[IMAGE]

Striped tundra (ZB IX) with espalier *Salix* species and frost heap strips on the Finland-Norway border (photo: Breckle)

[IMAGE]

*Cassiope hypnoides* between *Salix polaris* in the N tundra of Finland (ZB IX, photo: Breckle)

**II Special part**

**Part L -ZB IX: Zonobiome of the tundra and the Arctic climate, respectively**

1 **Climate and soils**

2 **The vegetation of the tundra**

3 **Ecophysiological investigations**

4 **Wildlife of the Arctic tundra**

5 **Man in the tundra**

6 **Arctic cold desert and the solifluction**

7 **Antarctica and Subantarctic Islands**

8 **Literature**

[IMAGE]

Tundra (zonobiome IX) in the vicinity of Soresby Sund, East Greenland (photo: Hannes Grobe, https.//commons.wikimedia.org/wiki/File:Greenland-sydkap-hg.jpg)

1 **Climate and soils**

Zonobiome IX comprises two very widely separated sub-areas, which differ greatly from each other due to the very different distribution of land and ocean areas in the N and S and in the corresponding latitudinal positions. In each case, the continentality decreases sharply from S to N.

The largest forestless tundra area occupies an area of three million square kilometres in N Siberia. The number of days with a temperature average above 0 °C there is 188 to only 55. This is related to the always low position of the sun. However, the low summer warmth is partly due to the heat consumed in thawing the snow and the permafrost ground (► Fig. L-15). Winters are quite mild in the oceanic region and extremely cold in the continental one (◘ Fig. L-1). However, the cold pole at Oimjakon (near Verkoyansk) is still in the forest area, although the mean annual temperature there is -16.3 °C and permafrost reaches deep into the ground (► Fig. K-14). Soil freezing does not have a major influence on vegetation conditions. It depends only on the thickness of the upper soil layers thawing in summer.

The growing season in the S tundra begins in June and ends in September. Of great importance is the wind, due to which the irregular deposition of snow is caused, which is the precondition for the mosaic of vegetation. The storms in winter reach 15 to 30 m per sec. Precipitation is low, often even less than 20 mm per month.

Nevertheless, the climate is humid with the very low potential evaporation. The excess water cannot seep into the soil due to the permafrost. The consequence is a strong siltation; but there is no significant peat formation, because the production of the plants is very low or too low. The snow depth is 20 to 50 cm, exposing the elevations, so that snow and ice abrasion play a major role as mechanical factors for vegetation.

With the low position of the sun in summer, steep, stony S-facing slopes are heated relatively strongly. Therefore, they often form real small scale "flower gardens". Such S slopes and the banks of streams and rivers are the most favorable locations. Flat elevations with stony patterned soils (polygon soils, stripes soils) are only weakly colonized, as are gentle slopes subject to solifluction. The soils are often mini-podsoles and rankers (◘ Fig. L-2).

2 **The vegetation of the tundra**

In the tundra, endless areas are covered with dwarf birch and willow, as well as Eriophorum and Carex species. On dry soils one finds a pure lichen tundra, on moist ones mosses play a major role, but not the Sphagnum species. Measurements of air temperature taken at a height of 2 m are not decisive for the low plant carpet. When the air temperature reaches 0 °C, the soil has already thawed half a meter and vegetation development is in full swing. The temperature of the plants during the day at the ground is often 10 K above the air temperature. Nevertheless, the short summer period is often not sufficient for the seeds to mature. This is why, for example in Greenland, half of all species have their flowers produced the year before, so that flowering can take place very early. The buds and also the green leaves usually overwinter under the snow, but the open flowers die.

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| **Box L-1** Distribution of tundra in both hemispheres |
| ZB IX comprises the areas around the poles of the earth. In the north, these are the tundra areas and the cold deserts N of the Arctic timberline; in the south, S of the Antarctic timberline, tundra occurs only in small areas and on individual islands. Antarctica itself is covered by a huge ice desert. |

◘ **Fig. L-1** Climate diagrams from the forest tundra of Sweden (oceanic), from the tundra of N America, and from the extreme continental boreal region of Alaska (► Fig. A-5, Verkoyansk and ► Fig. K-13).

◘ **Fig. L-2** A mini- or dwarf podsol of low profile thickness in the subpolar regions of the Northern Hemisphere. It forms on different bedrocks and is common in association with permafrost (photo: Breckle).

Particularly interesting are the aperiodic species, such as the small Brassicaceae Braya humilis. Their development is extended over several years and temporarily interrupted during the winter at any stage. These species are thus independent of the short summer and flower either at the beginning of the growing season or later, although the buds may have been laid down two years earlier.

Fruit or seed dispersal is by wind (gliding on snow) in 84% of species, and by water in 10%. Berry fruits occur only in the forest tundra. With low productivity in the tundra, seeds are small; in 75% of species they weigh less than 1 mg. Most plants are frost germinators, that is, they acquire the ability to germinate only after the action of the low winter temperature, then germinate immediately in the spring and have time to accumulate some reserves until the autumn. Viviparous are 1.5% of species, various grasses, but also Polygonum, Stellaria, Cerastium species, etc. With abundant seed production, open places, for example, on the lower Lena, are quickly colonized. Most species are hemicryptophytes and chamaephytes. Annual species (therophytes) are only Koenigia islandica, three Gentiana species, Montia lamprosperma, two Pedicularis species and few others. The short vegetation period here with low temperatures is not favourable for the annuals (compare, on the other hand, the desert). Most species have thick roots as reserve storage. The age of a single plant can exceed 100 years even in herbaceous species. For dwarf shrubs it is between 40 and 200 years.

The nitrogen balance plays a major role. Mineralization and nitrogen uptake are very inhibited due to the low temperatures. The legumes (Oxytropis, Hedysarum, Astragalus) have root nodules that lie directly under the warming soil surface. Where there is almost no nitrogen in the soil, only mosses and lichens are found. Fertilization by animal excrement is of importance. Dryas drummondii, which is a pioneer species growing in Alaska, is stated to have root nodules similar to Alnus. During the pioneer stage of colonization, soil nitrogen content increases from 33 kg/ha to 400 kg/ha.

Climatic conditions that differ from the rest of the Arctic are found in some trough valleys in the interior of Peary Land (N Greenland) at latitude 80°. In summer there is a lack of precipitation here due to the descendings winds blowing from the inland, desert-like conditions prevail with salt efflorescence on the soil surface with alkaline soils, where even some halophytes occur. Even otherwise, vegetation is not entirely absent, as drifting snow accumulates from the mountains in winter and melts in spring. The water seeps away as the soils thaw to a depth of 1 m. Accordingly, Braya purpurascens also has a taproot over 1 m long. The number of frost-free days reaches 59, the July temperature is 6 °C.

3 **Ecophysiological investigations**

The temperature of the low plants and the soil is fairly uniform during the polar day when the sun is low for 24 h, but the direction of irradiation still has an effect. The differences to the air temperature can then become very clear on fair weather days (◘ Fig. L-3). Sufficient temperatures are a prerequisite for active metabolic processes in plants.

◘ **Fig. L-3** Diurnal changes in soil surface temperature in a catena from Carici rupestris-Dryadetum (CD) to Salicetum polaris on 29.8.1990, a fair weather day at Liefdefjord in NW Spitsbergen (90 m asl) (modified after Dierßen 1996). **1** CD/ Carex *nardina* facies; **2** CD/*Dryas* facies; **3** CD/*Carex* *misandra* facies; **4** Salicetum polaris.

The water balance of the arctic plants is well-balanced, their cell sap concentration is 0.7 to 2.0 MPa. If the species nevertheless often show xeromorphic traits in their structure, they are probably inherited peinomorphs evolutionary caused by nitrogen deficiency, just as in the case of the raised bog plants.

Particularly important is the question of photosynthesis and thus the production of substances. The maximum intensity of CO2 assimilationis 12 mg/dm2.h-1. On cloudy days, CO2 uptaketemporarily falls below zero. However, since it can usually continue for 24 hours, with a minimum parallel to the light minimum at midnight, the yield on a summer day reaches 100 mg CO2/dm2= about 60 mg starch.

This yield is sufficient to build up sufficient reserves of material in the summer. The primary production of vegetation cover in one year is 2500 kg/ha in the subarctic region in Swedish Lapland near Abisko (vegetation period 111 days), 830 kg/ha in Alaska (vegetation period 70 days), and only 30 kg/ha in the high Arctic (vegetation period 60 days). The phytomass of an arctic willow scrub on Greenland reaches 5.5 t/ha.

The "tundra biome" (ZB IX) has been studied very intensively in Alaska within the framework of the I.B.P. (cf. Bliss & Wielgolaski 1973).

4 **Wildlife of the Arctic Tundra**

The vast tundra expanses of Siberia are one of the few areas on our planet where you can still find original wildlife reasonably undisturbed by humans and thus study their influence on the vegetation. In winter most of the large vertebrates leave the tundra, the birds migrate south. Only the lemmings (Lemmus) and ground squirrel (Spermophilus lateralis) remain in the tundra. Arctic fox and snowy owl retreat from the northernmost, low prey areas.

The lemmings do not go into hibernation, nor do they accumulate food stocks, but remain active under the hard shell of the snow cover and feed mainly on the renewal buds of the Cyperaceae. A lemming, although weighing only 50 g, needs about 40 to 50 kg of fresh plant matter per year. It usually inhabits well-drained southern slopes and builds a nest of cyperaceous shoots near its grazing area in winter, which is about 100 to 200 m2 for a family.An entire settlement covers about 1 to 1.5 ha, where 90 to 94% of the plants are grazed. Eriophorum angustifolium does not reach flowering on such areas. A maximum of lemmings occurs on average every three years. The dry plant parts are not eaten; in spring they form the "hay" (1 to 2 t/ha), which is washed together and piles up into peaty bulbs. After leaving their winter quarters, the lemmings make their burrows on higher ground, throwing out up to 250 kg/ha of soil.

At such disturbed sites one finds a characteristic plant community that initiates secondary succession. The same applies to squirrel burrows, comparable in Central Europe to a mole meadow. In this way, a constant dynamic is maintained within the plant cover. The flocks of waterfowl, especially geese, that come in spring also destroy 50 to 80% of the plant cover by biting off the young shoots of Oxytropis and tearing out the starchy rhizomes of Eriophorum. On the bare ground, solifluction sets in until a dense moss cover develops.

The nesting and gathering places of the birds are heavily fertilized, so that nitrophilous species (Rhodiola, Stellaria, Polemonium, Myosotis, Draba, Papaver and others) are established.

The animal kingdom of the tundra also includes the reindeer (Rangifer tarandus) (◘ Fig. L-4), which remains in the tundra in winter only if areas remains partly “aper”, i.e. not covered by snow.

◘ **Fig. L-4** The reindeer (Rangifer tarandus) is a mammal of the deer family. It lives in the circumpolar region in the tundra in summer and in the taiga in winter (photos left: Breckle; right: E. Fischer).

In summer, the reindeer graze dispersedly and have little impact on the vegetation. However, when they gather into large herds in autumn, their trampling becomes noticeable. In the process, the lichens and dwarf shrubs are eaten and destroyed, while the grass communities with Deschampsia and Poa spread. However, feeding behaviour is highly adaptable according to the food supply (◘ Fig. L-5). The number of wild reindeer is now decreasing in favour of domesticated ones. Reindeer are the main herbivorous animal in the tundra; in the North American tundra it is the caribou (Rangifer caribou), whereas in the Euro-Siberian tundra it is the reindeer proper (Rangifer tarandus). The effect of predators (arctic fox, sporadically bear and lynx) on the flora is small.

◘ **Fig. L-5** Seasonal foraging behaviour of wild reindeer in Hardangervidda (modified after Skogland 1983) 1 Loiseleurio-diapension; 2 Cladonio-juncetum trifidi; 3 Phyllodoco-Vaccinion myrtilli and Potentillo-Polygonion vivipari; 4 Nardo-Caricion gigelowi; 5 Adenostylion alliariae; 6 Caricion nigrae; 7 Ranunculo-Salicetum herbaceae; 8 Cassiopo-Salicetum herbaceae.

It is now known that numerous species of megafauna have only become extinct in the last 20,000 years (Martin 1984, Simmons 1996). It is even assumed that up to 200 genera of large mammals and birds disappeared by the end of the last ice age. In North America, about ⅔ of the large mammals that can still be traced toward the end of the last ice age (i.e., about 13,000 years ago) are extinct. These include 3 elephant-like species, 15 ungulate species, numerous large rodents and predators, 6 edentate species (giant sloth, armadillo, anteater, etc.). There is no evidence of similar extinction rates from earlier glacial epochs and interglacials that would suggest glacial climatic changes as the cause. Rather, it must be assumed that, especially at the end of the last ice age, the great waves of Indian immigration across the Bering Strait were the main cause of this mass exodus. The conquest of the continent from Canada to Mexico may have taken place in 350 to 500 years. Within a period of 500 years, most species also became extinct. Similar extinction periods are known from New Zealand, from Madagascar, from Java, each after the arrival of man.

In Eurasia, the extinction rate has not been quite so dramatic. While at least 24 genera have disappeared in North America, there were probably nine species in Eurasia, including the mammoth (Mammuthus primigenius), the woolly rhinoceros (Coelodonta antiquitatis), the great elk (Megaloceros giganteus), the musk ox (Ovibus moschatus), the steppe bison (Bison priscus), a buffalo species (Homoioceros antiquus), and three carnivores (Simmons 1996). Musk oxen have been reintroduced in some places today.

In addition to improved hunting techniques during the heyday of prehistoric man, rapid warming and the advance of forest vegetation may also be partly responsible for the suddenly high extinction rate of megafauna.

5 **Man in the tundra**

The seasonal migration of reindeer herds has had a lasting effect on the hunting behaviour of the people of the tundra. Domesticated reindeer herds, for example among the Tungus (a tribe in Siberia), migrate from the taiga to the tundra in summer and back to the taiga in early autumn. In the tundra of North America live different Eskimo tribes, which have adapted themselves completely to the arctic conditions. The individual tribes also trade among themselves, some hunt mainly whales and seals, others are active inland as caribou hunters, but also capture mountain sheep, moose, beavers, bears, snow hares, ducks and geese. Whale meat, blubber and fish oil are then traded for caribou meat and berries (Campbell 1985).

The way of life of the Eskimo in N Alaska and especially their way of living in mostly circular huts is an example of the possible way of life of the people during the ice age in Europe, for example during the Magdalenian period.

The huts are built semi-underground, thickly packed with grass sods, with a roof of whale ribs covered with animal skins, providing excellent thermal insulation.

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| **Box L-2** The subzonobiomes of the tundra |
| From south to north, three subzonobiomes can be distinguished in the Arctic tundra:1. the dwarf shrub tundra in the area of postglacial forestation,
2. the actual moss and lichen tundra and
3. the cold desert, commencing where plant growth becomes very sparse.
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Similar construction methods are known from numerous excavations from the Magdalenian period, with first evidence of Cro-Magnon man as early as 30,000 before today, with a heyday in southern France (Dordogne) between 19,000 and 13,000 years before today. Even today there are such constructions in Iceland or northern Finland (Lapland).

The reindeer was also the main source of meat for Cro-Magnon man. But also remains of bison (Bison bonasus), mammoths, horses, wild cattle have been excavated from the dwellings. It is very likely that the systematic exploitation of the rich wild animal population was forced by the Cro-Magnon man. In any case, by the end of the Upper Pleistocene, this form of foraging, based primarily on a wild animal species, was already fully developed. It is still evident today in a similar way among tribes of the tundra, albeit today with improved technological methods and the availability of dogs, boats, and sleds. However, both the Stone Age people in the ice-age tundra of Central Europe and the Eskimos had highly developed technical aids: thermally insulated huts, clothing, traps, etc., and also already simple machines such as harpoons and spear-throwers.

Today, Western civilization has caused profound changes. Alcohol is a big problem. Snowmobiles replace dog sleds, hunters use rifles. Today, a few Eskimos can decimate an entire herd of caribou in a day. Hunting has become so easy that it is no longer important to use all the parts of a shot animal; only the best pieces are taken. Surplus game is sold.

6 **Arctic cold desert and the solifluction**

The Arctic Cold Desert is the northernmost of the three subzonobiomes of ZB IX. Here, too, oceanic and continental areas can be additionally distinguished (Aleksandrova 1971).

In the cold desert, days of alternating frost, on which the temperature exceeds zero twice, are very frequent; this gives rise to the phenomenon of solifluction, the flowing of the soil. Already in the tundra itself, as well as in the alpine and nival altitudes of the mountains, the peat mounds and frost hummocks or bulbous tundra are formed by local formation of ice with a great increase of volume under the cover of plants in the wet soil. Even on slopes with very little incline, the soil is slowly pushed downward, the slope taking on an appearance as if it were covered with cattle steps. The frost stairs are low steps that run parallel to the isohypses. ◘ Fig. L-6 shows the cross section through such a step. Such soil movements become more conspicuous towards the north.

◘ **Fig. L-6** Earth flow on a shallow slope in the Arctic (Alaska). The fibrous peat layer (F) with the living plant cover has moved about 30 cm from I to II, forming a fold in which the free silt soil (S) is partially enclosed (modified after Walter 1960).

Where, in autumn, an unfrozen wetted layer is compressed between the permafrost soil below and a freezing layer above, it bursts the upper freezing layer in places and pours out as a liquid clay mush over the plant cover, forming a vegetationless patch several centimetres higher (◘ Fig. L-7). The spotted tundra is formed.

A consequence of the frost is also the pressing and sorting out of stones from the soil. Fig. L-8 explains this process: when the upper layer of soil freezes, it sucks in water from below and increases in volume; in the process, it lifts up the stones that are stuck in the freezing layer. A cavity forms under the stone into which fine sand falls; after thawing, therefore, the stone remains at a slightly higher level than before. If this is repeated many times on the days when the frost changes, the stone eventually lies above the surface of the ground. It may happen in winter also in gardens of temperate regions where stones are accumulating on the surface. Usually the freezing of the soils starts from single points, which are one or more meters apart. Then the stones are not only lifted out, but at the same time pushed aside. In the final result, they form a stone network pattern between the freezing centers, that is, a polygonal soil (◘ Fig. L-9). The plants find sporadic refuge between the stones of the polygonal floor, where the movement is least. If this process takes place on a slope, the stones are not only lifted but also pushed down the slope; the stone streams or slide, patterned strip soils are then formed (► Fig. D-67).

◘ **Fig. L-7** Spotted tundra with vertical section through a spot. The spots are formed by pressing up the liquid loam trapped between the permafrost soil below and the freezing layer above, which then pours over the surface and forms a vegetationless loam spot a few cm higher (after Walter 1990).

◘ **Fig. L-8** Top: Schematic representation of the processes involved in freezing and thawing the soil. 1 before freezing; 2 soil frozen on top, stone is lifted; 3 after thawing, stone has moved up to the surface. Bottom: stone net formation. A: at x freezing centre; B: arrows show the direction in which the stones move; C: original position of the stones in the soil; D: their final position when the frost stone network or polygonal soil (in section) has formed (after Walter 1990).

◘ **Fig. L-9** Tundra with larger stone rings (a) and earth polygons (b) in Spitsbergen (photos: Jaroslav Obu; Alfred-Wegener-Institute for Polar Research, [https://t1p.de/o03l](https://t1p.de/o03l%22%20%5Ct%20%22_blank)).

This constant soil movement in the Arctic does not allow the plant cover to come to rest and has an unfavourable effect. This can already be observed on Iceland (Lötschert 1974), much more clearly on Spitsbergen.

Solifluction is of equal importance in the mountains, too, in the upper alpine and subnival belts, but only locally and not over such wide areas as in the Arctic (► Fig. D-67).

As far as the composition of the vegetation is concerned, the floristic differences around the whole North Pole are relatively small. A relatively large percentage of the few species are distributed circumpolar.

7 **Antarctica and Subantarctic Islands**

, Only two flowering plants have been found native on the edges of the ice-covered Antarctic continent: Colobanthus crassifolius (Caryophyllaceae) (◘ Fig. L-10) and the grass Deschampsia antarctica (◘ Fig. L-11). Recently, Poa pratensis and P. annua have been imported, as well as *Stellaria media, Ranunculaus repens* and *Carex aquatilis*. Otherwise, only mosses, many lichens (Øvstedal & Lewis Smith 2001), and land algae occur, a total of several hundred species. They are restricted to intermittently snow-free sites on the coast, steep cliffs, and scree slopes (◘ Fig. L-12). Quantitatively, their biomass is of very little importance.

Where higher plants are generally absent, due to lack of water or low temperatures or human influences, so-called "biological soil crusts" made up of prokaryotic bacteria and cyanobacteria, eukaryotic algae, microfungi, lichens and mosses can instead develop extensive microecosystems. In the Antarctic, they regionally cover up to 55 percent of the open ground. They are joined by rock-colonizing organisms such as cyanobacteria, green algae and lichens, which live as so-called endoliths in the upper millimeters of rocks or as hypoliths on the underside of quartz pebbles. The astonishing diversity of these “primitive” communities is only revealed by looking through the microscope or looking at molecular genetic data (Kanz et al. 2020).

 and rock surfaces

In the sea around Antarctica, with its constant westerly storms, are scattered many small islands, most of them south of the 50th parallel. They are all characterized by their treelessness, for the summers are cool, the winters not cold; almost isothermy prevails on these islands, for example, the values of temperature vary almost throughout the year on the Macquarie Islands (54° 3' S) only between 2.8 °C and 7.7 °C (◘ Fig. L-13). Drizzle and fog are typical of the weather. One has spoken of a wind desert; for only in the windbreak is the vegetation more luxuriant.

**Fig. L-10** Deschampsia antarctica, the only grass species in Antarctica, Penguin Island, Antarctic Peninsula (photo: O. Krüger).

**Fig. L-11** Colobanthus crassifolius (Caryophyllaceae), Hannah Point, Livingston Island, Antarctic Peninsula (photo: O. Krüger).

◘ **Fig. L-12** Antarctic rock ice desert with thin lichen coverings on the rocks (Admirality Bay, King George Island). Penguins gather on the flat terrace banks to form a breeding colony (photo: L. Kappen).

◘ **Fig. L-13** Thermoisopleth diagram of Macquarie Islands with the course of isotherms parallel to the Y axis as an indication of a distinct seasonal climate of the polar regions (modified after Troll 1943).

The most common plant on the Kerguelen Islands is the dense rosette-forming Azorella selago (Apiaceae). In the past, the Kerguelen cabbage, Pringlea antiscorbutica (Brassicaceae) with its large leaves, was used by sailors as a fresh vegetable against scurvy (vitamin C deficiency disease) (◘ Fig. L-14). Acaena species (Rosaceae) are common on all islands. Tussock grassland (Festuca and *Poa* species) also occurs, as well as many mosses, ferns, and lichens. Various cushion-forming species are characteristic of the subantarctic, as always of very windy sites.

◘ **Fig. L-14** The Kerguelen cabbage (Pringlea antiscorbutica, Brassicaceae), which used to be a vital vegetable for the seafarers' vitamin C supply (photo: [https://t1p.de/blzc](https://t1p.de/blzc%22%20%5Ct%20%22_blank)).

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The mega-city Tokyo as an example of urbanization and globalization. A metropolis that is constantly expanding not only outwards to the peripheries, but also into the third dimension (Photo: Breckle)

Coal-fired power plant near Leipzig operated by opencast lignite mining, one of the anthropogenic contributions to the additional greenhouse effect (Photo: Breckle)