry, past cycles of population change coincided with changes in world demand for Arctic resources (Sugden 1982). In the twentieth century, the Arctic became important to international security; this led to increased military presence and to government policies that boosted industrial development (Armstrong et al. 1978; Osherenko and Young 1989). The easing of tensions after the collapse of the Soviet Union led to the scaling back and closure of military and industrial installations in most Arctic nations and to a reevaluation of regional industrial policies. This change had the greatest impact on the nonindigenous population in the Russian Arctic. Arctic areas of Russia have lost nearly 25% of their inhabitants since 1990, while the population of the Russian North as a whole has declined by 13%. The withdrawal of government support led to rapid outmigration of ethnic Russians and other nonindigenous people (Heleniak 2003). The indigenous population remained relatively stable but suffered a decline in living standards.

Net outmigration has tempered the effects on indigenous population growth of the relatively high birth rates and increasing life expectancy (AMAP 2003). Migrants seek education and jobs in northern urban centers or outside the Arctic; some, but not all, return later in life. In Alaska, for example, there may be as much as 1% per year net population outflow (Huskey et al. in press). More women than men leave small rural communities, leading to a gender imbalance among unmarried adults in many parts of the

Table 25.5. Arctic Indigenous Population, 1960–2000. Share of total population is shown in parenthesis. (Knapp 2000 for 1960–90; 2000 data from national census as noted)

Region	1960	1970	1980	1990	2000
			(thousand)		
United States	n.a.	33.9 (35%)	40.0 (36%)	50.0 (33%)	54.4[a] (34%)
Canada[b]	15.3 (41%)	21.2 (40%)	28.7 (42%)	39.1 (46%)	49.0[c] (50%)
Greenland	30.4 (92%)	38.9 (84%)	40.9 (82%)	46.1 (83%)	49.8[d] (88%)
Fennoscandia[e]	n.a.	34.0 (4%)	n.a.	50.0 (5%)	n.a.
Russia					
European Arctic[f]	n.a.	18.5 (2%)	18.2 (2%)	19.3 (2%)	19.5[g] (2%)
Asian Arctic, Excluding Sakha[h]	n.a.	66.0 (14%)	66.6 (7%)	77.3 (6%)	78.1[g] (8%)
Total Arctic	n.a.	212.5	n.a.	281.8	n.a.

[a] U.S. Census Bureau, Census 2000. Arctic Alaska includes all lands north of the Alaska Range.

[b] Approximately 9,000 Inuit living in the Nunavik region of Quebec are not included in the total. (Source: Indian and Northern Affairs Canada, Quebec Region, General Data on Indian Population available at: http://www.ainc-inac.gc.ca/qc/gui/population_e.html.) Canadian data provides for more than one definition of native origin. The definition used in this table is "aboriginal identity." Individuals that responded to "aboriginal" only are counted (no multiple responses). Figures for Nunavut count only Inuit and North American Indian ethnicity. There was no information on "aboriginal identity."

[c] Statistics Canada, 2001 Census, http://www.statcan.ca/.

[d] Statistics Greenland, 2001 Census, http://www.statgreen.gl/english/publ/figures/grfig-02.pdf.

[e] Population of the Saami in the Scandinavian North.

[f] Murmansk and Nenets Oblasts.

[g] Stepanov 2004.

[h] Yamalo-Nenets, Taimyr, Norilsk, Magadan, Chukotka, Koryak Oblasts.

Arctic (Hamilton and Seyfritt 1994). Consolidation of the population into larger settlements improves job prospects and reduces the cost of providing infrastructure and services. This trend also increases pressure on local renewable resources near population centers, as people attempt to continue hunting and herding traditions, and it weakens cultural ties to ancestral homelands. Traditions of reciprocity often continue between urban indigenous residents and their rural kin, so outmigration provides some economic benefits to rural communities, although the magnitude of these benefits is uncertain.

25.5.2 Patterns and Trends in Human Well-being

Most polar regions are governed by industrial nations with substantial economic resources. Human well-being in these regions is therefore largely the product of choices made by the people and leaders of these nations rather than a lack of national resources to fulfill human goals. The eight Arctic nations account for 40% of global carbon emissions, so there are direct within-country links between the anthropogenic sources of climate change and the components of the global society that are currently most directly affected by this warming.

Polar regions are important to the well-being not only of the residents but also of the global population, which depends on polar regions for climate regulation and for providing extensive areas that remain wild and relatively unaffected by human activities and serve as critical areas for many culturally and otherwise important migratory species. This potential to provide for human well-being has not been fully met and is currently threatened by global human impacts on the climate system and by inadequate attention to human impacts within polar regions on ecosystems and the services they provide. The increased pressure that polar systems are experiencing implies that we are approaching critical thresholds (such as the thawing of permafrost and vegetation change), although the nature and timing of these thresholds are regionally variable and uncertain. Crossing these thresholds would likely cause a cascade of ecological changes with large effects (some negative, some positive) on human well-being. These changes could appear quickly and be irreversible (Dasgupta 2001; Chapin et al. 2004).

There is substantial variation in the well-being provided by ecosystems in different polar regions (AHDR 2004). There are few permanent residents in Antarctica, and there have been no clear trends in the mass balance of the Antarctic ice sheet on which the global population depends for climate regulation and control of sea level, as described earlier. There are indications of greater deterioration in the capacity of Arctic regions to provide a cooling system for the planet and to provide the aesthetic values of wilderness.

25.5.3 Cultural and Economic Ties to Ecosystem Services

The deterioration of cultural ties to subsistence activities among indigenous peoples is the most serious cause of decline in well-being within the Arctic. (See Figure 25.11.) There has been a gradual loss of connection to the land through change in lifestyles, loss of indigenous languages, and dominance of nonindigenous

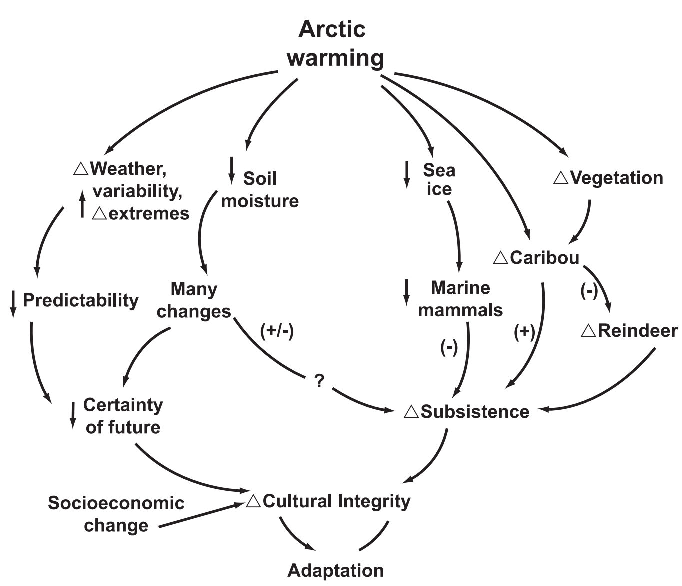

Figure 25.11. Specific Links between Arctic Warming and Well-being of Arctic Indigenous Peoples (see also Figure 25.9)

educational systems over indigenous peoples. In cultures with an important oral tradition, the death of elders and the reduced experience of a younger generation in living on the land have eroded traditional knowledge. Changes from nomadic to sedentary lifestyles (among Saami and Nenets herders, for instance), the moving of children to distant schools for education, economic infusions into communities from oil development, and migration to cities have all further weakened cultural traditions and the sense of self-sufficiency that makes these traditions meaningful.

The effects of regional climate warming on ecosystem services have contributed to the decline in cultural connections to the land. As the climate warms, traditional cues for predicting environmental variability no longer work. This strips Arctic residents of their considerable knowledge, predictive ability, and self-confidence in making a living from their resources and may ultimately leave them as ''strangers in their own land'' (Berkes 2002). This increases their vulnerability to both climatic and social changes (Norton 2002). Nonetheless, indigenous cultures continue to exhibit substantial resilience as a result of short-term coping mechanisms (such as prey switching in response to changing animal abundances) and long-term adaptation through application of new tools and technologies, such as global positioning system navigational aids (Sahlins 1999; Berkes and Jolly 2001).

Industrial development interacts with cultural and climatic change to create both positive and negative effects on human well-being. The greatest positive effect is increased income associated with oil development in North America and tourism in Fennoscandia and with government subsidies that are funded in part by industrial development. These wages enable people to buy snow machines, guns, boats, GPS units, and other equipment that enhances their capacity to harvest food from the land. Depending on the level of harvest, this can sustain subsistence activities or (for example, in the Russian Arctic) can lead to overharvesting. The environmental deterioration and changes in animal behavior associated with industrial development are major concerns of indigenous peoples throughout the Arctic because this threatens their subsistence lifestyles and cultural ties to the land. The jobs provided by industry and government sectors are important motivations for emigration of younger people from rural communities to urban centers.

Because of the interdependence between Arctic economies and global markets, indigenous peoples are doubly exposed: to both climate change and changes caused by the global processes affecting markets, technologies, and public policies. Having access to traditional food resources and ensuring food security will be a major challenge in an Arctic affected increasingly by climate change and global processes (Nuttall et al. in press). The low diversity of economic options in the Arctic renders it vulnerable to changes in both the local resource base and global economic trends and markets and explains the widespread northern phenomenon of boom-and-bust cycles (Chapin et al. 2004). Enhancing local economic diversification is a critical step toward increasing Arctic resilience.

The development and collapse of the Soviet economy in Russia had numerous impacts on the well-being of northern residents. Many non-indigenous residents of the Russian Arctic have left since 1990, whereas indigenous residents have largely remained, because they had no family ties outside the Arctic. Despite this reduction in demand for food and services, the economic subsidies and marketing system that were the primary economic base for Russians in the Arctic have virtually disappeared. This situation has reduced the economic incentive to maintain domestic reindeer, leading to a liquidation of some herds to support food needs. Hunting of wild mammals and birds has increased to meet food needs, straining the capacity of northern ecosystems to provide the services that northern people will require over the long term.

Resolution of the property rights of indigenous peoples in North America has been a key institutional change that strengthens their ties to the land. These changes in property rights promise enhanced resilience in the North American Arctic but remain a challenge in Eurasia (Osherenko 2001; Fondahl and Poelzer 2003).

25.5.4 Environmental Effects on Human Health

Increased UV-B radiation due to ozone depletion directly increases the risk of skin cancer and sight damage, particularly to people with fairer skin (Altmeyer et al. 1997). It also suppresses immune responses and thus increases susceptibility to disease (De Gruijl et al. 2002). Ozone depletion occurs at both poles but is most pronounced and extensive in the south. In the austral spring, when ozone depletion is strongest over Antarctica, ozone-depleted parcels of air move northward, leading to increased UV-B exposure to southern regions of Australia, New Zealand, Africa, and South America.

Bioaccumulation of contaminants in northern biota represents a potential health risk to northern peoples, as described in detail in Arctic Monitoring and Assessment Programme reports (MacDonald et al. 2002) The impacts of environmental deterioration on human health are regionally variable in the Arctic and are generally most pronounced in eastern Canada and the North Atlantic (AHDR 2004). However, studies conducted outside the Arctic have shown that even ''low'' concentrations of POPs and other endocrine disruptors interfere with hormone function and genetic regulation, indicating that developing organisms are easily put at risk of impaired reproductive, immune, and neurological function (Guillette and Crain 2000).

The ubiquity of POPs in the Arctic environment raises concern for the safety of future generations of Arctic peoples (AMAP 2003; Downie and Fenge 2003; Godduhn and Duffy 2003). As with POPs, the young and unborn are generally most vulnerable to subtle sublethal effects of heavy metals. In coastal Canadian and Greenland communities where marine mammals are a significant food source, concentrations of POPs in mothers' milk are high enough to be considered a health risk (Deutch and Hansen 2000; Muckle et al. 2001; AMAP 2003), and consumption of wild foods has been restricted in several cases in the eastern Canadian Arctic.

Of the small number of studies on the impact of environmental contaminants on human health in the Arctic, few have detected significant health effects. Health assessments suggest that the benefits of traditional foods, including lower risk of heart disease, generally outweigh the risks from contamination, because these foods are more nutritious than are store-bought substitutes (AMAP 2003). Regardless of the medical impacts of contaminants, the widespread perception of health risks by local residents reduces their sense of well-being.

Human populations that depend on caribou and reindeer are vulnerable to radionuclide accumulations whenever nuclear fallout occurs. Such populations suffer the physiological effects of radiation, the economic effects of lost resources, or both. For example, after the explosion at the nuclear power station at Chernobyl, cesium-137 and strontium-90 concentrations increased dramatically in lichens and reindeer in Scandinavia, where tens of thousands of reindeer had to be destroyed (MacDonald et al. 2002).

25.5.5 Aesthetic and Recreational Values

The Arctic and Antarctic include some of the largest wilderness areas on Earth. Establishment of protected areas of various types is the conventional way to protect landscapes, ecosystems, and habitats in the terrestrial environment. Treaties have provided Antarctica with a high level of protection that restricts development (as through Annex V of the Protocol on Environmental Protection to the Antarctic Treaty). Increasing tourism in Antarctica reflects the growing recognition of its aesthetic and recreational values.

Protected areas cover approximately 15% of the terrestrial Arctic. However, they are unevenly distributed across ecosystems and habitats. Over 27% of Arctic glaciers but less of the vegetated Arctic is protected (CAFF 2001). A strategic plan to establish a Circumpolar Protected Areas Network was completed in 1996 and endorsed by the eight Arctic nations (CAFF 1997). The initial burst of creating new protected areas has since come to a standstill, particularly in the Russian Arctic (WWF 2002). Owing to the rapidly changing climate, reserves cannot successfully protect species unless they have flexible boundaries or adequate interconnections that allow redistribution or migration in response to climate change (Elmqvist et al. 2003; Callaghan et al. in press). In addition to current practices of protecting rare and threatened species, conservation may become necessary for more widespread Arctic species that decline in response to climate warming.

25.5.6 Opportunities for Scientific Study

Polar regions have been key sources of new information that improve human understanding of the Earth system. Ice cores from Antarctica and Greenland have revealed detailed records of climatic and environmental changes that have occurred over the past million years (EPICA 2004). Antarctica, in particular, has been an important scientific platform for many disciplines, including space and atmospheric sciences, geomagnetism, astronomy, paleoclimatology, biogeochemistry, and human physiology. For example, subglacial lakes that have not been exposed to the atmosphere for 500,000 years may contain a unique archive of the past environment and biota (Karl et al. 1999).

Because of polar amplification of climate change, the ecological impacts of warming are evident earliest and most clearly at high latitudes, providing society with a preview of changes that may become more widespread. In a region of near-pristine wilderness, relationships between ecosystems, species, and environment are more clearly defined than in populated regions where human influences can mask these relationships. In addition, the lure of polar regions for young people wishing to experience wilderness provides a unique opportunity to involve the next generation in working toward a more sustainable future.

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