Woodcut by Aron of Kangeq,
Nuuk, 1860

FREDRIK EHRENSTRÖM
STEFAN LUNDGREN

Off Ilulissat, Greenland

Svalbard

Polar Ecology

The polar bear is hungry. Using her sensitive nose, she searches for a seal. She spots one lying on the ice, and as she creeps closer, her steps become careful. The seal has good hearing, good eyesight, and a good sense of smell. It is ready to dive into the water as soon as it senses danger nearby. So, very stealthily, the polar bear puts one paw in front of the other in the snow until she is only 30 meters from her prey. Her final rush is an explosion of energy, and she pounces on the seal. This time, luck is with her, and she enjoys a good meal of seal blubber, her favorite food. The rest of the seal is left behind when she moves on over the ice, but close behind comes the Arctic fox, like a shadow waiting for its share.

This meal on the ice illustrates two key points in discussing contaminants in the Arctic. Predation is the pathway by which contaminants move from animal to animal in Arctic food webs. Moreover, it is no coincidence that the polar bear is a picky eater when hunting is good, choosing only the blubber and leaving the rest of the seal. Energy is important for survival in cold environments and a preference for fatty foods is one of many adaptations shown by Arctic animals.

This chapter discusses plant and animal life in the Arctic, with a focus on adaptations that can make Arctic ecosystems especially vulnerable to contaminants. It also describes food webs on land, in lakes and rivers, and in the sea, including brief life histories of some species that appear throughout this report.

Faroe Islands

Arctic conditions

A cold climate and long, dark winters have profound effects on the environment in which animals and plants try to survive. In addition, the productive season is short, which means that there is limited time to reproduce and to gather stores of energy. Climatic conditions are most severe in the northern parts of the AMAP region, while some of its southern areas are better described as subarctic or even northern temperate, having fewer of the limitations typical of the polar region.

Low temperatures slow down biological processes

The Arctic is synonymous with cold. The effects of low air temperatures are increased by the fact that, in spring, the sun has to melt snow and ice before it can start to warm the ground.

Most biochemical processes are temperature-dependent, and the rate of biological activity slows down at temperatures below a certain level. Although adapted to a cold climate, many plants and some animals in the Arctic grow more slowly than they would elsewhere. For example, in Davis Strait, the transition from male to female in northern shrimp, which is part of normal development, takes four to five years, in contrast to two to three years in the North Sea. Microbial life in soil and in the waters and bottom sediments of lakes, rivers, and the ocean is similarly restricted by low temperatures, slowing the breakdown of organic material.

This slow degeneration is apparent in well-preserved artifacts from ancient Arctic cultures as well as in the long life of garbage left on the tundra or of oil spills. It also makes the environment slow to recover from physical destruction connected with exploitation of resources, human settlement, and overgrazing.

The ice alga *Melosira arctica* in old ice.

BJØRN GULLIKSEN

The cold creates a lack of nutrients

Reduced microbial activity also limits the rate at which nutrients can cycle in Arctic ecosystems. In cold, continental regions it has been estimated that a 95 percent turn-over of organic matter takes more than 300 years. Carbon thus accumulates in the soil, and many nutrients remain bound and unavailable. The slow degradation processes lead to deficiencies in many key nutrients in both terrestrial and lake ecosystems. Plant growth is often limited by lack of nitrogen and phosphorus, along with the low temperatures.

Low temperatures also limit the chemical weathering of bedrock, a process which supplies nutrient ions to the soil. Slow weathering rates can be compounded by permafrost.

The ecosystems of the marine surface layer are characterized by large variations in nutrient availability, both regionally and seasonally.

A substantial portion of the nutrients available to Arctic ecosystems comes from upwelling of water from water masses of southern origin, inputs from large rivers, and aerial deposition. These pathways tend to carry organic matter, nutrients, and contaminants.

Snow and ice limit available light

Low temperatures also create conditions for extensive ice cover on seas and lakes and for snow cover on land. Even if summer brings 24-hour daylight to the area north of the Arctic Circle, ice and snow limit the amount of light that can reach plants and plankton. As much as half of the total annual input of solar energy arrives before the end of snowmelt, so that much of it is reflected back into space.

Some organisms, such as ice algae, live in crevices in the snow and ice and can quickly take advantage of the light in spring. Other organisms are adapted to low-light conditions under the ice. Generally, however, solar energy has to melt snow and ice before it can be utilized by plants. Therefore, in spite of the long days and midnight sun, the growing season in the Arctic is short. In the High Arctic, snowmelt is usually not completed until the end of June, after the summer solstice, and fresh snow may come in August, leaving a growing season as short as one to two-and-a-half months. In the Low Arctic, the growing season can last three to four months.

For Arctic lakes, the open water period is also short. Lakes might be ice-free for only one to two months, and in cold years, the ice may not disappear at all. In the subarctic, the ice-free season for freshwater ecosystems can be four to six months.

In the marine environment, sea ice and snow on top of the ice also limit energy input. Even before all the ice has melted, however, enough light penetrates to initiate phytoplankton production. The sea ice starts to break up in May and June, and begins to form again in September. In some inlets and straits of the high-latitude regions, ice can remain unbroken for several years and vast areas of the Arctic Ocean are always covered by pack ice, limiting biological productivity. In the subarctic, sea-ice cover varies greatly depending on ocean currents, as described in the chapter *The Arctic*.

Freshwater comes in one short spurt

Most precipitation in the Arctic falls as snow, and most water becomes available during the two-to-three week snowmelt period. The cold air does not allow much moisture to evaporate and permafrost often keeps it from draining into the ground. The water from snowmelt and summer rains therefore creates extensive wetlands on the tundra of the Low Arctic.

In the High Arctic, soils are often thin and can hold little moisture. Snowmelt ends abruptly and small streams often run dry later in the summer. In High Arctic desert areas, lack of water can limit biological productivity.

Glaciers have created an evolutionary frontier

Parts of the polar region have undergone numerous glaciations over the past 1.8 million years. The most recent of these ended only 10000 years ago. Plants and animals, therefore, came to these areas fairly recently, and many of them are opportunistic, invading species adapted to survive under a range of conditions. Many animals can adjust their feeding habits, growth rates, and reproduction in response to variations in climate or food availability.

This recent colonization by plants and animals, together with low ecosystem productivity, can explain the low diversity of species typical of the Arctic. Often, few species are found in a particular area. Even if populations are large, some levels in the food chain may be occupied by only one or two species. Threats to such key species can endanger the ecosystem as a whole.

Even though Arctic ecosystems are young, they are considered to be in equilibrium under current climatic conditions.

Strategies for survival

The harsh living conditions of the Arctic have led to many unique adaptations, some of which make plants and animals especially vulnerable to contaminants in their environment.

Energy is stored in fat

The long winter makes it important for animals to store energy during the productive summer season since this energy might have to sustain them for several months with little food. The most efficient way to store energy is by producing fats, and Arctic organisms have an unusual propensity to produce and accumulate fat.

Such dependence on fats has negative consequences when environmental toxins enter the scene. Many organic toxins, such as pesticides and PCBs, are highly fat-soluble and therefore accumulate in the fat reserves of animals, such as the blubber of seals. When food becomes scarce, these fat reserves are used but the contaminants remain, and their concentrations increase in the remaining fat.

In freshwater systems, spring runoff carries both nutrients and contaminants into streams, ponds, and lakes. In the marine environment, the melting sea ice plays a similar role. Thus, the burst of productivity in the spring, when nutrients and energy are available, can provide an efficient uptake route for contaminants.

Perennial plants save their nutrients

The lack of nutrients in the terrestrial landscape has favored plants that preserve their nutrients from one season to the next. In contrast to the numerous annual species of southern ecosystems, Arctic vegetation consists mostly of perennial plants. Many keep their leaves over winter. Those that do not, withdraw nutrients to their stems and roots before winter comes. This makes it possible for them to begin developing shoots the following spring before the surrounding soil thaws, which is an advantage in a short growing season.

Not shedding leaves can be a disadvantage if a plant is damaged by contaminants or other environmental stresses, such as ultraviolet radiation. Damage in one year will affect growth for years to come, and even a small change can lead to large losses in productivity.

Slow growth gives long life

The short growing season for plants and the paucity of food allows little room for growth each season. It often takes many years before an organism has been able to store enough energy to reproduce. Both plants and animals compensate by having long life spans. A low alpine bush can easily be 50 years old. Many fish caught in the Arctic are much older than fish of the same size caught in warmer regions.

A long life also means that there is ample time to accumulate environmental contaminants. The ability of plants to draw material from the air is especially pronounced in long-lived lichens and in mosses that depend on leaf surfaces rather than roots to take up nutrients. Animals feeding on perennial plants can therefore ingest more contaminants than those eating mostly annual herbs.

For animals, the burden of contaminants stored in the body usually increases with age, unless they have some mechanism to get rid of the chemicals. Older animals are thus likely to have higher levels of persistent organic compounds and some heavy metals. In the food web, this age effect is further pronounced by the fact that prey animals in the Arctic are likely to be older than those in more southern climates.

Environmental fluctuations are the norm

Arctic summers are variable, and plants and animals have had to adapt to large fluctuations in temperature and soil moisture, as well as large seasonal fluctuations in light. In some areas, the snow might not melt at all one year, and there are many lakes that do not become ice-free every summer. The key to survival under these varying conditions is to be able take advantage of favorable times while also being able to survive the years when summer never comes.

One example of such an adaptation is that plants often reproduce vegetatively, by creating clones rather than only producing seeds. A mat of low brush can thus be one single plant. In such cases, genetic variation is low, making the plants potentially more vulnerable to new stresses.

Generally, adaptations to a harsh and unpredictable environment are an advantage. Most plants and animals have a certain tolerance range and can probably accommodate moderate changes in climate.

The fluctuating conditions of the Arctic affect the number of animals in certain years, as exemplified by the rise and fall of lemming populations. Their fecundity is also mirrored in the sizes of the populations of birds and mammals that feed on lemmings. Another example is the severe crash of a population of muskox in Canada after a winter when the ground was covered by ice for a long period, leaving the animals without access to their normal forage. However, enough animals survived to produce a new, viable herd.

The dynamics of such extreme fluctuations are poorly understood. An optimistic interpretation is that populations can recover, even when few animals remain. However, if there are other environmental stresses, such as toxins that affect reproductive capacity, the population might be even more vulnerable during years with few animals.

In the past, overharvesting and habitat destruction have reduced populations of many large Arctic mammals. In some cases, the remaining populations are small, and stressors that affect their reproduction could threaten their survival.

Animal life is concentrated in rich areas

The general lack of nutrients in the Arctic environment leads to an accumulation of plants and animals in areas where food is readily available. One example is high plankton productivity at the ice edge, which supports large populations of animals, especially sea birds. Another example is the gathering of sea mammals and birds at open patches of water, called polynyas, within the pack ice. If contaminants enter these hot spots of biological productivity, they will efficiently enter the food web. Moreover, because populations are often sparse elsewhere, a high proportion of Arctic animals will be affected.

The patchy availability of food has also made migration an important strategy for Arctic animals. Many birds move north only to breed during the most productive season, returning south before winter arrives. Some mammals and fish shift feeding grounds within the Arctic in response to changing ice and snow conditions. Contaminants or destruction of the physical environment along any parts of their migration routes are therefore of concern in an assessment of the Arctic.

Life on land

The Arctic terrestrial landscape can be divided into two biogeographical zones, each with its own typical vegetation: the High Arctic, which roughly corresponds to the polar desert, and the Low Arctic, which corresponds to the tundra. The tundra gradually turns into the subarctic zone, with richer vegetation and wildlife.

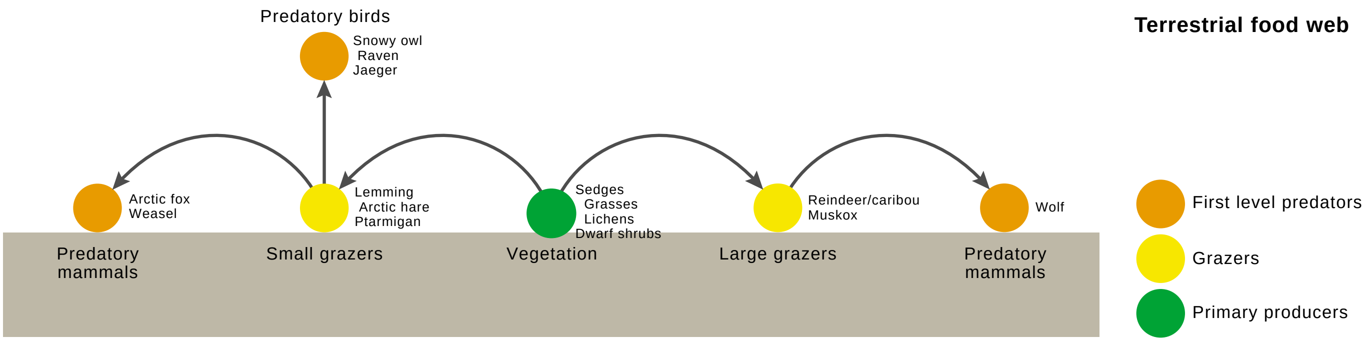
Low Arctic and subarctic vegetation zones.

The boreal forest also extends into the AMAP region. The map above shows the different zones. In mountainous landscapes, the vegetation zones are similar but depend on altitude rather than latitude.

The High Arctic is a desert

The High Arctic growing season lasts for only one to two-and-a-half months. Mean July air temperatures range from 4 to 8°C. Large parts of the ground do not support any vegetation at all. The cold leads to a lack of weathering of

Terrestrial food web



Examples of organisms at different levels in terrestrial food webs in the AMAP area.

Common English name	Latin name
Plants	
Lichen	
Mosses	
Sedges	
Grasses	
Cushion and rosette plants	
Labrador tea	*Ledum* spp.
Lingonberry (Lowbush cranberry)	*Vaccinium vitis-idaea*
Cranberry (Bog cranberry)	*Vaccinium* spp. *(e.g V. oxycoccus)*
High-bush cranberry	*Viburnum edule*
Cloudberry (Salmonberry)	*Rubus* spp.
Blueberry	*Vaccinium* spp.
Eskimo potato (Indian potato, masu)	*Hedysarum alpinum*
Dock (Sorrel)	*Rumex arcticum*
Willow	*Salix* spp.
Aspen	*Populus tremula*
Birch	*Betula* spp.
Firs	*Abies* spp.
Spruces	*Picea* spp.
Pines	*Pinus* spp.
Animals feeding on plants	
Caribou, reindeer	*Rangifer tarandus*
Moose (Elk)	*Alces alces*
Kolyma moose	*Alces americanus*
Muskox	*Ovibos moschatus*
Dall sheep (Bighorn sheep)	*Ovis dalli (O. canadensis)*
Snow sheep	*Ovis nivicola*
Bison	*Bison bison*
Siberian ibex	*Capra ibex sibirica*
Black bear	*Ursus americanus*
Hares	*Lepus* spp.
Parka squirrel (Arctic ground squirrel)	*Citellus parryii*
Red squirrel	*Sciurus vulgaris*
Ptarmigan	*Lagopus* spp.
Spruce hen (Spruce grouse)	*Canachites canadensis*
Ruffed grouse	*Bonasa umbellus*
Sharp-tailed grouse	*Pedioecetes phasianellus*
Voles	*Microtus* spp.
Lemmings	*Dicrostonyx groenlandicus, Lemmus sibericus*
Lapland bunting and snow bunting	*Calcarius lapponicus, Plectrophenax nivalis*
Common redpoll and Arctic redpoll	*Carduelis flammea, C. hornemanni*
First-level predators	
Wolf	*Canis lupus*
Arctic fox	*Alopex lagopus*
Red fox	*Vulpes vulpes*
Wolverine	*Gulo gulo*
Lynx	*Lynx canadensis*
Brown bear	*Ursus arctos*
Stoat (Ermine)	*Mustela erminea*
Least weasel	*Mustela nivalis*
Marten	*Martes americana*
Snowy owl	*Nyctea scandiaca*
Raven	*Corvus corax*
Rough-legged hawk (Rough-legged buzzard)	*Buteo lagopus*
Golden eagle	*Aquila chrysaetos*
Gyrfalcon	*Falco rusticolus*


KNUT BRY


STAFFAN WIDSTRAND


STAFFAN WIDSTRAND


HENRY HUNTINGTON

the rock, and there is not much soil. Water comes in one short spurt during the snowmelt. These factors, combined with the lack of soil that would have been able to retain some of the moisture, make conditions for colonizing plants very harsh.

Lichens and mosses are the most prominent colonizers. Arctic vegetation also includes tightly growing cushion plants and willow shrubs that hunch close to the ground. Sedges and grasses are also typical. Meadow communities cover about 40 percent of the land area in the southern part of the High Arctic. In the far north, meadows appear only in scattered Arctic oases amid the polar desert, covering as little as 2 percent of the area.

Prominent grazers of the High Arctic are muskox and Peary caribou in North America and some subspecies of reindeer in Eurasia. These large herbivores are protected from the cold Arctic winter by thick insulating fur. They graze intensively during the brief summer to store up fat reserves for the winter, when only poor-quality forage is found on windswept slopes or by digging through the snow.

Smaller mammals include the Arctic hare, which is adapted to the cold Arctic environment, but seeks protection in snow dens or natural shelters in extreme weather. Some invertebrates, such as the widespread mites and spiders, also survive the harsh conditions.

A few true terrestrial birds, such as the rock ptarmigan, thrive year-round, even in the High Arctic zone. Most birds, however, only come north for the summer. About 20 species nest in the High Arctic. They include migratory waterfowl such as geese and ducks, and smaller seed-eaters, such as buntings and redpolls. Predatory birds, such as snowy owls and ravens, hunt small mammals and young birds. Thick plumage and subcutaneous fat protects these High Arctic birds from the cold.

Wolves are the major predator of caribou and muskox. The Arctic fox also makes its home in the High Arctic. It is an opportunistic feeder, hunting small mammals and birds, or feasting on prey left behind by wolves and bears. Foxes living near the sea often follow polar bears to scavenge seal kills, thus becoming part of the marine food web.

The Low Arctic is a region of rich tundra

The Low Arctic or tundra region supports a much richer biological system than the High Arctic. The growing season is longer, three to four months, and the mean July air temperature ranges from 4 to 11°C.

Permafrost governs life on the tundra. The roots of plants are restricted to the shallow active layer that thaws in the summer, keeping trees from growing well.

Mosses, lichens, cushion plants, sedges, and grasses dominate the vegetation, along with heath shrubs such as dwarf willow and birch. Plants cover most of the ground and alter the microclimate at the ground surface. If the vegetation is damaged, conditions might change enough to make it difficult for the same plants to grow back. A scar in the landscape easily becomes permanent.

Permafrost restricts water drainage, so that extensive areas become waterlogged during snowmelt and when it rains. The amount of water in the ground has a profound effect on tundra plant life. In waterlogged areas, the decomposition of plant matter is very slow, which leads to an accumulation of dead plant matter and the build-up of peat.

Many animals, but short food chains

The Low-Arctic tundra vegetation is rich enough to support a number of mammals and birds. Large grazers include caribou/reindeer and muskox.

Small herbivorous mammals are also abundant on the tundra, of which the lemming is known best. Lemmings and voles seek shelter under the snow during the Arctic winters, keeping themselves protected from the cold, and gaining access to grass and other food on the ground surface.

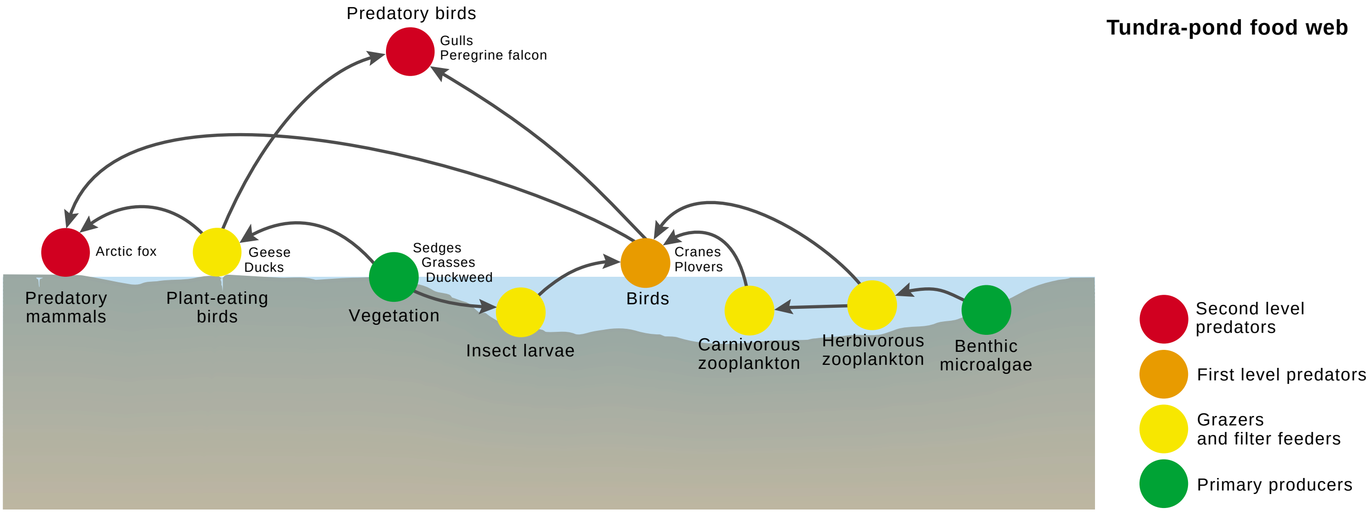
Insect life is more abundant in the Low Arctic than in the High Arctic, and warm tundra areas can support beetles, moths, butterflies, and bumblebees as well as parasitic warble flies that lay their eggs under the skin of caribou and reindeer. Visitors to the Arctic are all too familiar with the sometimes dense populations of biting flies and mosquitoes.

A number of birds take advantage of the productive tundra. A few stay year-round, such as the Lapland bunting, snow buntings, and redpolls. They survive by maintaining high metabolic rates and by eating continuously. Two species of ptarmigan, rock and willow, are well adapted to their year-round stay on the tundra. During the winter, their feathers, which also cover their feet, are white, and the birds blend extremely well into the landscape. They eat buds, leaves, berries and the stems of shrubs and trees.

The predators of the Low Arctic, representing the upper levels of the tundra food web, include mammals and birds of prey. The most important terrestrial predatory animals are the wolf and the wolverine, which prey on small mammals, birds, and caribou/reindeer. Arctic fox hunt small mammals and birds. They also scavenge kills made by wolves and bears. People are also top predators in the food chain involving reindeer/caribou. Brown and black bears feed mainly on plants, but also eat fish, small mammals, and birds.

Arctic birds of prey include a few year-round dwellers, the snowy owl, the raven, and the gyrfalcon. The migratory predators include the long-tailed jaeger and the peregrine falcon. The peregrine falcon feeds mostly on migra-

Tundra-pond food web

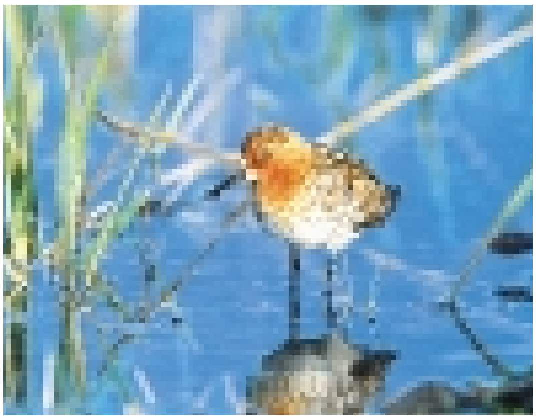


Exampes of organisms at different levels in wetland/tundra pond food webs in the AMAP area.

Common English name	Latin name
Plants/primary producers	
Sedges	
Grasses	
Duckweed	
Horsetail	
Water smartweed	
Mosses	
Birds and mammals feeding mainly on plants	
Whistling swan	*Olor buccinator*
Canada goose	*Branta canadensis*
White-fronted goose	*Anser albifrons*
Snow goose	*Chen caerulescens*
Brant	*Branta bernicla*
Ducks	*Somateria* spp., *Anas* spp., *Bucephalus* spp.
Muskrat	*Ondatra zibethica*
Decomposers and grazing zooplankton	
Chironomids (midge larvae)	
Daphnia	
Fairy shrimp	
Zooplankton feeding on other zooplankton	
Copepods	*Cyclops* spp., *Heterocope* spp.
Birds feeding mainly on benthic invertabrates, insects, zooplankton	
Plovers	*Eufromias morinellus, Pluvialis dominica, Squatarola squatarola, Charadrius semipalmatus*
Cranes	*Grus* spp.
Long-tailed duck (Oldsquaw)	*Clangula hyemalis*
Spoon-billed sandpiper	*Eurynorhynchus pygmeus*
Predators and scavanagers	
Peregrine falcon	*Falco peregrinus*
Gyrfalcon	*Falco rusticolus*
Herring gulls	*Larus argentatus*
Arctic fox	*Alopex lagopus*
Lesser weasel	*Mustela nivalis*

STAFFAN WIDSTRAND

STAFFAN WIDSTRAND



STAFFAN WIDSTRAND

MINEK ROSING

tory waterfowl, which can accumulate contaminants in their overwintering areas, and is therefore highly exposed to persistent contaminants. There are also Arctic populations of several eagle and hawk species.

In spite of the apparent abundance of tundra wildlife, the number of forage species can be low and the food chains short. Thus, if one or two foods are lacking in a given summer, replacements may be scarce, making it difficult to obtain the energy needed to raise young. For example, fluctuations in the populations of lemmings can severely limit the number of owls and jaegers.

Wetlands are typical of the tundra

Wetlands cover vast areas of the Arctic tundra, about 1.5 million square kilometers north of 60° N. Permafrost hinders drainage, and the resulting waterlogged conditions, along with cold ground temperatures, limit decomposition and productivity. In many wetlands, dead plant matter and animal waste accumulate, and leached humic acids color the water brown. The large amounts of organic material in the wetlands are important for the fate of organic compounds and metals, whether they be natural or anthropogenic, as they dissolve poorly in water and instead bind to organic matter.

The amount of water in the ground influences what will grow in a particular wetland. The dominant plant species will in turn have a great effect on the rest of the ecology. There are five basic types of wetland: bogs, fens, swamps, marshes, and shallow open water, of which bogs and fens are the most common in the Arctic.

Bogs usually have a surface carpet of mosses, mainly *Sphagnum*. The wet and acid peat that builds up due to poor decomposition of *Sphagnum* also supports sedges and, in the subarctic, trees.

Fens, in the subarctic or southern Arctic, are covered by sedges and sometimes by grasses and reeds, *Sphagnum* is unimportant or even absent. There is often a low to medium shrub cover together with sparse trees.

In swamps, the ground is saturated with water and is periodically flooded. Herbs and mosses cover the ground along with woody plants (coniferous and deciduous shrubs and sometimes trees). Peat does not build up in a swamp.

Marshes develop on wet but non-peaty soils. There are emergent non-woody plants such as rushes, reeds, reed grasses, and sedges. Open water can be overgrown by submerged and floating aquatic plants, while trees and shrubs form the border of the marshes.

Shallow open waters, such as small ponds and sloughs within bogs, fens, and marshes are usually less than 2 meters deep without much vegetation.

Summer growth supports migratory birds

The wetlands are covered by ice and snow for most of the year, but are not devoid of life. Once the growing season starts, many shallow lakes are rapidly overgrown by horsetail, water smartweed, duckweed, and pondweed. Somewhat dryer areas support mosses, cotton grass, and lichen.

The rich vegetation attracts an immense number of migratory birds. Waterfowl, geese, ducks, swans, and gulls arrive soon after snowmelt. Many arrive with fat reserves for breeding and thus their contaminant levels

Caribou

STAFFAN WIDSTRAND

Reindeer

KNUT BRY

Caribou/reindeer

Caribou and reindeer are the North American and Eurasian representatives of the same species. There are several different subspecies. The Peary caribou, which makes its home in the Canadian High Arctic, is smaller than the barren-ground caribou that roams the Low Arctic tundra of North America.

The wild reindeer of the European mainland can be divided into several subspecies. The Svalbard reindeer inhabits the High Arctic environments of the Svalbard archipelago and another subspecies occupies a similar environment on Novaya Zemlya. A few herds of wild forest reindeer live on the Kola Peninsula and south of the Arctic in Finland. The wild Scandinavian mountain reindeer still exists in southern Norway and as a small population in the Murmansk region of Russia, both of which interbreed with domesticated reindeer. There is also a herd of wild Scandinavian mountain reindeer in Iceland.

Herding of domesticated or semidomesticated populations of reindeer is important throughout the Saami region and in most of northern Russia. A few herds of domesticated reindeer have also been introduced into Alaska and Greenland.

Most caribou and reindeer migrate between summer and winter range lands, from the tundra or mountains to the forest, or from the coast to further inland. The summer diet consists mainly of grasses while the animals depend on lichen and mosses during the winter. Domesticated reindeer are sometimes fed hay to supplement their natural diet.

largely reflect uptake in overwintering areas; see the box to the right. They stay in the Arctic only long enough to mate, hatch their eggs, and molt before they start their gradual migration south. Some of the birds are herbivorous, while others depend heavily on mosquitoes and midge larvae during the brooding period. Bird life is richest on wooded mire margins and on the wettest tundra, but poor in treeless areas without open water.

Muskrats also feed on aquatic vegetation and are found as far north as 72°N in Russia. Small wetland areas within boreal forests have wildlife similar to the surrounding boreal forest.

The top trophic level in wetland food webs includes predatory birds and foxes, which feed on eggs and young birds.

Tundra ponds are small and acidic

Tundra ponds are small, about 30 to 40 meters across, and less than half a meter deep. Water flow within the lake is minimal as the surrounding ground is saturated with water. The ponds do not dry up, in spite of low rainfall. In winter, the water and bottom sediments freeze completely. The water is naturally acidic from the surrounding ground.

The short ice-free season limits productivity in the ponds even if daily productivity during the growing season is quite high. Sedges and grasses are the dominant primary producers. Grazing food chains are of lesser importance in tundra ponds, while life thrives in the bottom sediments. Bacteria and fungi feed on the roots and leaves of the plants, and in turn serve as food for midge larvae.

There are also benthic diatoms and blue-green algae that serve as food for grazing zooplankton. These herbivores are in turn preyed on by other zooplankton. By different behavioral and physiological adaptations, the zooplankton can tolerate the complete freezing of a lake. For example, the eggs of some zooplankton can tolerate a long period of frost before they hatch in spring.

Birds form the upper levels of the food web. There are no fish in these shallow ponds.

Warmer climate can support forests

As one moves southward away from permafrost, or downhill in a mountainous area, trees appear in the landscape. In the subarctic, stands of black spruce are common in North America, while Scots and stone pine are typical of Eurasia. The trees closest to the treeline or the edge of the tundra are likely to be low and stunted. As temperature and snow conditions grow more favorable, treeline vegetation is gradually replaced by the typical boreal forest of spruce, pine, and fir. Under the single-layer canopy, dwarf shrubs of heather occupy the ground, along with crowberry, mosses, and lichens. Deciduous trees, such as birch, aspen, and alder, thrive in warmer, more oceanic climates. The scattered trees in these areas let through enough light to support an understory vegetation that is made up, depending on the amount of soil moisture, of lichens, mosses, low brush, grass, herbs, and willows.

Subarctic and boreal forest ecosystems have a longer growing season that can support rich wildlife. In addition to the reindeer/caribou that migrate into the forest for winter, plant eaters include rodents, hares, squirrels, moose, muskrat, and numerous bird species. Predators include foxes, martens, minks, wolves, wolverines, and lynx. The food webs in the forest ecosystem are often more complex than on the tundra.

Many Arctic dwellers depend on subarctic regions for part of the year, and this environment is an integrated part of their yearly life cycle. For example, the forest provides winter habitat for migrating reindeer. People living on the tundra often use the forest for protection in wintertime and for access to firewood and fur-bearing animals.

Migratory birds

Many birds spend only part of the year in the Arctic. During the winter, they migrate south to less hostile climates and better supplies of food. The map shows some of the major migratory routes. Their overwintering areas are often much more contaminated than the Arctic, which has two important consequences.

First, the body burden of contaminants in a migratory animal will not reflect the environment of one particular area. For example, high levels in bird eggs probably say more about overwintering habitat, where the birds build up their reserves, than about the conditions around Arctic nesting sites. Many overwintering sites are extremely polluted, including sewage lagoons, garbage dumps, and bodies of water that receive agricultural and industrial runoff.

Second, migratory animals bring contaminants to the Arctic, carrying them in their bodies. The further fate of these substances will depend on what happens to the birds, their eggs, or the young chicks that hatch from contaminated eggs. If they are preyed upon or scavenged in the Arctic, southern environmental toxins will enter the Arctic food webs.

Lakes and streams

The lakes in the AMAP region range from typical temperate lakes in boreal and subarctic regions to High-Arctic lakes that are ice-covered for most of the year. The typical temperate lowland and coastal lakes have a long ice-free season, become warm in the summer, and can thus be highly productive with complex food webs. In contrast, High-Arctic lakes are extremely poor in nutrients and often have very few species in simple food webs.

Freeze–thaw cycle governs lake environments

Lake ecology is dominated by ice-cover and the timing of the spring melt. In the High Arctic, water temperatures rarely exceed a few degrees Celsius. Surface water in Low-Arctic lakes may reach 15 to 25°C, but the heat quickly dissipates in fall when high winds mix the water.

Lakes freeze over when the temperature of surface water drops to 0°C, and the ice thickens continuously until early May. Depending on latitude, snow cover, and the severity of the winter, ice thickness typically ranges from one to three meters.

When ice forms, it efficiently excludes dissolved gases and chemicals, leaving the ice 95 to 98 percent purer than the water from which it was formed, and clean enough to be used as distilled water. The remaining lake water consequently becomes enriched with oxygen as well as with contaminants that are present.

In May and June, the ice melts, both from the top and from the bottom. The ice crystals disintegrate and even if the ice is a meter thick, it can be treacherous to walk on. The melt water floats on top of the rest of the lake water and usually flows out of the lake before it mixes with the deeper water.

Productivity in Arctic lakes is limited by low temperatures and also by the lack of light and nutrients. Most of the nutrients come in one short spurt during snowmelt. During winter, there is no photosynthesis and no mixing of the water, and the resulting lack of oxygen can become critical for aquatic animals. If the oxygen concentration drops too far, fish in the lake will die. Most such winter kills occur in shallow lakes.


HARALD WELCH

Arctic char

The Arctic char is the northernmost freshwater fish in the world and occurs throughout the Arctic. Some populations have been locked into lakes where they feed on midge larvae and grow very slowly. A few individuals grow larger, probably because they are cannibalistic. Many stocks of Arctic char migrate to the sea in summer, where they have a larger resource base to exploit and thus are able to grow faster. While at sea, they feed on crustaceans and small fish. Before winter, these migrants return to rivers and lakes to avoid the low winter temperatures in the ocean. In extreme conditions, they hardly feed at all during the winter. Despite these regional and behavioral variations, all Arctic char belong to the same species.

Food webs carry nutrients from algae to fish and birds

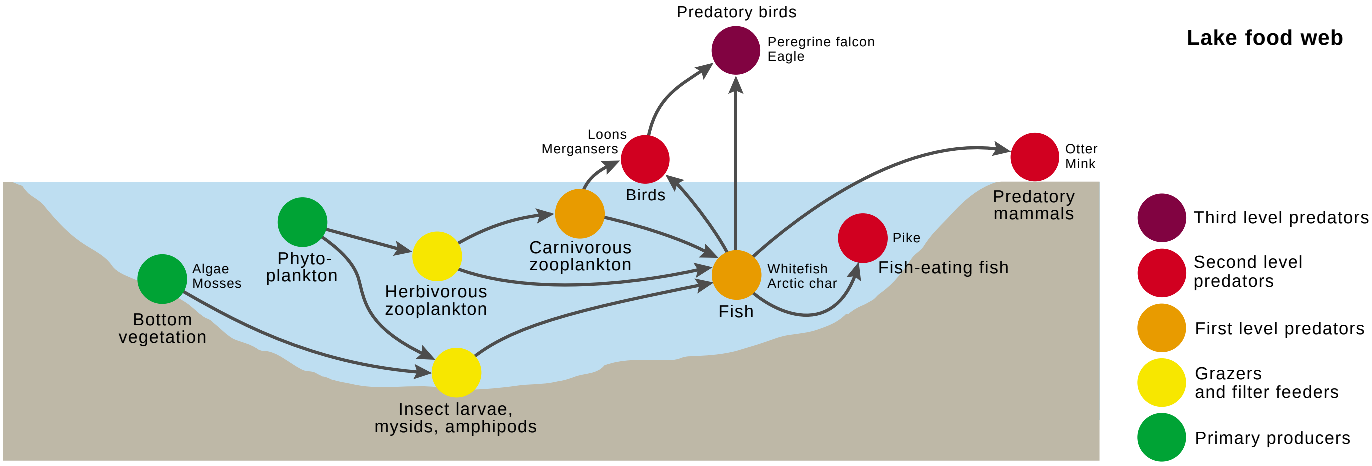
Lake food webs are based on the photosynthesis carried out by free-floating and bottom-dwelling algae. Small single-celled algae predominate. Their activity depends on the amount of light. In lakes where winds sweep away most of the snow from the ice surface, some light is able to penetrate, and photosynthesis can start under the ice from April to June. In some clear lakes, mosses and benthic algae cover the bottom sediments and add to primary productivity.

The algae serve as food for zooplankton, such as copepods and rotifers. The number of species is low and in some Arctic lakes, zooplankton are completely lacking. Their growth rates depend on temperature. In general, the biomass is comparable to winter levels in temperate lakes. In the southern area of the AMAP region, including Iceland, northern mainland Fennoscandia and Russia, both the diversity of species and the total number of zooplankton increase drastically. In the subarctic region, crustaceans play a major role in lake ecology, serving as food for many fish species.

In some lakes, benthic food webs, i.e. those on the lake bottom, are more important than those in the water column. Plankton that fall to the bottom, decaying organic matter, and bacteria support many insect larvae. Midge larvae are the most abundant. In several High-Arctic lakes, midge larvae are the only food source for Arctic char. In addition to fish, the third level in the aquatic food web includes insect-eating birds, which link the aquatic and terrestrial food webs.

Fish populations have wide regional variations, depending on immigration opportunities after the last glaciation. Coastal and high mountain lakes of Iceland, the Faroe Islands, northwest Scandinavia, and the Kola Peninsula have been cut off from other freshwater ecosystems and normally host only three to five species. Atlantic salmon, stickleback, brown trout, and Arctic char are the most common. In Greenland, three-spined stickleback occurs in many lakes, and open lake-river systems often have a mixture of sea-run and lake-bound char.

In the lowland tundra and in the forest and wetland areas of Fennoscandia, the Kola Peninsula, and western Russia, rivers and lakes connect to more southern regions, and the fish fauna is richer and the food webs more complex. Freshwater ecosystems in the western part of this region have up to 10 species, increasing to 20 in the region of the large



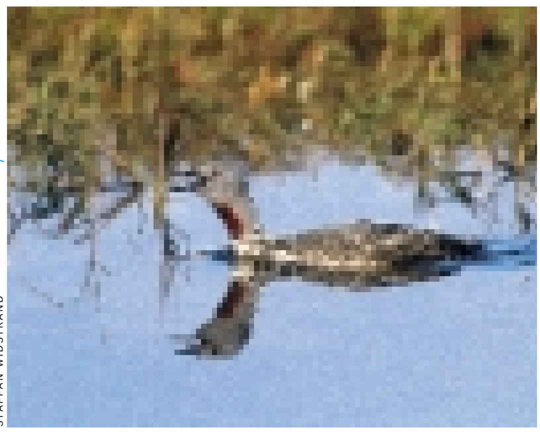
Exampes of organisms at different levels in lake food webs in the AMAP area.

Common English name	Latin name
Primary producers	
Chrysophytes (golden algae)	
Cryptophyta	
Diatoms	
Dinoflagellates	
Green algae	
Bluegreen algae	
Mosses	
Grazing zooplankton	
Rotifers (wheel animacules)	
Cladocerans (water fleas)	
Copepods	
Predatory zooplankton	
Copepods	
Bottom-dwelling invertebrates feeding mostly on plant matter and detritus	
Chironomids (midge larvae)	
Cladocerans (water fleas)	
Chydorids	
Ostracods (musselshrimps)	
Oligochaetes (ringed worms)	
Amphipods (sandhoppers)	
Copepods	
Nematodes (roundworms)	
Fish feeding mainly on plankton or insect larvae	
Brown trout	*Salmo trutta*
Arctic char	*Salvelinus alpinus*
Whitefish	*Coregonus* spp.
Cisco	*Coregonus* spp.
Grayling	*Thymallus* spp.
Lake trout (Lake char)	*Salvelinus namaycush*
Fish, mammals and birds feeding mainly on fish	
Burbot (Lingcod, Loche)	*Lota lota*
Northern pike	*Esox lucius*
Lake trout (larger individuals)	*Salvelinus namaycush*
Otter, Eurasian otter	*Lutra lutra*
European mink	*Mustela lutreola*
American mink	*Mustela vison*
Arctic tern	*Sterna paradisaea*
Loons	*Gavia* spp.
Mergansers (diving ducks)	*Mergus* spp.
Bald eagle	*Haliaeetus leucocephalus*
Osprey	*Pandion haliatus*

FREDRIK EHRENSTRÖM


BJØRN OLAV ROSSELAND


FREDRIK EHRENSTRøM


STAFFAN WIDSTRAND


Pechora River in Russia. Different species of whitefish dominate, but perch, pike, and burbot are also important.

In North America, there is a similar increase in the number of species as one moves from north to south. Arctic char is the main High-Arctic fish species, whereas trout, stickleback, and grayling appear farther south. In the western and Low Arctic, the fauna is as diverse as in the Russian rivers.

Most fish feed on benthic invertebrates and surface insects, and pike is the only species that feeds strictly on other fish.

Fish fall prey to birds, such as white-tailed sea eagle, bald eagle, osprey, and loons, and to fish-eating mammals such as mink, bears, and otters. Freshwater fish, especially Arctic char, are an important food source for people.

Streams are unstable environments

Most streams in the High Arctic are short and fed by glaciers. They freeze or dry up during the winter. Almost all the water comes during snowmelt, scouring the bottom with its violent flow. These extreme fluctuations make the stream environment very unstable. Unless plants and animals maintain their hold against the turbulent runoff, the streams are stripped of life during the spring melt. Deeper streams support larvae of midges and gnats, which feed on diatoms and organic material in the bottom sediment. The deeper glacier-fed streams are also important spawning sites for Arctic char.

Spring-fed streams have a more even flow over the seasons. Mosses are abundant along the banks, while sun-nourished diatoms form a film on the bottom. The bottom sediment supports many insect larvae, which are food for Arctic char and insect-eating birds.

In the southern area of the AMAP region, diversity in river ecosystems increases. In Fennoscandia, streams fed by glaciers and melting snow often grow into large rivers extending more than 200 kilometers and connecting to extensive lake systems. Where the current slows, there are often rich bottom-dwelling communities of plants and animals.

The flat landscape of the Russian tundra is crossed by several large rivers, some of which have vast flood plains. Constant erosion and build-up of new material along the river bed limit plant and animal life in the lower reaches of the rivers. Even the deltas can only support a poor fauna of zooplankton. However, the upper reaches of the rivers feature 15 to 20 different species of fish, including omul and Atlantic salmon. Many of the rivers freeze solid during the winter, even if they become warm in the summer. The water is often acidic and rich in organic material from the surrounding landscape.

In Iceland, the rivers are similar to other Arctic areas, but with a poor fauna because of their geographic isolation.

Life in the ocean

The Arctic Ocean and its surrounding seas are unique marine ecosystems because of the cold, the extreme variation in light conditions, and extensive ice cover. Melting and freezing of ice create rich habitats close to the sunlit surface. The wide continental shelves provide large shallow areas, where freshwater from north-flowing rivers creates estuarine conditions. Life in the ocean occupies three major environments: ice, open water, and bottom sediments.

The pack ice has a unique food web

The central Arctic Ocean is covered by constantly moving multi-year ice. It is a cold environment in which little sunlight reaches the water. In spite of these limiting conditions, the pack ice is not devoid of life. In fact, recent measurements show a productivity that is much higher than most people thought only a few years ago. Plants and animals which live in the ice are referred to as epontic.

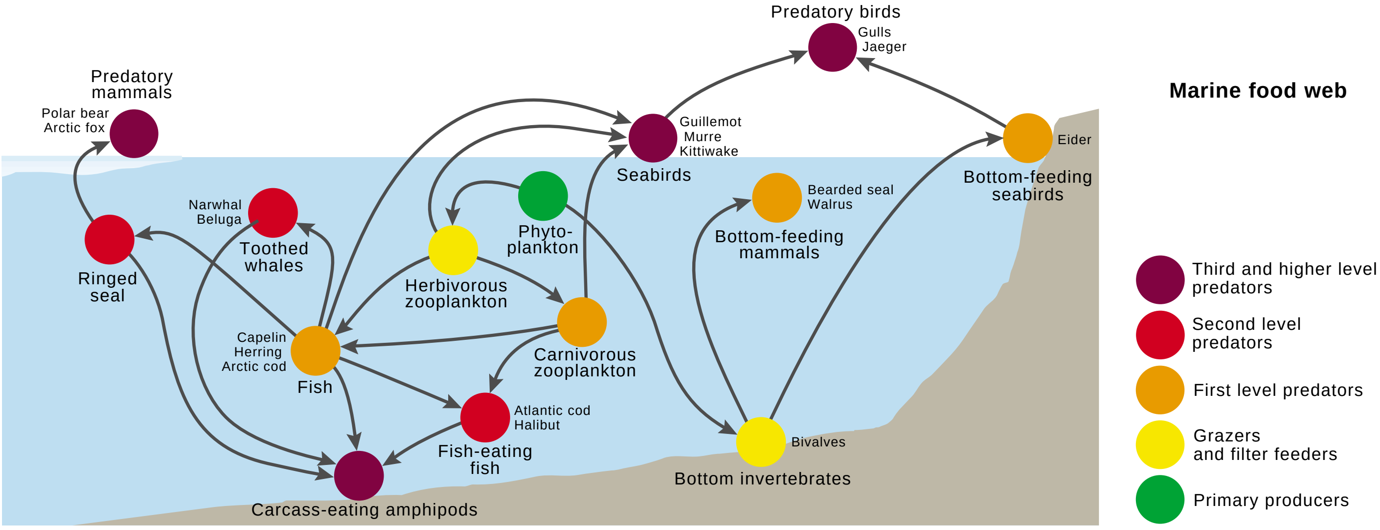
Among the epontic life forms are colony-building diatoms and blue-green algae that utilize the scant light that penetrates the ice. They can support a few species of zooplankton. Most numerous are small crustaceans. Some zooplankton species rise from the bottom sediments to reproduce. The young zooplankton feed and store lipids during summer before they descend several hundred meters to the bottom sediments, where they overwinter in an inactive stage.

The algae-grazing zooplankton serve as food for predatory plankton and for Arctic cod, one of the few species of fish that survives in the conditions of the polar basin.

Away from the Arctic continental shelves, most plankton primary production is consumed by animals in the water column. Therefore, the benthic ecosystem tends to be low in biomass and has only a few species. On the continental shelves, however, a high proportion of plankton productivity is consumed by bottom-dwelling animals. An important point is that Arctic marine ecosystems tend to continuously re-use organic carbon. Therefore, contaminants that are strongly associated with organic matter also re-circulate. Consequently, bottom-dwelling animals that scavenge the remains of surface animals often carry appreciable loads of such contaminants.

Life is most abundant along the ice edge

The richest marine areas in the Arctic occur at the edge of the ice and in the shelf seas, where the interaction of water currents and ice creates ideal conditions for high productivity. Some of the shelf seas are among the most productive ecosystems in the world, providing food for immense populations of migratory birds as well as an economic base for several large fishing fleets.



Exampes of organisms at different levels in marine food webs in the AMAP area.

Common English name	Latin name
Primary producers	
Diatoms in the ice	*Nitzschia frigida, Melosira arctica*
Diatoms in the water mass	
Prymnesiophytes	*Phaeocystis pouchetii*
Ice fauna and grazing zooplankton	
Amphipods	
Copepods	*Calanus spp.*
Small krill	
Zooplankton feeding mostly on other zooplankton	
Larger krill	
'Gelatinous' plankton, including jellyfish and hydras	
Animals feeding mainly on zooplankton or filter feeders	
Capelin	*Mallotus villosus*
Herring	*Clupea spp.*
Arctic cod (Polar cod)	*Boreogadus saida*
Redfish	*Sebastes spp.*
Sculpin	*Myoxocephalus spp.*
Little Auk (Auklet, Dovekie)	*Alle alle*
Great shearwater	*Puffinus gravis*
Eider	*Somateria spp.*
Bowhead whale (Greenland right whale)	*Balaena mysticetus*
Humpback whale	*Megaptera novaeangliae*
Bearded seal	*Erignathus barbatus*
Walrus	*Odobenus rosmarus*
Animals feeding mainly on fish and other predators	
Cod	*Gadus spp.*
Atlantic halibut	*Hippoglossus hippoglossus*
Long rough dab (American plaice)	*Hippoglossoides platesoides*
Greenland halibut	*Reinhardtius hippoglossoides*
Salmon (Pacific)	*Onchorynchus spp.*
Salmon (Atlantic)	*Salmo salar*
Black guillemot (Tystie)	*Cepphus grylle*
Thick-billed murre (Brünnich's guillemot)	*Uria lomvia*
Common murre (Atlantic guillemot)	*Uria aalge*
Atlantic puffin	*Fratercula arctica*
Northern fulmar	*Fulmaris glacialis*
Black-legged kittiwake	*Rissa tridactyla*
Beluga (White whale)	*Delphinapterus leucas*
Narwhal	*Monodon monoceros*
Ringed seal	*Phoca hispida*
Harbor seal (Common seal)	*Phoca vitulina*
Fur seal	*Callorhinus ursinsus*
Harp seal	*Phoca groenlandica*
Gray seal (Ranger seal)	*Halichoerus grypus*
Hooded seal	*Cystophora cristata*
Third-level predators	
Arctic fox	*Alopex lagopus*
Polar bear	*Ursus maritimus*
Glaucous gull	*Larus hyperboreus*
Herring gull	*Larus argentatus*
Jaegers	*Stercorarius spp.*
Bottom-dwelling animals (predators and filter feeders)	
Cnidarians, including sea anemones	
Crustaceans, including Northern shrimp	*Pandalus borealis*
Molluscs, including mussels and clams	
Echinoderms (e.g. sea stars, sea cucumbers, and sea urchins)	

STAFFAN WIDSTRAND

STAFFAN WIDSTRAND

FREDRIK EHRENSTRÖM

This high productivity is a result of the seasonal cycle of growing and melting sea ice, which allows nutrient-rich water to reach the sunlit surface of the ocean. In the spring, fresh meltwater from the ice forms a stable lens on top of more saline ocean water, keeping the phytoplankton in this lens near the surface where there is plenty of light. Algae that overwinter in crevices in the sea ice make effective use of the returning light in spring. In many areas, the food web connected to the ice-edge bloom follows the retreat of the ice margin as it moves northward during summer.

Contaminants enter the biota

The processes by which persistent contaminants enter and remain in plants and animals and their food webs can be summarized by three terms: bioconcentration, bioaccumulation, and biomagnification.

Bioconcentration refers to the process by which plants and animals take up contaminants directly from air, water, or soil. The uptake is determined by the chemical and physical characteristics of the contaminant. For example, many organic compounds dissolve well in lipids and will preferentially end up in the lipid components of the biota. Water-soluble contaminants can enter aquatic organisms through the gills or membranes in the gut.

Bioaccumulation is a broader term. It includes bioconcentration as well as the uptake of contaminants from the food an animal eats. The body burden due to bioaccumulation will thus depend on contaminant concentrations in air, water, and soil, as well as in the animal's diet. The body burden will also depend on an organism's ability to rid itself of contaminants. Some compounds will be excreted or broken down into less toxic components, while others will accumulate.

Biomagnification occurs when a contaminant is not broken down or excreted, but accumulates as it passes up the food web. Biomagnification is the major reason that persistent environmental contaminants reach high concentrations in top predators even when levels in air, soil, and water are low. The Arctic marine environment has long food chains compared with many ecosystems, making it especially vulnerable to biomagnification. The role of fat in the diet of many Arctic animals further promotes biomagnification of lipid-soluble organic contaminants.

The melting ice itself may act as a vehicle for contaminants. These can be incorporated into the ice along with sediments at the mouth of a polluted river or be deposited directly on the ice surface from the air. These contaminants can then be carried over long distances as the ice makes its trans-polar voyage. They may be released in highly productive areas when the ice melts in spring and summer, just when plants and animals enter their peak growth period.

In the Bering and Chukchi Seas, most of the nutrients come from the cold Pacific water flowing north through the Bering Strait. Upwelling of nutrient-rich bottom water, such as in Lancaster Sound, can also create favorable conditions for photosynthesizing plankton.

Zooplankton and fish provide links from algae to mammals

Zooplankton, the grazers of the sea, take immediate advantage of the productivity of marine plant life. They become a rich food source for various crustaceans, such as krill and prawns. These, in turn, serve as food for fish, some seabirds, and baleen whales.

Important fish species at this level of the marine food web are capelin and Arctic cod, on which Atlantic cod, fish-eating sea birds, and marine mammals depend for food.

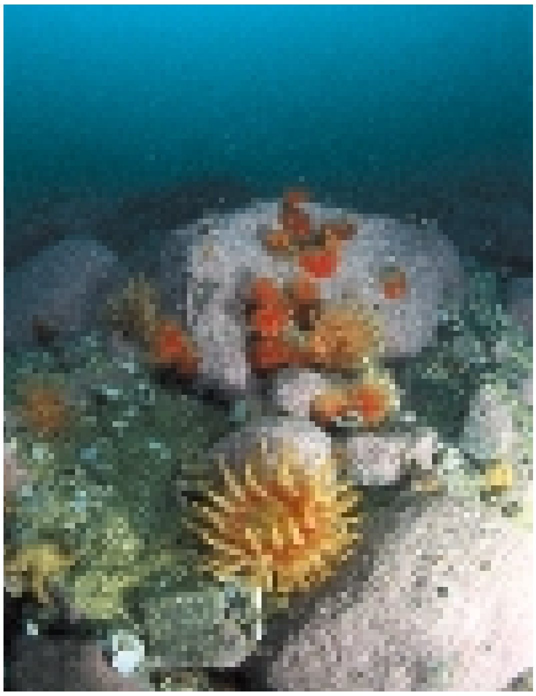
At the top level of the marine food web are polar bears and humans. Polar bears feed mostly on ringed seals. By way of the marine food web, seals, toothed whales, polar bears, and people may ingest contaminants that have entered the water via deposition from the atmosphere, the melting of ice, or by river runoff in coastal areas, or in the case of heavy metals from naturally-occurring minerals in sediments and water

The marine food webs are complex, and some paths are longer than in many other ecosystems. This accentuates the role of biomagnification (see box left), and makes top predators especially prone to accumulating high levels of environmental contaminants.

The AMAP region also covers areas of subarctic marine waters, such as the Barents Sea and the Nordic Seas (the Norwegian, Iceland, and Greenland Seas). The mixing of water masses at the polar front, along with more moderate water temperatures than in the Arctic, makes these waters highly productive with many commercially important fish stocks. These include zooplankton feeders, such as capelin and herring, and fish eaters, such as cod and haddock.

Shallow waters have a rich bottom fauna

Sediments in shallow seas and along coasts teem with life. Crustaceans, sponges, and mollusks are some of the animals that take advantage of dead plankton and other organic material that



FREDRIK EHRENSTRÖM

Tealia and *Psolus* from Disko Bay.

fall to the sea floor from productive surface waters. Some fish, eider ducks, bearded seals, and walrus feed mostly on this benthic fauna.

Benthic feeders are likely to ingest contaminants if bottom sediments have been polluted. This is an important pathway into biota as many contaminants will follow sediments and settle on the bottom. Benthic feeders can also stir up contaminants which are then carried away by water currents.

The benthic food chain is shorter than that at the ice edge, which limits the potential for biomagnification. Walrus that only feed on the bottom can thus be expected to have lower levels of contaminants than, for example, seals that feed on fish or walrus that eat seals. Animals feeding on bottom fauna provide a link that can transport contaminants from sediments to predators at the surface.

Benthic organisms that feed on carcasses of dead animals such as fish and sea mammals are at a very high level in the food web.

The shelves provide an estuarine environment

The continental shelf seas, including the Kara, Laptev, East Siberian, and Beaufort, differ from the rest of the marine environment in that freshwater from north-flowing rivers plays a central role. These seas are covered by

FREDRIK EHRENSTRÖM

landfast ice for most of the year, the edge of which can extend as far as 400 kilometers from the coast. Rivers flowing into these seas bring large amounts of particles, including organic matter, that are an energy source for bacteria in the water.

In the estuarine zones where the rivers meet the sea, this bacteria-based food web is the most important. It supports small crustaceans and fish that migrate from freshwater ecosystems during the summer. In the Beaufort Sea, Arctic cod is the dominant fish species. Seals and bowhead whales take advantage of the rich supply of bottom-dwelling crustaceans. The estuarine waters of the Mackenzie River attract beluga during the summer.

Water-column productivity is restricted to open-water areas between the landfast ice and the pack ice, many of which occur at the same place year after year. The offshore ecosystem is high in productivity of diatoms, which serve as food for grazing zooplankton that in turn support fish, jellyfish, and other predators.

STAFFAN WIDSTRAND

Gull with seal blubber.

Along Arctic shores, conditions for plants and animals vary. In areas with ice, the bottom is usually scraped bare so often that very few species manage to survive. Along the ice-free coasts, on the other hand, bottom-dwelling communities can be very rich. Kelp forests and seaweed become nursing grounds for many fish species.

Summary

Low temperatures and extreme seasonal variations in light are some physical characteristics that limit the productivity of Arctic ecosystems and can make them more vulnerable to contaminants in the environment. In terrestrial ecosystems, lack of nutrients, waterlogged conditions on the tundra, and the lack of water in the Arctic desert areas also limit productivity.

The ability to gather and store energy is a prime concern for survival during the dark and cold winter. Therefore, fat plays a more important role in animal metabolism in the Arctic than in temperate regions. The importance of fat increases biomagnification of fat-soluble contaminants. Bioaccumulation of contaminants is also accentuated in many Arctic animals by long lives.

Seasonal fluctuations are the norm in the Arctic, and many species migrate north to take advantage of the productive summer season. This includes large numbers of migratory birds that concentrate in wetland areas in the terrestrial environment and along the marginal ice zone in the marine environment.

Terrestrial food webs in the Arctic are generally short, though long-lived lichens gather contaminants very efficiently and transfer these to grazing animals, such as caribou and reindeer. Freshwater food webs are also short, and predatory fish occur mostly in Low Arctic to subarctic ecosystems. Arctic marine food webs can be very complex but with only a few key species connecting the different levels.

The jellyfish *Mertensia ovum* from Greenlandic waters.