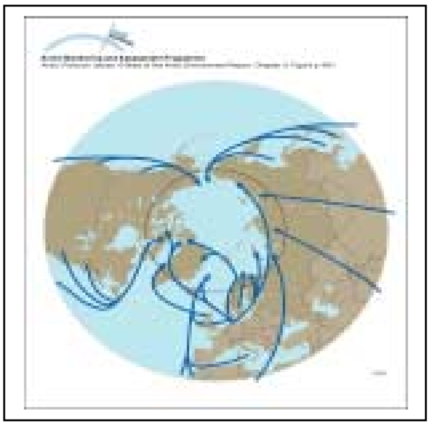
The Arctic Is an Ecosystem

As you look down from outer space, through the solar winds generated by the outpourings of the sun gusting to 200 km per minute, through the -200° C ozone depleted stratosphere, through the boundary layer at 3 km between the upper and lower atmosphere, you see the Arctic lying in winter darkness dominated by the 15 million square miles of polar sea ice. In summer this is reduced to about 8 million square kilometres. The sea ice extends south to three exits of the Arctic Ocean - the narrow exit west of Greenland into the North Atlantic; through the 500 km wide strait between Greenland and Svalbard; and through the 70 kilometre Bering Strait between Chukotka and Alaska into the Bering Sea and onwards to the Pacific Ocean. The land surrounding the Arctic Ocean is covered by many glaciers but is dominated by the Greenland Ice Cap covering 1.7 million square kilometres and with a maximum thickness of 3200 km - a massive volume of 2.8 million cubic kilometres.   Glacial fingers extend down the mountain ridges in Norway, the Urals, Kolyma, Alaska, the Yukon and Baffin Island reaching well below the Arctic Circle.

Deep snow blankets land near the oceans but barely covers the polar deserts and semi-deserts of the continental land masses. Here, on patterned ground, musk ox and reindeer scratch for fodder while fox and wolf scavenge and female Polar Bears sleep and give birth in their snow lairs. Below the frozen soil are solid ice wedges and permafrost, deep and continuous in the high Arctic but discontinuous in the sub-Arctic. The ice covering the surface of deeper lakes, rivers and seas overlies water which is still above freezing while the air temperature is -50°C or below. As you follow the seasonal cycle, the sun rising above the horizon radiates the Arctic, warming the air, causing the sea ice to thin and retreat.

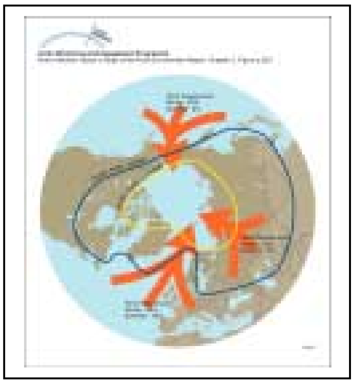
The snow and ice melt on land, rivers flood with melt water, large volumes flow into the coastal waters lowering both the temperature and salinity. The waters circulate within the Arctic Ocean and force their way under the warmer surface waters, through the narrow exits into the North Atlantic and Pacific Oceans (see figure 1). Whales and seals move northwards providing food for the polar bears. On land the sun's radiation warms the surface vegetation and bare ground, raising temperatures above that of the air. The land bursts into colour almost 'overnight' - partly because there is no night. Migrating reindeer, geese, ducks and waders return to feed on new plant growth and emerging insects(see figure 2). Salmon run the rivers and the bears gorge. Below the land surface temperatures rise more slowly and the soil melts to form an 'active layer' where microorganisms and insect larvae resume activity, and organic matter starts to decompose above the permafrost.



This is the Arctic Ecosystem - the Cryosphere. It is relatively self-contained (a Northern Mediterranean); the atmosphere, land, freshwater and sea are highly interconnected (coupled) vertically and laterally. There is circulation within the system from air to land to water to sea and back again. There is circulation of ice and sea, of chemicals, of animals and plants, and Humans within and around the Arctic Ocean.

If you 'push' one part of the system, the affects will be felt in other parts of the system. Thus, if the climate changes - as it has always done - increased melt water will circulate in the Arctic Ocean; if the capelin population crashes in the sea the effects are felt on land through the food web; if pollutants are released into the atmosphere or the sea in one place they are transported to other parts of the region.

This is a single, integrated, dynamic ecosystem on a massive scale, driven by the sun.



But it is not isolated from the rest of the Globe - no ecosystem is completely isolated. The Arctic Ecosystem grades into warmer Southern regions of the World and interacts with them. The Arctic air mass brings cold air to the South in the winter but the winds from the South bring warmer air - and contaminants - northwards. Mammals, birds and fish migrate in summer to feed and breed at the rich sea ice margins, coastal zones, estuaries and wetland, then return South for the winter. Sea water cools as the currents bring it North and the cold fresh water from melting snow and ice adds to the great ocean 'conveyer belt' -the thermohaline circulation - which significantly affects the climate on land as well sea conditions(see figure 3).

The Changing Arctic Ecosystem

If you follow the system over decades or centuries you see periods of naturally warmer or cooler climates. Short periods of cooling may be caused by volcanic ash circulating in the stratosphere and reducing radiation for a few years as with eruption of Tambora in 1815, Krakatau in 1883 and Pinatubo in 1991. Longer periods of change result from shifts in the balance of two major circulation systems - the North Atlantic Oscillation which results from cold air from the North meeting warm air from the South, and the Global Conveyer Belt which brings warm water to the North where it is cooled by Arctic waters and returns South. Changes in these atmospheric and oceanic systems produce climatic shifts such as the Little Ice Age of the 16th and 17th centuries. Thus the Arctic experiences long-term fluctuations as well as the dramatic seasonal changes.

Ice and snow extends and retreats, glaciers flow and carve U-shaped valleys in softer rocks, deposit moraines and change the shape of the land. Rivers surge, carving new channels and extending flood plains or the flow rate slows and sediment is deposited further downstream and the flood plains become drier with fewer pools. The land surface is repeatedly perturbed by freezing and thawing (cryoturbation), the permafrost and ice wedges slowly move up or down as climate changes, generating diverse patterns on flat and sloping ground. As glaciers and snowbeds retreat, plant growth increases, organic matter accumulates as soils mature and peat forms on wet ground. On land and in the sea the boundaries of plants and animals extend or retreat at both the northern and southern ends of their geographical range. On the islands and mountain tops, species which are at the edge of their ranges may become locally extinct - they have nowhere to go

Over millennia, even the surface of the Earth responds to climate change, rising and falling as the weight of the ice mass changes, creating new raised (or sunken) beaches and river terraces, and causing rivers to change direction. You notice this over millennia, but you can also measure the current rise of 2-3 mm per decades in some areas - one of many slow but continuous processes within the Arctic Ecosystem

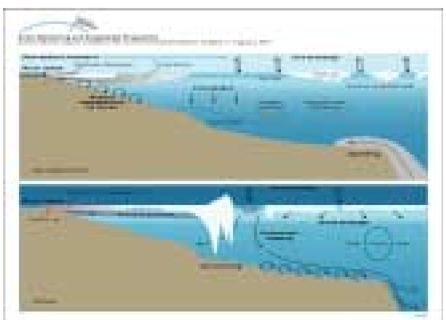
Climate variability has shaped the Arctic and been a way of life for millennia. Not only does it vary over time, it also varies in different parts of the region. Animals and plants which are best adapted to the conditions prevailing at the time are the ones which survive and thrive. But local habitats can be very varied and are particularly important on land where the climate is most severe and changeable. Warm sheltered south-facing pockets of land enable species which are less cold-tolerant to survive. Damp or wet depressions in a dry landscape are refuges for species during periods of low precipitation. Freeze-thaw perturbations allow species which are good colonisers but poor competitors to survive. Thus physical variety in the landscape and the past history of climate variability has selected animals and plants which may be 'pre-adapted' to resist the pressures of future changes in climate.

The Arctic Gradients

The Arctic Ecosystem is a jigsaw. The picture is made up of many parts. The ecosystems that we normally recognise, the different habitats, are each systems that have interconnected parts and processes. But, as you have seen, they are not completely self-contained and isolated from each other. They also change gradually along distinct environmental gradients. It is these physical gradients which determine the structure and function of the ecosystems, their dynamics and their responses to the ever changing environment.

What are these gradients? On land, in freshwaters and in the sea, a dominant gradient is the rise in temperature from North to South, but other large scale physical gradients have major effects on the structure and function of the ecosystems.

- On land, from the coast to inland areas, the oceanic-continental gradient in climate gives increasing seasonal range of temperature and decreasing rain and snowfall. Ranges of mountains, especially near the coast, intercept clouds and cause major local increase in rain and snowfall. The mountains also provide sharp local altitudinal gradients in temperature.



- Freshwater systems are dominated by topography (slope and steepness), determined mainly by geology. The mountain glaciers and rivers flow sharply to the sea or spread over the vast continental areas of flat tundra.
- Marine systems grade from the shore, through the tidal zone, over the extensive, gently sloping continental

shelf and down to the deeper ocean floor, with its submerged valleys, troughs and mountains - a mirror image of the land surface (see figure 4).

How do these systems respond to the environmental gradients? How do the structures and processes change? How do the pieces of the jigsaw change? Examine the dynamics more closely as you move along the gradients of the three subsystems - the land (terrestrial), the freshwater (hydrological), and the marine.

The Terrestrial Ecosystem - or Ecosystems.

From space you see the **Polar Deserts** in the 'High Arctic' - the Earth's cold deserts - where the cover of shattered rocks bear only occasional cushions of saxifrage, small poppies and dwarf willows, with a few mosses, and lichens crust the south faces of larger rocks. But it is not all barren. For example, there is a small lowland cove, sheltered by south facing cliffs carved from the limestone plateau of Devon Island in northern Canada. The Truelove Lowland has a series of beach ridges, formed as the land rose from the sea at various times. The ridges hold back melt water and plants thrive, warmed by the sun's rays rather than the air temperature. Similarly, where melt water seeps from snow-beds, relatively lush swards of mosses and lichens grow through the month or so of 'summer'. Local topography can override the devastating regional cold. But availability of water is critical. The widespread stony soils have not yet accumulated organic matter, drain freely and dry in summer.

Further South or near the coast, plant cover gradually diversifies and extends to cover half or more of the soil surface - **the Semi-Desert**. Again more lush vegetation grows in sheltered and moist areas with grasses, sedges, shrubs and dwarf willow, birch, and larch. Here, germinating seedlings survive better than on the open ground which drains and dries in summer.

The distinction between desert and semi-desert is blurred; it is more of a gradient, with small patches and tongues of one system mixed into the other. Three features, two obvious, one hidden, play key roles in the dynamics of these landscapes:

- **Snow**. Depth, quality and timing are critical. Fresh snow is an excellent insulator but compaction and ice crusts caused by thawing and freezing increases heat conduction up to a hundredfold. With its insulating properties, early deep falls buffer the soil and the upper layers (the 'active layer') remain unfrozen well into the winter despite the extreme cold. Lemmings and voles shelter and breed beneath the snow; ptarmigan burrow to escape predation by foxes; but reindeer and muskox have difficulty in exposing plants to eat. In spring, late snow lie prevents nesting of birds and emergence of insects. Shallow snow exposes plants to low temperatures and to grazing, but ice crusts can resist the hooves of reindeer. Early melt, before the ground thaws, floods the nest of small mammals, drowning them or exposing them to predation. Water in frozen and liquid form is critical.

- **Cryoturbation.** Perturbation by daily and periodic freezing and thawing gradually moves soil particles, stones and blocks, sorting them into different patterns; circles, boils, medallions and on slopes stripes and flows. This patterned ground disturbs plants but also creates finer, moister soil for recolonisation, however briefly. Cracks open with the freeze-thaw cycles providing further colonisation sites. The power of water, changing between solid and liquid, moulds the land surface.

- **Permafrost.** The surface layers may thaw to 20 centimetres in fine-grained moist or wet soils, deeper in coarser dry soils. But lower layers remain frozen, even if only a few degrees below zero. Surface temperatures may rise to and fall by 50º C or more over 24 hours in summer through the sun's radiation but slow diffusion of heat and cooling by the underlying bed of frozen soil damps these daily and seasonal oscillations. The permafrost remains at -1 to -3º C. This impermeable bed also prevents drainage, holding water in the active layer and causing surface or near-surface flow on slopes. The hidden element of the landscape.

The deserts and semi-deserts of the High Arctic are sparsely covered and extend over vast areas, especially in Russia and Canada. The patterns are on a small scale within the vast landscapes - at the meso-scale of small landscapes covering a few hundred square metres or kilometres; at the micro-scale of centimetres or metres. At each scale you can see a basic structure, usually defined by the plant cover or physical form. At each scale there are the process of primary production, decomposition and circulation which define an 'ecosystem', including inputs and outputs. The ecosystem is never completely closed. In these deserts and semi-deserts the connections between the small scale ecosystems are often through surface water movement and through animals, often moving across large distances and using the small patches of richer vegetation in sheltered river valleys.

There is no clear-cut end to these deserts and beginning to the **Tundra** that spreads across the Low Arctic. Small patches of tundra vegetation with dwarf shrub heaths or cotton grass tussocks or wet mires occur further North but they become the dominant and extensive systems in the Low Arctic, varying with the climate, underlying geology, soil conditions and slope.

Shrub Tundra, with dwarf birch, willows and alders, bilberry, blaeberry, heaths, rhododendrum, some sedges and saxifrages often form a canopy extending 50-8-centimetres over a continuous mat of mosses and lichens. In sheltered areas the canopy may form a thicket up to 2 metres. Shrub Tundra occurs mainly in drier soils and its distribution reflects the climate. Thus it extends to 74ºN in west Greenland but only to 62º on the east coast which lacks the warming influence of the Labrador Current. The plants respond to subtle changes in the physical environment and Sedge - Dwarf Shrub Tundras are identified over large areas of Russia, grading into Tussock - Dwarf Shrub **Tundra** with tussocks of cotton grass or sedge often on rather wetter and poorer slightly acid soils. Where drainage is poor because of permafrost, clay soils and / or flat land, **Mires** (muskeg, bog) tend to dominate large areas. These mires often have sedges as dominant plants but mixed with many other species and a strong moss and Sphagnum cover. Hummocks and pools cover much of the surface and, as with all the other types of Tundra, there is patterning resulting from freeze-thaw action. Frost boils, polygons, medallions, cracks and many other patterns occur and disrupt the vegetation. As the vegetation becomes more dense and continuous and increasingly insulate the ground surface, these phenomena become less frequent. But the power of the ice and permafrost can still alter the landscape as large mounds or even small hills (Pingos) force the surface to heights of 100 metres or so.

As the climate eases towards the South, birch trees become more frequent, then pine, spruce and larch forming the **Forest-Tundra**. The ground vegetation remains similar to the more northerly Tundra but gradually gives way as the tree cover expands into the classic **Taiga** or **Boreal Forest.** Here the domination of spruce and pine shades out much of the ground cover and tends to dry the soil. It also keeps the soil cool and although the climate may be warmer, permafrost may remain in the forest whilst it disappears from open areas and is thus 'discontinuous permafrost.'

This gradient from Polar Desert to Taiga, with its many variations and diverse patterns, is the landscape of the North. Much is written and the debates are vigorous over definitions of different plant communities, the beautiful adaptations of the animals and plants and their natural histories. But what about the System? What are the dynamics of this landscape? How does it function as an integrated Ecosystem or as a series of Ecosystems? These questions are becoming more and more important as the environment changes through climate, land use, industrial development and pollution. So let us explore some of so-called Ecosystem dynamics and function - Change over time; Food webs; Carbon and nutrient circulation; Biodiversity.

Change over Time.

As the glaciers and ice caps retreated 10-20,000 years ago, the bare ground, shattered rock debris and boulder clay formed the initial 'soil'. On hard granite rocks weathering by the climate was slow, producing few coarse soil particles and little soluble nutrients. On limestone weathering was much faster and generated alkaline soils, but the particles dissolved quickly, drainage channels opened and nutrients tended to leach out of the system. On other sedimentary rocks, sand and clay particles were more abundant and essential nutrients such as phosphorus and potassium retained. The geology set the course of ecosystem development. Nitrogen was the missing element needed to start the plant succession. Input in rain was minimal, but blue-green algae with the ability to 'fix' atmospheric nitrogen grew where water was available. Some algae, using reflected light, even live under stones which efficiently absorb heat from the sun. Lichens grew slowly on rock surfaces. Made up of an alga and a fungus, lichens have the capacity to produce, decompose and recycle - a self-sufficient internal ecosystem.

It is these early colonisers, with the capacity to capture essential nitrogen and nutrients from the racks, which initiate succession in places where there was no organic matter from previous systems - accumulation of nutrient capital is essential. Bacteria that can extract elements from the rocks - the chemolithotrophs - aid the process. As small amounts of organic matter accumulate, other plants begin to colonise by seed, the tiny amounts of organic material providing focal points for successful germination. In other areas where some organic matter remains from vegetation that preceded the ice cover or has been redistributed on river banks. Here, colonisation is more rapid, but is still often initiated by plants with associated nitrogen fixing bacteria.

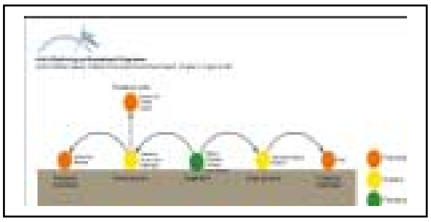
Early colonising plants tend to have a strategy of rapid growth and reproduction to take advantage of the sites that have colonised. Gradually other species come into the site, taking advantage of the protection of existing plants and the accumulated organic matter. Gradually the cover increases, moss cover increases and the ground becomes more insulated from the low temperatures. Ironically, this can cause the permafrost to thaw less, the active layer to become thinner giving more difficult rooting conditions, often waterlogging, and reduced recycling of nutrients. The plants that conserve their resources and recycle them internally to give them a kick-start at the beginning of summer, now tend to have the advantage. These are often the better competitors - what they have they hold. The gradual changes in plants and soil are followed by the fauna. The 'hotspots' of early colonising plants attract migrant grazers. Small insects are blown by the wind, the fortunate ones landing on the patches of vegetation. In the later stages, many of the plants are long-lived, woody and often produce 'defense' compounds that protect them against animals. The fauna then becomes more specialised and grazing is reduced to times when more palatable food is not available.

The time scale of these dynamics, the primary succession, is measured in centuries and the sequence varies greatly from place to place, as do the initial conditions causing succession. Ground disturbance through freeze-thaw cycles, erosion, lake drainage, fire and Human activity such as trampling or industrial development, can all restart succession. Adjacent land with its vegetation and fauna, provides sources for colonisation. Thus the time scale of such secondary succession is often measured in decades.

Fundamentally, the whole region has been subjected to variations in climate over thousands of years, sometimes warmer, sometimes cooler. The animals and plants have been selected to survive these changing, yet continually harsh conditions. They have adapted. Sophisticated adaptations, such as the use of anti-freeze chemicals, will enable them to respond and survive under the expected changes in climate caused by the carbon pumped into the atmosphere by Human activity. The distribution of species will change; some will move into new areas, others will withdraw; patterns will change - just as they always have done. The ebb and flow of varieties of reindeer around Greenland over the last 10,000 years illustrates these long-term dynamics. In this case caused by changes in land form, ice connections and glacial barriers, combined with climate, overgrazing, and predation by Man and wolves.

The Web of Life - and Death

From a distance, who eats who seems clear when you take a snapshot in time:



Lichen ---> Reindeer ---> Wolf

Grass ---> Lemming ---> Snowy owl

Birch ---> Autumnal moth ---> Warbler ---> Falcon

Seeds ---> Bunting ---> Merlin

The reality is a complex food web in which the distinction between herbivores and predators is blurred; most species take a wide variety of food, depending on what is available (see figure 5). The so-called 'top predators', the big ones, take a wide variety of prey and many resort to feeding on insects and plants when their main food is in short supply.

Large animals cannot be eaten by smaller ones - but that is not true when you see foxes feeding on remains of reindeer that died of starvation, or on undefended new-born calves.

Lemmings and other small mammals form a key food for many predators. The large fluctuations in lemming populations may seem a problem for predators which depend on them to meet the demands of their young during the their breeding season. A particular adaptation of some predators to lemming cycles is to adjust the number of young to be fed. When lemming populations are high after winter breeding under the snow, large clutches or broods are produced by snowy owls, skuas, stoats and other predators, some of which migrate to areas of lemming 'highs'. Even reindeer eat lemmings at this stage.

Predation, disease and overgrazing cause the lemming populations to crash. In the following year(s) predators produce fewer or even no young or emigrate. The lemming population then recovers.

This is the classic lemming cycle with classic predator-prey dynamics - the prey population expands, followed by expanding predation, which drives the prey population down, and the predator population then declines. The truth is rarely so simple, but it illustrates some of the food web dynamics and the key place of lemmings in the Arctic system. Hidden within this dynamic is another dimension of the system - the decomposer cycle.

Lemmings feed on the leaf bases of grasses and sedges. At a lemming 'high' a tundra meadow can resemble a hay field after cutting but before harvesting. The fresh leaves and the lemming faeces are consumed by bacteria, fungi, soil invertebrates and insect larvae, which are consumed by other invertebrates. The decomposer cycle leads to a flush of emerging adult insects preyed on by surface beetles and spiders. The early summer flush of craneflies (tipulids), midges and mosquitoes are a key food source for another group of the larger, more obvious predators - the insectivores - pipits, larks, buntings, and in wetter areas the waders. These now join the above-ground food web as prey for falcons, skuas and owls. Thus, again, different parts of the ecosystem are joined together.

Material Flow: Carbon and Nutrient Cycling.

The food or trophic web indicates the ways in which matter is transferred through the ecosystem. It looks efficient but, in terms of productivity, it is very inefficient. The transfer from plant to herbivore to carnivore to carnivore results in a drop in production of more than 95% - at each step! For example, of the annual plant production above ground rarely is more than 10-20% eaten by herbivores. Only about half of that is digested. Most of the digested plant material is then used to maintain activity, especially in warm-blooded animals, and only a small part is converted into new production. The predator steps may be slightly more efficient because the food is more digestible. Invertebrate convert a higher proportion of digested food into new tissues because they do not have to maintain their body temperature.

Although there is some variation, the overall pattern remains - each trophic level supports only a small biomass at the next level of the food chain. Hence, to find enough food, the herbivores have large ranges, the carnivores even larger. They also use a wide variety of foods - they tend to be generalists rather than specialists. They are also well adapted to conserve as much energy as possible through hibernation and insulation, particularly because of the low plant production in the Arctic. It is possible that Arctic food webs, because of their various adaptations to the particular climatic conditions and sparse food supplies, are just as efficient as more southerly ecosystems.

So, much of the primary or plant production appears to be wasted. No! The plants transfer a significant part of their production below ground into storage organs at the end of the growing season. This is part of the conservation strategy that enables them to grow rapidly in spring. The actual mass of plants as roots, rhizomes, tillers etc below ground is far greater than above ground - a general feature of the North. This below-ground plant mass is used by some large herbivores which dig it up, and also by soil animals such as nematodes, aphids and other insects. Thus the food chain continues in the soil, with the important addition of dead plant material and faeces as alternative food sources. In one form or another, most of the plant production ends up in the soil. There, it supports a much greater species diversity of micro-organisms and invertebrates, and a much larger production, than occurs above-ground.

Dead plant matter is a key to ecosystem development. It contains much of the small amounts of nutrients, especially nitrogen, that the plants have managed to absorb. As it is decomposed by bacteria and fungi and passed through the soil food web, the nutrients in the plant remains are transferred from organism to organism, gradually released and reabsorbed by the plant roots. At the same time the carbon in the plant remains is also recycled through the organisms, gradually being released through respiration and returning to the atmosphere. The process of decomposition in the Arctic is very slow, partly because of the low temperatures and the cooling effect of the permafrost. Both the lack of moisture in well drained soils and excess water where drainage is inhibited reduce decay rates. Most litter falling from plants looses only about 5-10% of its weight in the first year. The rate decreases after that as the more resistant material is left and it moves into colder layers of the soil. The soil organic matter from generations of plant input gradually accumulates forming more mature soils. In mires, lack of oxygen and very low temperatures through waterlogging, cause large accumulations as peat.

The circulation of carbon and nutrients through the ecosystem follows many pathways and processes.. It is not a closed system. Both C and nutrients enter from the atmosphere and circulate within the system. Some of the C and Nutrients is leached from the system into streams and rivers. Most of the C is eventually returned to the atmosphere. It is the delicate balance between input and return which is the focus of much attention in the question of the role of these northern regions in climate change.

Although plant production in the North is low, rates of decomposition are very low. The result is that through gradual accumulation, northern soils contain almost 25% of the World's soil C, mainly in the mires, bogs and muskeg. As the northern soils are relatively young - a mere 10,000 or so years old - they have gradually accumulated C in the plant cover and soil organic matter. Although much of the C has been returned to the atmosphere through respiration of plants, animals and micro-organisms, the ecosystems have been 'net sinks' of C. In this way they have helped to counteract the rise of carbon in the atmosphere which is causing climate change. Ironically, the current, and predicted, climate warming is likely to increase the rate of decomposition and release more of the C stored in the soil. The balance between uptake through photosynthesis and release through decomposition will fluctuate. Tundra ecosystems will probably become ' net sources' rather than 'net sink' of C in the future. There is already evidence that this change is occurring in Alaska.

The Future for Terrestrial Ecosystems?

Predicting changes over the next 50-100 years is difficult! It is not only the changes in the balance of production and decomposition within the system that have to be considered. It is also the rate of spread of vegetation following the gradual changes in climate. This is where the computer models come into play. The most recent model summarises the climatic factors driving change, and the responses of plant growth and soil organic matter. It is expected that the mean annual temperature of the region will rise by about 4^{o}C this century, more in the High Arctic, less in the subArctic and Boreal forest (**). Snow and rain will change much less, probably increasing by only a few centimetres each decade. Based on these assumptions, the model is then run from 1850 to 2100, covering the circumpolar region from 50^{o} Northwards. It predicts that

- Coniferous forest will expand at the expense of tundra.

- The present tundra area will be halved by 2100.
- The increased growth of forest will exceed increased decomposition so that the region will continue to be a carbon 'sink' throughout this Century.

Many factors have to be taken into account and such models are always tentative. Changes will not be smooth and regular. There will be periods and places where the trend is briefly (decades) reversed because of local conditions and variations in the climate. Short-term changes will be difficult to detect, partly because the biological response will lag behind the climate trend - but the system will change, that is sure.

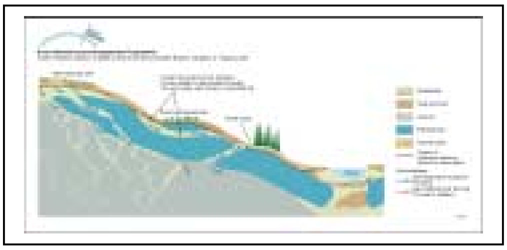
Terrestrial Ecosystems: the Overall Message

- Terrestrial ecosystems have changed in the past, are changing now, and will change in the future.
- The systems respond to climate variations in space and time, ranging from the small scale tundra polygons to circumpolar movements of vegetation and animals.
- Plants, animals and micro-organism are intimately linked locally, both above and below ground, and across landscapes.
- Heat (energy), water, carbon and nutrients are transferred into, within and out of the systems by biological and physical processes.
- Changes in the atmosphere affect the land, but changes in the land have 'feedback' effects on the atmosphere.

You may recognise different types of vegetation (scientists spend lots of time arguing about classification) and think that they are the Terrestrial Ecosystems. They certainly have distinct characteristics and have many internal links. In that sense they are 'ecosystems'. But it is equally certain that they are dynamic; they are changing; and they are intimately linked to each other and dynamically linked to the wider physical environment. Understanding these wider links is critical when considering protection of species and habitats, and the use and management of resources. Changes in one place affect other places. And that applies to changes in the North affecting the South, and vice versa. One System!

Snow, ice and water.

The three different phases of H_2O are the major driving forces that form the landscape and determine the biology and human occupation. Over millenia, snowfall has accumulated and packed down to form the great ice caps and glaciers of the Arctic. The annual layers now form the 'frozen archive' that scientists are exploiting to chart the climate history, especially on the vast mass of the Greenland Icecap. This icecap is up to 3000m deep and virtually the largest freshwater reservoir in the North. Icecaps spill over to form the glaciers. These are pushed down slope by the pressure from above, moving by up to 30 metres a year, grinding away the rock surface, picking up debris and transporting it to the glacier tongue where it is deposited as lateral or terminal moraines, or transported away by melt water. The melt water forms the streams and rivers, deep and fast flowing where the terrain is steep, wider and slower on flatter landscapes where the water spreads over the floodplain. Over large areas, water from glaciers and snow melt contributes to the many thousands of ponds and lakes and the wetlands which are such a feature of much of the Arctic.



But it is the permafrost - another water store - which prevents the water from draining into the deeper layers of soil and rock (see figure 6). So, even with the very low snowfall, less than 300mm in continental areas, the landscape is usually dominated by water. The exception is where stony ground provides drainage, drought conditions inhibit plant growth, and the polar deserts occur. One reason why the snowfall is so low is that cold air carries much less water than warm air. So, near the coast, warm air comes off the sea, it is cooled by the land, especially where it is forced to rise by mountains, and the moisture in clouds is deposited as rain or snow. Thus, whilst coastal areas may be warmer, they have precipitation of up to 3000mm.

A consequence of the relationship between temperature and the water holding capacity of air is that climate warming is likely to be linked to increased snow and rain, especially near the coast.

The Golden Fish of the Arctic.

In much of the Arctic the waters are oligotrophic (literally 'little nourishment') because they are derived from ice and snow and the hard rocks provide few nutrients. Despite the lack of nutrients algae grow well even below the ice in frozen lakes and provide the basis for the food chain in the High Arctic. The algae are grazed by a variety of crustaceans (water fleas and fairy shrimps) and insect larvae which are preyed on by the Arctic char - the Golden Fish of the Arctic - which is the only fish living naturally in the High Arctic lakes *(* Arctic char eg AMAP p24).* It is extremely successful, living to 25 years or more, growing up to 15-16 kg and distributed throughout the circumpolar region. This one species illustrates many of the key features of freshwater biology, and of Human ecology, in the North.

The Arctic char is genetically adapted to survive low temperatures and its distribution extends up into the islands of the far North such as Svalbard (or Spitspergen as it used to be called). It lives for most of the year in the rivers and lakes but migrates to coastal waters for 1-2 months in summer to feed on the rich food supply before returning to breed. The age of maturity varies widely and spawning may take place every year, every two years or less frequently, depending on environmental conditions. But some populations also live year round in landlocked lakes and may develop particular characteristics different from those in distant lakes. Populations sometimes show two distinct size groups, a smaller group feeding on the bottom fauna and zooplankton while a larger group feeds on the smaller group - cannibalism. They resemble two different species. Thus, at the northern edge of its range where it is the only fish species, the Arctic char shows a highly flexible life style.

Further South, or at lower altitudes, the Arctic char overlaps with other fish species which cannot withstand very low temperatures but are competitors in warmer waters. Where it lives with the brown trout in northern Sweden, the Arctic char tends to feed on zooplankton in the surface waters while the trout utilises the bottom fauna. But in winter the char continues to feed and moves to the bottom while the trout tends to stop feeding because it is less well adapted to low temperatures. A similar pattern of co-existence through seasonal partitioning of resources occurs between the Arctic char and the brook trout (sometimes known as brook char) in eastern Canada. As the number of fish species sharing the habitat increases even further, the diet of the char becomes even more limited until eventually it cannot survive.

Thus the **ecological 'niche'** of the Arctic char, and its variation in size and other biological features, are very wide at the northern edge of its range. The niche and life history are more restricted by competition from less cold-tolerant species when biodiversity increases towards the southern edge of its range (environmental gradients again!).

The ecological features shown by the Arctic char illustrate the flexibility that is probably widespread, but not so obvious, amongst northern animals and plants. Further, the Arctic char can also interbreed with closely related species such as brook trout. Interbreeding is a feature of many northern fish species, suggesting that evolution is still in progress in this young region.

Human ecology has also had a great influence on the ecology of the Arctic char. The following catalogue of local and general influences, illustrate the general role of Humans in the North:

- For hundreds of years, the **Inuit** people in Greenland and Arctic Canada chose sites for permanent settlement to harvest sea-run fish. Sami people traditionally stocked alpine freshwaters with char to establish larders along reindeer migration paths.

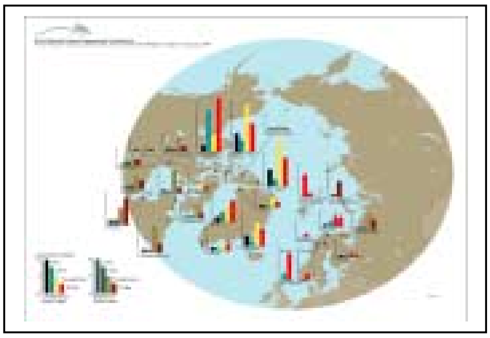
- Long-term selective **fishing** with gillnets removes larger fish, affecting population structure and life history traits. Use of poison and dynamite has eliminated populations on Svalbard. Repeated total removal of migrating fish using stone weirs ('saputit') has led to elimination of local populations Greenland.

- Widespread construction of **hydroelectric reservoirs** has changed water levels, reduced shoreline spawning, increased open water and limited feeding options.

- **Overfishing** of important prey species (capelin, Arctic cod) has reduced food supplies during important periods at sea for migrating char.

- **Introduction** of other fish species and freshwater shrimps to 'improve' fishing has reduced char through competition, caused genetic changes through interbreeding, and affected food chains. Other unexpected results have been, for example, reduction or loss of populations of oldsquaw and longtail ducks and predators of fish (loons, mergansers and ospreys).

- **Acidification** by atmospheric contaminants from southern regions, accumulated in snow over the long winter, are released as an acid pulse by the spring thaw. This has eliminated fish from many northern Scandinavian lakes, enhancing zooplankton and insect feeding birds but reducing fish feeders.



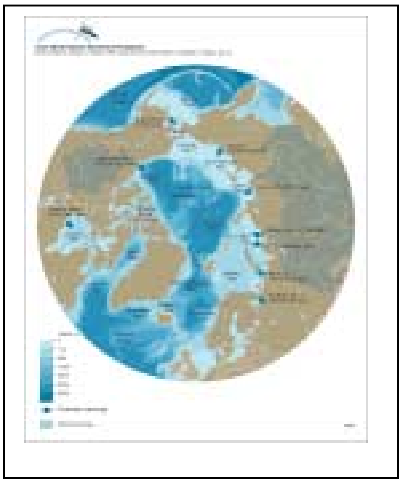
- **Persistent organic pollutants** (POPs), including many pesticides, are transported to the North, accumulate in fatty tissues and are concentrated up the food chain (biomagnification)(see figure 7). Arctic char are at an intermediate stage in the chain and many populations have levels which are above national guidelines.

- **Climate warming** is going to enable competitors to survive better where they are already at their northern margins change of their range. The previous advantage of winter feeding by char will be reduced because warming is expected to be greatest in winter. Char will tend to increase their range in the far North but loose ground in the South.

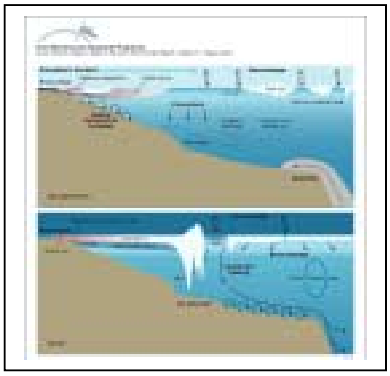
Into the Seas and Oceans

The early flush of spring melt water from the land generates a surge of cold water from the land surrounding the Arctic Ocean. Annually about 4000 cubic kilometers of water flows from the rivers. This is only about 2% of the water coming into the Ocean from the Atlantic and, to a much lesser extent, from the Bering Sea, but it is a high proportion compared with other oceans. It carries with it nutrients and sediment ground from the rocks by the glaciers. The coarser sediments are deposited as the flow rate decreases, especially over flat ground, but enormous amounts of fine silt are transported to the estuaries and seas (see figure 8).

The Yenisey River passes about 6 million tonnes of sediment into the shallow Kara Sea each year, carried by the 600 cubic kilometers of water. In contrast, the Mackenzie River brings 7x more sediment to the Beaufort Sea although the water volume is only about half that of the Yenisey. The reason for the difference is that the Yenisey crosses flat frozen tundra while the catchment of the Mackenzie is shorter, steeper, with less permafrost and much exposed soil and rock.



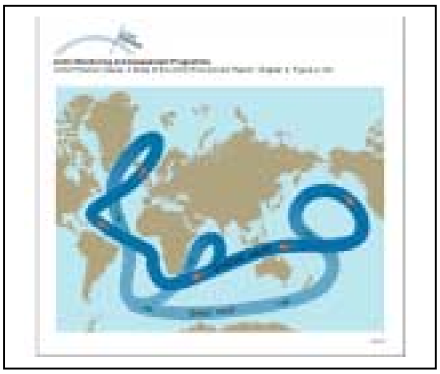
The estuaries and deltas act as a major sediment trap, followed by the extensive continental shelf which extends up to 900km off Siberia. Only 10-20% of particles from the Ob and Yenisey Rivers are transported beyond the borders of the deltas and the Kara Sea shelf. The Mackenzie Delta accumulates several centimeters of sediment through the year. Some of the sediment flows over the sea ice in spring, later it extends as a plume into the sea and flocculation continues the deposition process (see figure 9).



The shape of the sea bottom, distance from shore, and ice cover determine the physical characteristics and processes over the continental shelf (see figure10). The water from the rivers and from sea ice cools the sea water over the shelf but the summer sun raises the shallow water temperatures up to 4-5°C in summer.

The surface waters and the sea ice circulate in the Beaufort Gyre and generally move westwards from the eastern Arctic towards the

Fram Strait where they exit into the North Atlantic. It takes only 5-6 years for sea ice to move from the Chukchi Sea off Alaska to the Fram Strait although the general pattern masks many more localised movements. The warm waters influence temperatures on land and one useful consequences of the circulation pattern is that the temperature on Iceland is similar to that on Svalbard - but delayed by about 2 years!



As the cool surface water (near 0ºC) with low salinity exits the Fram Strait it meets and overlaps with the warm (3.5-6ºC) water from the Atlantic. The warm water brings heat from the southern oceans of the World and is responsible for the Gulf Stream. It is the reason that Svalbard, Iceland and Western Europe have warmer climates than comparable latitudes in North America and Russia. As this warm, salty water reaches the Arctic and meets the cool waters escaping through the Fram Strait it becomes denser as it cools and sinks to deeper layers. This is a slow process but every winter several million cubic kilometers of water sink to deeper layers and move south on the bottom of the Atlantic. This is the 'Ocean Conveyer Belt' - the thermohaline circulation - that moves heat around the globe (see figure 11).

The biological riches of the seas and ocean.

The combination and variation of physical factors (ice, rock, sand and mud substrate, temperature, salinity, water movement, nutrients, light) determine the biology of the system.

The coasts. Estuaries and deltas with salt marshes and mudflats, sandy and rocky shores, bays, inlets and fjords, cliffs. These are the transition zones between land and sea - a foot in both camps. The narrow shores and wider deltas provide places to feed and breed. It is the birds that give the outward and visible signs of the productivity of the seas. They migrate North for the short summer, covering thousands of kilometers from temperate and tropical regions, even as far as the Antarctic in the case of the Arctic tern - an annual round trip of 32 thousand kilometers.

On the mudflats and sandy shores, vast numbers of waders pick and probe for small crustaceans, molluscs, worms and small fish. Waders (dunlin, knot, sandpipers and stints) breed almost exclusively in the Arctic with total populations of individual species of up to 3.5 million birds, some of them also using the tundra wetlands. Terns breed in colonies and dive for small fish in coastal waters. Vast colonies, sometimes several hundred thousands, of guillemots (murres), auks, gannets, cormorants and puffins nest on high cliffs or burrows in the turf. They fish for capelin, sandeels, Polar cod and other fish. They are harassed by skuas and gulls. Their guano fertilises the vivid green patches of vegetation. The cliffs, filled with their cacophony in summer are silent in winter.

Continental shelves, **seas and oceans.** The shallow coastal waters support considerable and diverse bottom fauna of crustacea, molluscs, sponges, worms, anemones and starfish with various small fish. They graze the algae or feed on detritus or plankton and provide a food source for larger fish, birds and mammals such as walrus and seals. The shallow waters are also the spawning ground for capelin, polar cod and other fish in March and April. Each school of capelin can contain many hundreds of tonnes of fish which then move out to deeper waters and the sea ice edge to feed on plankton - and to be preyed on by seabirds, larger fish such as cod, seals and whales.

Ice plays an important role in the marine ecology. In winter the sea ice extends far South with maximum extent in March. It retreats during summer, leaving the Arctic Ocean permanently covered by three meters or more of pack ice, with ridges both above and below. Yet even in the pack ice, there is open water (polynyas) even in winter, caused by wind and water movement and the upwelling of warmer water. In summer about 10% of the pack ice is open water (see figure 12).

Nutrients transported from the rivers, from upwelling deeper waters or deposited from the atmosphere, provide the chemical base for the growth of algae. They grow on the surface, in and under the ice, and in the open water. They are adapted to grow at low temperatures, but also thrive where temperatures are enhanced by water from the Global Conveyer Belt. They can also grow in the minimal light that diffuses through the ice. These algae - the primary producers - are the key to the productive food chains of the Arctic seas and ocean.

The **ice edge**, especially in shallower waters, is a very productive zone. A complex food web is developed that extends from the algal grazers, through various predators up to the polar bear and Arctic fox which move far out onto the ice to feed. In the **open water** the floating algae or phytoplankton are the food source for small and large crustacea (krill) which are the food for the herring, capelin and the various species of baleen whales - the filter feeders.

The Ulitmate Predator?

The food webs outlined so far are a gross simplification of the real world. Many more species are involved. Species change their habits and habitats at different stages in their lives, at different times of year, and in different parts of the Arctic. A truer picture is drawn by the Inuit and Cree of the Hudson Bay food web *(* Fig 5 in Voices from the Bay).* Here the marine, freshwater and terrestrial systems are interlinked, from the primary vegetation source in the outer ring, through the herbivores and predators in successive rings, to the Inuit and Cree in the centre. The links are multiple and overlapping, and the food sources change from season to season.

Mans position as Top Predator in the food web has unfortunate consequences, particularly for Indigenous peoples. An important physiological adaptation of many Arctic animals is the accumulation of fat as an insulator and as a food reserve. This feature, combined with the solubility of persistent organic pollutants in fat, has meant that this contaminant, although present in minute amounts in the environment, is accumulated up the food chain and is now present in Indigenous peoples in significant amounts.

Indigenous peoples have sustained their use of natural resources for millennia. In recent centuries, whalers, hunters, trappers and fishermen from lower latitudes have increasingly exploited the northern resources. The effects have been direct in that populations are significantly reduced, e.g. through overfishing, or indirect when a predator switches to a new prey because its usual food has been overfished. Populations fluctuate greatly. Cod, herring and capelin have been major targets for centuries and the exploitation of cod in particular has influenced the fortunes and culture of many nations. But even the exceptionally productive cod, a key prey and predator for other species, has been reduced to a shadow of its former strength by **Man - the ultimate predator!**

Man is not only the ultimate predator. Man is an integral part of the Arctic Ecosystem with a pervasive influence, directly or indirectly, in a continuum from the immediate effects of hunting or fishing to the diffuse and distant effects of pollution, emission of greenhouse gases or the global economy. Many of the adaptations adopted by Man reflect those of other animals ranging from insulation through clothing to migration when prey populations are depleted. We tend to view Man as unique, but this anthropocentric view underestimates our continuity with the rest of nature. It also artificially distinguishes between natural and Man-made ecosystems when all ecosystems are influenced by Man; it is just a question of degree and mechanism. So we, all of us, are part of the Arctic Ecosystem. Or is it that the Arctic is actually part of an even bigger ecosystem - the Global Ecosystem - Gaia - the self regulating Earth postulated by James Lovelock. But that is another story!

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A creative, stimulating and credible vision of the Earth as a self-regulating system which has evolved over eons. A highly readable book by an eminent scientist, reprinted with a new preface (the first edition was published in 1979).

Nuttall, Mark & Terry Callaghan (eds.) (2000). The Arctic: Environment, People, Policy. Harwood Academic Publishers, Amsterdam, 647pp.

A comprehensive coverage of the physical environment; land, freshwater and marine biology including human health; social and political dimensions; human impacts on the Arctic environment and the policy responses. The 22 chapters are written by 35 authorities from 8 different countries and give a balanced, in-depth coverage. An expensive but valuable source of information.