[IMAGE]

The imperial crown (*Fritillaria imperialis*) is not rare in the mountains of Iran and Afghanistan (orobiome VII), here from the Panshir valley from 2800 m elevation (photo: M. Keusgen)

[IMAGE]

Pine-spruce taiga (zonobiome VIII) in S Finland at Nuuksio (photo: Breckle)

[IMAGE]

*Linnaea borealis* in the herb layer of the N taiga (zonobiome VIII) in Finland (photo: Breckle)

**II Special part**

**Part K - ZB VIII: Zonobiome of the taiga or of the cold temperate boreal climate**

1. **Climate and soils**
2. **The coniferous species of the boreal zone**
3. **The oceanic birch forests in ZB VIII**
4. **The European boreal forest zone**
5. **On the ecology of the coniferous forest**
6. **The Siberian taiga**
7. **Extreme continental larch forests of eastern Siberia with the thermokarst phenomena**
8. **Orobiom VIII - mountain tundra**
9. **Man in the taiga**
10. **Zonoecotone VII/IX (forest tundra) and the polar forest and tree line**
11. **Literature**

[IMAGE]

Lichen pine forest (zonobiome VIII), a taiga with a dense carpet of fruticose (mini-shrub like) lichens (Cetraria, Cladonia, Alectoria etc.) in the herb layer near Begna-Stormyrhaugen, E Norway (photo: E. Fischer)

1 **Climate and soils**

The actual boreal zone (► Fig. J-49), Zonobiome VIII, begins where the climate becomes too unfavourable for the hardwood-deciduous species, i.e. where the summers become too short and the winters too long. It can be recognised in the climate diagram by the fact that the duration of time with daily means above 10 °C falls below 120 days and the cold season lasts more than six months (◘ Fig. K-1). This zone is identified on the map of ecoclimates (► Fig. A-50) as a cold-temperate region with 3-4 thermal months of vegetation and is divided into four categories according to humidity levels despite the uniform vegetation cover. The N boundary of the boreal zone against the Arctic is where about only 30 days with daily means above 10 °C and a cold season of eight months are typical for the climate.

However, with the wide extension of this zone, one cannot speak of a uniform climate, but one must distinguish a more cold-oceanic climate with a relatively low amplitude of temperatures and a cold-continental one, where in extreme cases the range between the temperature maximum (+30 °C) and minimum (-70 °C) can reach 100 K. Likewise, the temperature ratios change from N to S.

2 **The coniferous species of the boreal zone**

Due to the climatic conditions, the following subzonobiomes can be distinguished: a northern, a middle, a southern (each with evergreen conifers) and an extreme continental (with the deciduous Larix). Separated from these are the oceanic forms with birch trees in NW Europe and NE Asia.

Similarly structured, but not as extensive, is the taiga in Canada and Alaska.

In the oceanic area, birch species *(*Betula*)* play an important role (Ahti & Jalas 1968). The floristic composition of the tree layer is naturally different across the vast distances. For coniferous forests, the number of coniferous species is very large in N America and E Asia, but very small in the Euro-Siberian region. As a cause, the same vegetation history is reflected here as already in ZB VI.

In N America we have plenty of species of the genera Pinus, Picea, Abies, Larix, but also Tsuga, Thuja, Chamaecyparis and Juniperus, which, however, belong more to the transition zone. The species of these genera on the Pacific coast are different from those in the E part. Only the Norway spruce (Picea glauca) goes from Newfoundland to the Bering Strait. Black spruce (Picea mariana), which otherwise occurs mostly on poor soils, also grows at the tree line toward the Arctic, as does Larix laricina in the continental areas. In addition, Abies balsamea and Thuja occidentalis grow, as does Pinus banksiana, the latter especially on burnt areas. Very diverse species are found in the coniferous forest belt of the mountains.

In contrast, only the spruce (Picea abies) and the pine (Pinus sylvestris) play a role in the boreal zone of Europe. Only in the E part is the spruce replaced by the closely related Siberian species, Picea obovata, and Abies sibirica, Larix sibirica and Pinus sibirica, a subspecies of the Swiss stone pine (Pinus cembra) are added. The proportion of spruce decreases, and in continental E Siberia it is completely absent. At the same time Larix sibirica is replaced there by *L.* dahurica. Larch forests alone cover 2.5 million km2 in Siberia. In the N part of Japan, the number of coniferous species is increasing again.

In N Europe, the traces of the Ice Age are omnipresent. Especially in the area of the European taiga (Scandinavia), the transformation of the landscape by the large inland ice masses from last glacial and their melting can be seen above all in the formation of the Baltic Sea (◘ Fig. K-2). It was only a few thousand years ago that the Baltic Sea was formed in its present shape. In the surrounding landscapes, the glacial traces can be read in the formation of countless dead-ice waters (◘ Fig. K-3) and in the various deposits (moraines, glacial soils, bedloads, etc.).

K-1 Climate diagrams from the boreal zone of N Europe (Archangalsk), the mixed forest zone (Moscow) and the boreal zone of Siberia (Irkutsk). With horizontal lines number of days with mean above +10 °C (top) and above -10 °C (bottom).

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| Box K-1 Features of the zonobiome VIII |
| Zonobiome VIII is characterized by long, cold winters and short summers, extremely large temperature fluctuations occur during the year. ZB VIII occupies huge areas in Eurasia: accordingly, one can distinguish several subzonobiomes. |

◘ **Fig. K-2** Late glacial and Holocene development of the Baltic Sea. **A** Baltic Ice Lake with fresh water (10,200 years ago); **B** Ancylus Lake with fresh water (8,000 years ago); **C** Litorina Sea (about 5,000 years ago) (from Dierßen 1996).

**Fig. K-3** Formation of water bodies after melting of the dead ice in the bedload (left), the deposits from the advancing ice, and in the moraine material (right).

3 **The oceanic birch forests in ZB VIII**

The strong differences in continentality across the taiga zone of Eurasia are clearly noticeable floristically, as already discussed. In the oceanic climate zone on the Atlantic in Norway on the one hand, and on the Pacific in Kamchatka on the other, sparse forests of birch and pine occur. In Norway, spruce is almost entirely absent, so a taiga zone is not actually developed. The tree line in N Scandinavia is formed by Betula tortuosa (closely related to B. alba) (◘ Fig. K-4). Betula tortuosa is low-growing with an irregularly curved trunk ('drunken trees') (◘ Fig. K-5A).

Similar looking sparse forests occur in Kamchatka (◘ Fig.K-5B). There Betula ermanii, partly with the crooked pine Pinus pumila, again forms the polar forest boundary. The forests of Kamchatka are dominated by Betula ermanii, which forms very heavy wood (specific gravity >1; hence the name stone birch) and can live for several hundred years. Its distribution is very wide, it also reaches Japan and Korea. Other birches (B. japonica, B. middendorfii) and *Larix species* (L. gmelinii, L. kamtschatica, L. cajanderii) are sporadically associated. Kamchatka forests also do not belong to the taiga in the strict sense. Only rarely do spruce forests occur (with Picea ajanensis).

◘ **Fig. K-4** Forest tundra in a mosaic of forest plots of Betula tortuosa and dwarf shrub tundra near Abisko (N Sweden) (photo: Breckle).

◘ **Fig. K-5 A** Low-growing trees of Betula tortuosa with an irregularly curved trunk ('drunken trees') in the tree tundra of the Kola Peninsula (photo: O. Agachanjanz).

◘ Fig. K-5 B Curved trunks of *Betula ermanii* in the subarctic region in Kamchatka, N of Petropavlovsk (photo: Breckle)

◘ Fig. K-5 C The species rich herb layer in the stone birch forest of Kamchatka has attractive species like *Cypripedium jatabeanum* (photo: Breckle)

◘ Fig. K-5 D *Trillium camchatkense* in the herb layer of *Betula ermanii* forests in Kamchatka (photo: Breckle)

◘ Fg. K-5 E *Trollius riederana* in the herb layer of open stone birch forests in Kamchatka is common on less shady sites (photo: Breckle)

◘ Fig. K-5 F There are many genera which are the same in Europe as well as in Kamchatka but represented by other species like *Geranium erianthum* in the *Betula ermanii* forest (photo: Breckle)

4 **The European boreal forest zone**

Typical for ZB VIII in N Europe is the dark spruce forest, called taiga, on podsol soils with a layer of raw humus, a bleached horizon and a compacted B horizon (◘ Fig. K-6). Such soils form in the humid boreal zone on any parent rock, but become more pronounced the more base-poor it is. The litter of spruce is difficult to decompose and lies above the A0 horizon, which consists of organic matter interwoven by the rhizomes and roots of dwarf shrubs as well as fungal mycelia and is called the raw humus layer. It can be easily lifted off from the underlying A1 horizon(mineral soil containing humus,hence also called overlying humus or dry peat) as a soft layer. The humic acids formed in the raw humus migrate with the rainwater into the depth and on their way cause a complete leaching of the bases and sesquioxides (Fe2O3, Al2O3), so that only bleached fine quartz sand remains in the A2 horizon(bleached horizon). At the boundary of the unleached subsoil, the humus brine with the sesquioxides are precipitated as a result of the decrease in acidity or by the water withdrawal of the tree roots. The B horizon is formed, which is dark brown (humus podsole) or rusty red (iron podsole) in colour.

In the spruce forest (Piceetum typicum), in addition to the tree layer, a herb layer and a closed moss layer can often be distinguished. The herb layer is dominated by blueberry (Vaccinium myrtillus), in dry forest types also by cranberry (Vaccinium vitis-idaea) or in the S zone often by wood sorrel (Oxalis acetosella). Lycopodium annotinum, Maianthemum bifolium, Linnaea borealis, Listera cordata, Pyrola (Moneses) uniflora, etc. are also very characteristic. At high groundwater levels and high precipitation, the accumulation of raw humus increases, leads to peat formation, and results in the formation of raised bogs (► Fig. K-18). The moss layer is first dominated by Polytrichum and in the later stage by Sphagnum. If waterlogging occurs due to flowing, oxygen-rich groundwater, the spruce forests change into floodplain forests.

◘ **Fig. K-6** Podsol soils form in the humid boreal zone on any parent rock. Their special feature is the formation of the A2 bleaching horizon (photo: Breckle).

In addition to spruce forests, the proportion of pine forests is always very large in the boreal zone. The pine (Pinus sylvestris) displaces the spruce on drier sites. The herb layer of these sparse forests is formed by heather (Calluna vulgaris) together with lingonberry (*Vaccinium vitis-idaea*), many lichens (Cladonia, Cetraria) are found in the moss layer; characteristic species of the herb layer are Pyrola species, Goodyera repens, Lycopodium complanatum, etc. However, pine is often also widespread on sites favourable for spruce, but only after forest fires, which can also be caused by lightning. On burnt areas there is often a mass development of Molinia coerulea, Calamagrostis epigeios or Pteridium aquilinum, according to an increasing dryness of the habitat.

On such burnt sites of the tree species, the birch and aspen grow up most rapidly; they are then displaced by the pine. Under the pine the spruce grows slowly. In N Sweden the birch stage lasts about 150 years, the pine stage 500 years. New fire often occurs before the spruce stage corresponding to the zonal vegetation is reached. The large proportion of pine is therefore understandable. Pine is absent only on moist sites with low fire danger. Corresponding forests are found in North America, only they are somewhat richer floristically. Several species are distributed throughout the taiga (circumboreal). Others differ regionally, typically with each genus having several distinct species, each occupying different regions of the taiga.

The forests of the taiga in N America are as in Siberia largely coniferous, dominated by larch, spruce, fir and pine. The woodland mix varies according to geography and climate so for example the Eastern Canadian forests ecoregion of the higher elevations of the Laurentian Mountains and the northern Appalachian Mountains in Canada is dominated by balsam fir *Abies balsamea*, while further north the Eastern Canadian Shield taiga of northern Quebec and Labrador is notably black spruce *Picea mariana* and tamarack larch *Larix laricina*.

5 **On the ecology of the coniferous forest**

The denser the stand, the less the sun's rays penetrate to the ground. Under a spruce forest, the ground is therefore 2 K colder than in open places. The snow cover is also less thick, so that the ground freezes deeper. The frost depth was 85 cm in the soil of a dense stand compared to 50 cm in the thinned stand, where the ground frost disappeared at the beginning of June, while in the dense stand it persisted until the beginning of August.

The spruce roots very shallowly in the upper 20 cm and even shallower at high groundwater levels (◘ Fig. K-7). A constantly good water supply at a medium groundwater level is necessary for a high production of spruce forests. The deeper-rooted pine is not so sensitive to soil dryness. The total annual water output of typical spruce forests is about 250 mm in the northern taiga, 350 mm in the middle, and 450 mm in the southern. The average production of organic matter is 5.5 t/ha per year, wood increment is 3 t/ha, whereas in the southern taiga it is up to 5 t/ha. The greatest annual increment is reached by forest stands in the north only at the age of 60 years, in the south already at the age of 30-40 years. The phytomass of the tree layer in pine forests is a maximum of 270 t/ha, that of the understory in old stands up to 20 t/ha. Similar data from a pine forest in central Sweden are compiled in ◘ Fig. K-8.

◘ **Fig. K-7** Pine-spruce taiga, south of Saint Petersburg, with large windthrows and thus upright root plates (for size comparison: Prof. Okmir Agachanjanz). The herb layer is dominated by Vaccinium species, deeper parts are boggy, there are small Sphagnum depressions (photo: Breckle).

◘ **Fig. K-8** Carbon stocks (in boxes in g C/m2) and carbon fluxes (arrows in g C**·**m-2**·**J-1) in a pine forest in central Sweden. Mineral soil is included to a depth of 30 cm. Arrows with R: respiration losses. Blue lines indicate transport via dead organisms or via excreta. Values in brackets are uncertain (modified after Dierßen 1996).

The quantity of litter produced during the growth of old stands may exceed 1,000 t/ha; however, it is not accumulated, but continuously decomposed until a state of equilibrium between inflow and outflow is reached at a litter mass of 50 t/ha. Only at very wet sites by peat formation is organic mass stored. Under such unfavourable conditions, the annual increase in dry mass of the tree layer is often lower than that of the other layers, for example, in the herbaceous spruce swamp forest for the tree layer 850 kg/ha (total 1,906 kg/ha), and in the pine raised bog for the tree layer 104 kg/ha (total 1780 kg/ha). The leaf area index is relatively high because there are at least two years of needles (for pine forests of the boreo-nemoral zone LAI = 9 to 10, for spruce forests of the taiga above 11).

The conifers always have an ectotrophic mycorrhiza, whereby the area of the root system is greatly expanded by the fungal hyphae. In this way, the nutrients contained in the raw humus layer are more easily accessible to the trees. Tree root competition is very high for herbaceous layer species. On shallow granitic soils, pines can consume all water, so the herb layer is completely absent and the soil is covered only with lichens (◘ Fig. K-9). Under these circumstances, young pine growth cannot occur, although the light conditions are favourable. It only occurs where an old tree dies (► Fig. K-7), forming a gap and root competition is lacking. With greater soil moisture, root competition makes itself felt by competing for the nitrogen that tree roots take up, so that only dwarf shrubs with extremely low nutrient requirements (Vaccinium myrtillus) can persist. However, if the tree roots are cut to eliminate their competition, more demanding species such as Oxalis acetosella or even the nitrophilous raspberry (Rubus idaeus), which otherwise only occurs in clearings where tree-root competition is also absent, are established under unchanged light conditions. Thus, it is often not the light factor that determines the composition of the herb layer, but the amount of nutrients available to the herbs under competitive root conditions.

◘ **Fig. K-9** Dry lichen pine forest in central Norway near Grimsdalen (350 mm annual precipitation). The herb layer consists almost exclusively of a dense carpet of shrub lichens (Cetraria, Cladonia, Alectoria, etc.) up to 25 cm high (photo: Breckle).

The following information is given on the water balance of a spruce forest in Sweden:

A large proportion of the precipitation is lost through wetting of the crowns (interception), amounting to just over 50% (in the less dense E European stands it is only 30%). The moss and litter layer also retains further water, so that only about the 1/3 precipitation is available to the roots. There was 90 mm in the summer months, and 202 mm in the others, making a total of 292 mm. These are almost completely consumed by transpiration of the 40-year-old stand. In humid locations, as much as 378 mm are released to the atmosphere by transpiration; for this reason, part of the water losses must be covered by drawn from the groundwater.

Most ecophysiological studies have been carried out in the spruce stage of the Alps, but conditions in the boreal zone are likely to be at least partly analogous.

The active transpiration goes in parallel with a correspondingly intensive photosynthesis. In spruce one can distinguish between sun and shade needles. The conditions are reminiscent of those of the beech. In contrast to the beech, the active period of the evergreen spruce starts very early in spring and continues in autumn until the occurrence of occasional frosts. The seasons with low night temperatures and thus low respiration losses are particularly favourable for the net gain of dry matter. After a night of frost, however, photosynthesis is temporarily inhibited, but it is only after the onset of the actual cold period that the spruce falls into permanent dormancy and no longer assimilates even on sunny days.

At the same time, however, respiration drops to such low levels that it is hardly measurable and does not cause any significant loss of substances. During this time, the needles lose their fresh green coloration, and the chloroplasts are difficult to see under the microscope.

After a long cold period, photosynthesis needs a certain start-up time in spring until it returns to normal. The photosynthetic apparatus must first be reactivated. In the case of mountain pines, it was found that young saplings overwinter under snow with green needles and then immediately start CO2 assimilationin spring at higher temperatures.

The transition to winter dormancy is associated with hardening, that is, with a strong increase in frost resistance. The same processes as in defoliated deciduous trees can be observed in the evergreen conifers of the boreal zone. The hardening is still much more definite. While spruce needles in the unhardened state are killed by frosts as low as -7 °C in autumn, they can withstand temperatures of nearly -40 °C in winter without damage. Very sensitive to even light frost are the very young spruce shoots in spring. They can therefore be damaged by late frosts.

The frost hardiness of the needles can also be changed artificially, namely hardening by exposure to low temperature especially in late autumn and spring, dehardening by normal room temperature especially in December and late winter. Hardening causes that frost damage of conifers is not observed in their natural habitat, even in Siberia at temperatures below -60 °C. As a result of hibernation, conifers can withstand polar winters in complete darkness. Adaptability is species-specific, which is reflected in the distribution of individual species. Only a few species can withstand the extremely continental Siberian winters (► Fig. K-13), the needle-throwing larch better than the evergreen species. Certainly there are also differences within a species according to provenance. Spruces from the Alps will behave differently than those from the northern boreal zone, spruces from the upper tree line differently than those from lower altitudes. Even the shape of the tree is different; the more extreme the conditions, the more conical, pointed-crowned the trees become, i.e. the growth of the lateral branches is more inhibited than that of the main shoot. The same can be observed with the pine in the polar region.

It is difficult to say whether this tree form is due to the selection of mutants which suffer less from the danger of snow-breakage, for the same phenomenon is observed in fir in Albania at the lower, i.e. the dry limit, where there is no danger of snow-breakage; it seems rather that under generally unfavourable conditions the inhibition of the lateral branches occurs earlier than in the main shoot (under unfavourable light conditions it is the reverse). In Utah (N America), for example, Picea, Abies, and Pseudotsuga had extremely pointed crowns on dry slopes, but blunt crowns on the valley floor, with the same risk of snow breakage.

Another phenomenon must be mentioned here: the waves of regeneration. In coniferous forests in Japan, it has long been observed that broad strips of dead trees gradually move on and are replaced by a new wave of young growth of almost the same age. This so-called Shimagare phenomenon (◘ Fig. K-10 and ◘ Fig. K-11) only occurs in monospecific forests with a nearly equal-age structure of trees, which usually grow up very densely as a natural monoculture.

◘ **Fig. K-10** Schematic transect through an Abies *balsamea* forest(Maine, NE USA) showing a regeneration wave, as is also known as the Shimagare phenomenon (► Fig. K-11) from Japan (modified after Sprugel 1976, from Burrows 1990).

◘ **Fig. K-11** Abies veitchii forest on the Shimagare slope (Japanese Alps) with a dieback wave. A regeneration wave starts from the left (photo: Breckle).

This natural forest dieback not only presupposes certain, albeit rare, events (storms, fire streaks) that contribute to age cohort synchronization, but it is also an example of spatial self-organization, whereby cohorts of trees of the same age die synchronously and young growth follows synchronously; from other regions this phenomen also was described (Mueller-Dombois 1987, Iwasa et al. 1991, Jeltsch 1992).

6 **The Siberian Taiga**

Throughout the Eurasian taiga region, the pine (Pinus sylvestris) occurs, of which many forms are distinguished. However, it does not form a zonal vegetation, but only fills gaps, for example on burnt areas, on poor sandy soils and on boggy soils. Instead, Picea obovata, which is closely related to the European P. abies, often occurs dominantly. Together with the Swiss stone pine (Pinus sibirica, closely related to the alpine P. cembra) and with Abies sibirica it forms the Dark taiga. However, pure stands of Abies sibirica also occur and are called Black or Gloomy Taiga. Conversely, in extremely continental E Siberia Larix gmelinii (= L. dahurica) occurs in pure stands, forming the Light Taiga. All these taiga types also contain Larix sibirica in the more N zone, which forms the polar tree line in W Siberia, and L. gmelinii takes its place in E Siberia. But also in the Siberian taiga, birch repeatedly appears in open places (◘ Fig. K-12). It not only forms pioneer transition stages on fire or storm areas, but also persists for a long time in undisturbed stands.

Fire is of the most important factors shaping the composition and development of boreal forest stands, it is the dominant stand-renewing disturbance through much of the Canadian taiga (Amiro et al. 2001). The average time within a fire regime to burn an area equivalent to the total area of an ecosystem is its fire rotation (Heinselman 1973) or fire cycle (Van Wagner 1978). However, as Heinselman (1981) noted, each physiographic site tends to have its own return interval, so that some areas are skipped for long periods, while others might burn two-times or more often during a nominal fire rotation.

The dominant fire regime in the taiga is high-intensity crown fires or severe surface fires of very large size, often more than 100 km2, up to 4,000 km2. Such fires kill entire stands. Fire rotations in the drier regions of W Canada and Alaska average 50–100 years, shorter than in the moister climates of E Canada, where they may average 200 years or more. Fire cycles also tend to be long near the tree line in the subarctic spruce-lichen woodlands. The longest cycles, possibly 300 years, probably occur in the W boreal taiga in floodplain white spruce.

Amiro et al. (2001) calculated the mean fire cycle for the period 1980 to 1999 in the Canadian taiga)at 126 years. Increased fire activity has been predicted for W Canada, but parts of E Canada may experience less fire in future because of greater precipitation in a warmer climate (Flannigan et al. 1998).

7 Extreme continental larch forests of eastern Siberia with thermokarst phenomena

The shady coniferous forests of W Siberia with Picea obovata, Abies sibirica and Pinus sibirica (Dark Taiga) differ substantially from the very light forests of needle-throwing Larix dahurica (Light Taiga) in E Siberia. This is a vast subzonobiome with an extremely continental boreal climate (absolute annual temperature variation up to 100 K), which can be seen from the climate diagrams on ◘ Fig. K-13. In N America, a similar limited but somewhat less extreme climate area is present around Fort Yukon (Alaska).

Precipitation in this area is very low (less than 250 mm); however, this is compensated for by the slowly thawing upper layer of permafrost soil. The roots absorb the meltwater so that a forest can grow. The larch forests usually have a dwarf shrub understory of Vaccinium uliginosum, Arctous alpina, on dry soils Vaccinium vitis-idaea, Dryas crenulata, on moist soils Ledum palustre and on very dry only a soil layer of lichens. Further north, the sparse forests change into open tree meadows (Redkolesje) and then into a dwarf shrub tundra (ZE VIII/IX) with Betula exilis (knee-high) and Rhododendron parviflorum.

◘ **Fig. K-12** Original pine-birch taiga between Irkutsk and Kultuk, with Rhododendron dahuricum and Ledum palustre in the low shrub layer (photo: U. Kull).

The extent of thermokarst phenomena in the coldest part of the northern hemisphere is particularly impressive here.

Burkhard Frenzel reported on thermokarst (oral communication):

"The permafrost (◘ Fig. K-14) of Siberia, probably also of Alaska, developed since the early glacial periods. Each ice age contributed to its expansion, whereas in the warm periods its area and thickness were reduced. However, warm-period climates are also favourable to the formation of new permafrost in these landscapes, even if the thickness of the seasonal thaw is greater than during cold or glacial periods: decay and formation of permafrost go hand in hand. These appearance and dissolution processes become ecologically and geomorphologically effective especially on fine-grained sedimentary rocks".

◘ **Fig. K-13** Climate diagrams from the extremely cold continental region of E Siberia. Oimjakon is the cold pole of the N hemisphere.

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| Box K-2 The permafrost in Siberia |
| At low mean annual temperatures of -10 °C, the soil in E Siberia is permanently frozen to depths of 250 to 400 m: it is permafrost soil. In the relatively warm summers, only the upper 10 to 50 cm thaw, in well-drained soils at most 100 to 150 cm. |

◘ **Fig. K-14** The permafrost cover at Herschel Island, in the western Canadian Arctic in Yucon Territory. In summer, only a few cm of the upper layer of this thick permafrost cover thaws. The vegetation uses the meltwater for its growth (photo: Boris Radosavljevic, Alfred Wegener Institute for Polar Research: [https://t1p.de/o03l](https://t1p.de/o03l%22%20%5Ct%20%22_blank)).

During the ice ages, loesses (an aeolian sediment) and their derivatives were formed over large areas of what was then the extremely cold winter climate zone. In today's highly continental climates of the boreal coniferous zone, they are filled with permafrost ice up to 80 percent by volume. Local disturbances of the radiation balance and of the heat flow between atmosphere and soil, for instance by the natural forest fires occurring per area approximately every 180 to 240 years, by river erosion, etc., initially lead to an increase in thickness of the summer thaw soil. Since the rock had previously been far oversaturated with ice, this layer now slides away on sloping land surfaces. The soil is literally eaten up, which is why in Siberia we speak of the 'Jedom' series ('**Yedoma**'), i.e. the (Russian) 'eating away' loose rocks. Thus, due to increased summer thawing of the topsoil, a decrease in volume has occurred. It is commonly referred to as Thermokarst (◘ Fig. K-15). On horizontal surfaces, when thermokarst develops, the soil collapses: Drainless depressions up to several kilometres in size are formed, the so-called 'Alases', in which the rise of groundwater drowns the forest that may have existed previously.

◘ **Fig. K-15** Thermokarst-induced destruction of coniferous forest in the Canadian taiga. The top 5-8 m of the soil supporting the forest thaws, and the waterlogged mud transports the fallen trees downslope (photo: http://bit.do/bFRC6).

These phenomena have already been described by the travellers who roamed Siberia in the mid-17th century, a clear indication that Alas formation is a natural process, the beginning of which can now be traced back to the end of the Late Glacial (about 12,000 to 10,000 years before present). At present, Alas formation is promoted by clearing and construction activity.

Alases occur particularly frequently in the Viljuij depression, which is subject to a highly continental climate, and in its peripheral areas of C and E Yakutia. If the Alas are first as a rule in their center water-filled, then the steep, up to 50 m high edges offer due to improved natural drainage and intensified irradiation very multicolored steppe societies suitable starting points. About ⅓ of the approximately 900 kinds of higher plants of Jakutia belong to such plant communities, whose total area amounts to only few per cent of the country(Troeva et al. 2010).

If the lowering of the soils of the Alas proceeds slowly and does not accumulate too much water, then natural meadow communities, which are important today for the local cattle breeding, take the place of the destroyed larch or pine forests. Their species composition often refers to salinated sites.

Alas lakes can silt up. Hereby again the heat flow is changed and the permafrost spreads. However, as there is now a great deal of water in the Alases, large, ice-core-filled hills form in them, the 'Bulgunnjachi' or 'Pingos', which can also occur in the tundra (ZB IX) (◘ Fig. K-16). They grow in height until summer. Insolation prevents further growth of their ice cores, or until they rupture as a result of their high growth and summer heat can act deep into the Bulgunnjachi, leading to their disintegration. Such mounds have a life span of a few decades to a few millennia at most. However, it is always true that they also contribute to the increase of biotope diversity, since their steep slopes often provide abundant starting points for colorful steppe communities due to good drainage and increased insolation.

◘ **Fig. K-16** Bulgunnjachs or Pingos in a water-filled Alas in the tundra near Tuktoyaktut, NW Territories, Canada. The slopes of the Pingo, already split again and thus decaying, are occupied by grassy steppe vegetation (photo: Emma Pike: http://bit.do/bFT5R).

The occurrence of steppe communities in Yakutia is characteristic for all dry and in summer very warm, steep southern slopes, for example on the flanks sloping down to the large rivers.

In general, the climate of Yakutia can be described as at least semi-arid. This is clearly evident from the climate diagram on ► Fig. K-12, i.e. the potential evaporation is higher than the low annual precipitation even on euclimatopes.

In accordance with this, in the larch forests one finds treeless places - the "Tscharany" (Charani) - on which some salt accumulation takes place due to the strong evaporation. On such brackish, solonized soils grow salt plants, which also occur on sea coasts, such as Atriplex litoralis, Spergularia marina and Salicornia europaea, on wet salt soils also the grasses Puccinellia tenuiflora and Hordeum brevisubulatum (Walter 1974).

Since in the far north the steep S slopes are struck perpendicularly by the rays of the low sun at noon, individual steppe species can even still grow on Wrangel Island (71° N) (Yurtsev 1981). The following typical species are cited: Ephedra monostachya, Stipa krylovii, Koeleria cristata, Festuca spp. and other grasses, Pulsatilla spp., Potentilla spp., Astragalus and Oxytropis spp., Linum perenne, Veronica incana, Galium verum, Artemisia frigida, Leontopodium campestre, Aster alpinus (typical for Siberian steppes) and others.

These steppe islands occur today extrazonally on warm S slopes. They are relics of zonal steppes of glacial times, when the climate was more continental. At that time, foehn-like, strongly warming downdrafts came off from the huge icecap in summer, deflected to the east and blew over the ice-free periglacial surfaces, depositing the thick loess layers. The summers were obviously so hot that large dry cracks formed in the loess, in which the permafrost caused ripening and filling with ice (Jedome series). On the basis of recent Russian investigations, it must be assumed that during the glacial period such periglacial steppes extended zonally over the whole of Eurasia and North America and made possible a rich steppe fauna with steppe rodents, antelopes, wild horses up to the woolly rhinoceros and mammoth. And it was only with the appearance of man that the large mammals disappeared.

The tundra vegetation was probably only bound to boggy and swampy places around lakes, i.e. as pedobiomes to the lower parts of the relief. The frequent occurrence of Ephedra and Artemisia pollen in the pollen spectra of peat samples from the glacial period proves that steppes with these species grew all around, cold steppes, as they are found today rather restricted in a few places, especially in Yakutia. It could be called a very arid sZB VIIIa, which was widespread during glacial but very restricted today.

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| Box K-3 The dynamics of permafrost regions |
| The permafrost area, where all life seems to be so reduced because of the winter cold, is full of dynamics. |

Only when the ice melted in the postglacial period, the sea level rose, the Arctic Ocean was formed, the land connection between East Asia and Alaska was interrupted, and the Gulf Stream in the North Atlantic brought warm water to the Arctic Ocean, did the entire atmospheric circulation change. The air fronts moving westward from the Aleutian Islands on the one hand and from Iceland on the other reshaped the climate of the northern latitudes; it became humid and strongly oceanic in tint on the western flanks of the land masses. In the N part of the former periglacial steppes, tundra vegetation now spread and conquered the areas that had become ice-free, followed by forest vegetation, starting from the refugia, until the tundra and forest zones assumed their present position.

The periglacial steppe vegetation retreated into the arid area of today's continental steppes, and with it the corresponding fauna. But the animal species that could not keep up with the changes, parallel to the appearance of man, became extinct. These were just the largest forms such as mammoth, woolly Rhinoceros, giant deer (Megaloceros) and others (cf. Walter & Breckle 1991).

These remarks are intended to suggest that today's zonal tundra vegetation, but also the boreal coniferous forest zone with the many bogs in their present form, are in geological terms rather recent new formations. Today's raised bogs probably did not exist in the past either. Certain relicts of the periglacial steppes can be found on chalk cliffs in central Russia. Carex humilis with its scattered occurrence in the steppe heaths is also considered a periglacial relict. In the alpine mats grow many species that genetically belong to typical steppe genera, such as Astragalus, Oxytropis, Potentilla, Pulsatilla, Festuca, Avena s.l., especially also Artemisia, the edelweiss (Leontopodium) and Aster alpinus.

8 **Orobiome VIII - Mountain tundra**

The elevational sequence is very short in these N latitudes of ZB VIII. Already at low altitude the forest line is reached, formed by Picea, Pinus sibirica or Larix, depending on the geographical position. Above this in the alpine belt, however, one does not find a typical tundra, but a mountain tundra (Stanjukovitsch 1973).

In the Alps, the first snow falls on unfrozen ground and the temperature on the ground remains at about 0 °C throughout the winter under a thick blanket of snow. The perennial herbs are therefore not exposed to deep frosts or frost-drought and the vegetation consists of dense alpine mats.

It is different in the mountain tundra: the snow falls on ground that is already frozen, the snow cover is thin and blown off from the summits. There is permafrost, which is almost non-existent in the Alps. Winter storms are very strong, frost weathering is very intense; the debris moves slowly downwards (solifluction), and the fine soil is blown out. All this results in the mountain peaks in the mountain tundra being bare and called 'Golzy' (Russian golyj = bare). They are covered only by lichens and a few mosses, as well as isolated dwarf shrubs between the rocks. The conditions are reminiscent of the wind-swept ridges of the Alps with Loiseleuria and the same lichens.

Conditions are somewhat more favourable in the subalpine or 'Podgolez' belt, where the drifted snow can accumulate. The mountain tundra is found in the continental climatic area as far S as 50° N, even still in the Altai.

In the oceanic area of the boreal zone (Scandinavia, Kamchatka) mountain tundra is absent, and the alpine belt is somewhat more reminiscent of conditions in the Alps. Winters here are very snowy. The timberline is formed by birches (Betula ermanii, B. tortuosa).

9 **Mire types of the boreal zone (Peinohelobiome)**

The climate of the boreal zone is largely humid, i.e. precipitation exceeds potential evaporation due to lack of energy for evaporation, so the water balance is positive despite low precipitation. When the runoff of excess water to rivers is impeded, the water table rises and bogging occurs. Since the soils in the boreal zone are poor and acidic (podsols), the groundwater also has an acidic reaction and contains few mineral components. Mostly the groundwater is brown coloured by humus brine. Only in the case of limestone the conditions are different. Since large areas of the boreal zone in both Eurosiberia and N America are very flat, the groundwater table is high. As long as it remains more than 50 cm below the ground surface for most of the year, tree growth is possible, otherwise it is inhibited and the forests turn into bogs.

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| Box K-4 Boreal peatlands |
| Extensive areas in the boreal zone are not occupied by the zonal vegetation of coniferous forests, but by peatlands. |

In sub-regions of Finland, peatlands account for more than 40%, and in some cases even more than 60%, of the total area. The same applies to the boreal zone of E Europe and especially W Siberia, which is entirely covered by peatlands except for the parts near rivers. Similar conditions are found to some extent in Kamchatka (◘ Fig. K-17), Alaska, and Labrador and in the areas south of Hudson Bay. It is therefore necessary to treat the pedobiome of bogs following the coniferous forests. Often the boundary between coniferous forest and bog is difficult to draw. The already mentioned spruce forests with Polytrichum and Sphagnum already show strong peat formation.

◘ **Fig. K-17** Bog lakes in W Kamchatka with species-rich bog banks, partly with *Myrica tomentosa, Rubus chamaemorus* between low *Salix fuscescens* trellis, but mainly Cyperaceae such as *Carex rotundata, C. middendorfii*, in addition *Comarum palustre, Drosera rotundifolia, Pedicularis labradorica, Hammarbya paludosa, Platanthera tipuloides* and *Sphagnum*, in the water floating *Sparganium* (photo: Breckle).

In the geological sense, peat bogs (mire, “Moor” in German) are deposits of peat with a layer thickness of at least 20 to 30 cm. If the peat layer is thinner or the content of combustible substance is only 15 to 30%, we speak of anmoor bogs. In the ecological sense, bogs are communities of life that are bound to high groundwater, regardless of the thickness of the peat layer on which they grow. Because of the poor aeration of the soil, the bog plants root very shallowly, so that only the condition of the uppermost peat layers is important for them. The following types of peatland can be distinguished:

**1.** Topogenous bogs, which are bound to a very high water table and therefore occupy the lowest parts of the relief or occur where spring water escapes. This subheading includes fens of various kinds.

**2.** Ombrogenous bogs, which are wetted exclusively by rainwater falling on the surface and which rise above the surrounding area. These are **raised bogs** (► Fig. K-18).

**3.** Soligenous bogs, which are also wetted by precipitation, but do not rise above the surrounding area and are additionally overflowed by water that runs off the slopes when the snow melts.

The groundwater of topogenous peatlands may contain many mineral substances and can be rich in nutrients. Such bogs are therefore eutrophic or minerotrophic. Rainwater, on the other hand, is very pure and nutrient-poor; therefore, ombrogenic peatlands are oligotrophic or ombrotrophic. The trickle water that the soligenic peatlands receive is, if it is not only meltwater, again more nutrient-rich; these peatlands are therefore mostly minerotrophic, otherwise moderate oligotrophic.

In the boreal zone the groundwater is low in mineral salts, so that it is difficult to distinguish between fens and raised bogs; one often speaks of mesotrophic transition bogs. If the water contains less than 1 mg Ca/litre, then one already finds the less demanding species of oligotrophic bogs.

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| Box K-5 The bog types |
| Topogenous, ombrogenous and soligenous bogs can be distinguished according to the origin and composition of the water in the bog soil. |

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| Box K-6 Climatic types of oligotrophic peatlands |
| The nutrient-poor, i.e. oligotrophic bogs, which are found only in cool to cold humid climates, are peinohelobiomes. According to their structure and topography, several types linked to specific climatic conditions can be distinguished (◘ Fig. K-19): blanket bogs - raised bogs – aapa mires - palsa bogs. |

The eutrophic bogs, in which sedges (*Carex* species) play the main role, occur in the temperate zone, regardless of climate, wherever the soil is wetted by calcareous but not brackish groundwater. They all belong to the pedobiomes, namely the helobiomes.

1. Blanket bogs. We had already mentioned these in the extreme oceanic climate of the Atlantic heath region of the British Isles and all along the west coast of Scandinavia. They cover the whole terrain.
2. Raised bogs. They are characteristic of the somewhat less oceanic NW corner of C Europe with heath areas, the whole boreo-nemoral zone and the S part of the boreal zone (◘ Fig. K-18, ◘ Fig. K-19). When typically formed, they are treeless. However, if the climate becomes more continental and drier, pines are also found on these bogs, which are then referred to as forest raised bogs (◘ Fig. K-20). They run along the entire S border of the boreal upland bog area (◘ Fig. K-21).
3. Aapa mires or string bogs. They are found N of the high bog zone in Fennoscandia and in W Siberia. They are soligenous bogs with shallow slopes. They consist of somewhat elevated ridges perpendicular to the slope and ombrotrophic; between them are elongated deepened areas filled with minerotrophic water (Finnish "rimpis", Swedish "flarke"). The whole bog slopes down in steps, reminiscent of terraces in rice cultivation. The thrusting effect of the ice sheet, which covers the rimpis in winter and expands them in a horizontal direction, plays a role in the upward curvature of the strings (◘ Fig. K-22).

4. Palsa peat bogs of the peat hummock tundra. These occur already outside the boreal zone in the forest tundra in areas with a mean annual temperature below -1 °C. Soil ice plays a significant role in the formation of peat mounds, which can be 20 to 35 m long and 10 to 15 m wide and reach a height of 2 to 3 m (up to 7 m). If less snow is deposited on slightly elevated areas, frost penetrates the peat soil more rapidly. Ice layers form, and these attract water from the unfrozen surrounding peat soil. The ice lenses become thicker and lift the peat up. Since not all the ice melts in summer, some of the elevation remains. As a result, the next year the snow cover is even less, the ground freezes even more rapidly; the ice masses grow larger year by year, and the peat mound with the ice core grows higher. In summer the whole thing sinks in, creating a ditch-like depression around the peat mound, filled with water, in which the dwarf birch (Betula nana) and cotton grasses (Eriophorum) grow (◘ Fig. K-23). The top of the peat mounds (Palsen) may dry out in summer, in which case it develops cracks. It is then eroded by the wind and may be worn away completely. Most of the Palsen are thought to be subfossil formations from a colder climatic period and are in the process of disintegration. They may be considered as thermokarst phenomena of smaller extent (► Chapter J).

**5.** Polygonal bogs: These are typical of the Arctic (ZB IX). They are discussed further below.

◘ **Fig. K-18** Schematic representation of a raised bog and the formation of the stratification.

◘ **Fig. K-19** Bog lakes and taiga alternate, C Sweden near Sunnersta (photo: Breckle).

◘ **Fig. K-20** Forest raised bog in the Saamaa region in Estonia (photo: Breckle).

**Fig. K-21** Distribution area of mire types in N Europe (modified after Walter 1990). 1 Palsen bogs; 2 Aapa bogs; 3 typical raised bogs; 4 blanket bogs; 5 forest raised bogs; 6 mountain bogs. Light areas of the S regions with predominantly topogenous bogs.

◘ **Fig. K-22** Endless expanse of the West Siberian moors: Noyabrsk Moor with a very large proportion of open water areas (photo: M. Succow).

◘ **Fig. K-23** Palsen or peat hummock bogs near Abisko in Sweden (photo: Breckle).

**9.1 Ecology of raised bogs**

The most important plants that cause the development of a raised bog are the sphagnum mosses (Sphagnum species). Since they consist for the most part of large dead cells which easily fill with water by capillary action, they act like sponges in the cushion-like growth and hold many times their dry weight in water. At the upper end, they grow upward; at the lower end, they die and perish and are converted into peat (◘ Fig. K-24). The cushions grow larger and larger, merging together, and eventually a watch-glass-shaped raised bog arches over the surface (►Fig. K-18). Because *Sphagnum* mosses do not tolerate drying out, evenly moist and cool summers are a prerequisite for raised bog formation. Peat mosses settle only on poor acidic soils; podsol soils are very suitable for this purpose. Raised bogs therefore often emerge from waterlogged coniferous forests.

**Fig. K-24** Peat profile of a typical raised bog with indication of biological processes at different depths (modified after Burgeff 1961). The circles in the yellow layer indicate gas bubbles (mainly methane).

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| Box K-7 Dependence of peatlands on climate |
| The true raised bogs are bound to an oceanic climate in both Eurasia and N America, whereas Aapa and Palsen bogs have a circumpolar distribution. |

◘ Fig. K-25 illustrates the structure of a typical raised bog. In a large growing raised bog, a distinction is made between the very wet and little arched upland surface, the better drained and relatively steeply sloping marginal slope, and a minerotrophic bog surrounding the raised bog, called a Lagg. The plateau is not completely flat, but consists of small elevations, the Bults, which protrude above the moss surface, and of depressions (“schlenken”) sunk into the moss carpet, in which the water stands close to the surface; in them grow hygrophilous S*phagnum* mosses as well as Carex limosa or Scheuchzeria. When several depressions join, bog pools, called “blänken” or “kolks”, are formed (► Fig. K-19). Their depth is usually only 1.5 to 2 m; however, they have no solid bottom but are filled with soft detritus. Excess water drains from the upland surface in small channels called gullies (“rüllen”). The types of raised bogs are shown in ◘ Fig. K-26.

**Fig. K-25** A typical raised bog (Augstumalmoor in the Memeldelta, after Weber, modified from Walter 1968) with Blänken (raised bog oaks), gullies, and a Lagg (mesotrophic intermediate bog merging into a eutrophic low bog, fen).

The number of flowering plants growing on raised bogs is not large, they are extremely undemanding species in terms of nutrients: *Eriophorum vaginatum, Trichophorum caespitosum* and the dwarf shrubs *Andromeda polifolia, Vaccinium oxycoccus, V. vitis-idaea, V. uliginosum, Calluna vulgaris* and *Empetrum*; in the Atlantic area *Narthecium,* in the E *Ledum palustre* and *Chamaedaphne calyculata*, inthe N *Rubus chamaemorus, Betula nana* and *Scheuchzeria palustris* are added.

◘ **Fig. K-26** Schematic representation of the different oligotrophic bogs (after Osvald, modified from Overbeck 1975): **1** = forest raised bog, **2** = typical raised bog, **3 =** plan raised bog, **4** = soligenous bog, **5** = Aapamoor (string bog, a northern type), **6** blanket bog. From 1 to 6 increasing humidity of climate or waterlogging.

In addition to nutrient poverty, the second ecological factor that determines the distribution of the species is the overgrowth by *Sphagnum* mosses. The substrate on which the flowering plants germinate is the growing living tips of the *Sphagnum* mosses. Depending on the water supply, the height growth of the *Sphagnum* mosses is 3.5 to 10 cm per year. By this amount, the flowering plants must raise their shoot base each year by stretching the rhizomes or forming adventitious roots, otherwise they will be overgrown by the *Sphagnum* mosses (◘ Fig. K-27). They can escape overgrowth all the more easily the slower the mosses grow, which is the case on the relatively dry hummocks or on the well-drained marginal slopes. It is in these places that most dwarf shrubs are found. Each hummock shows a certain zoning: Eriophorum vaginatum and Andromeda grow at the base, Vaccinium oxycoccus higher up, other dwarf shrubs at the very top. Often the top of the hummock is so dry that other mosses (Polytrichum strictum, Entodon schreberi) or even lichens (Cladonia species, Cetraria) thrive instead of Sphagnum.

◘ **Fig. K-27** Growth of *Vaccinium oxycoccus* in a Sphagnum bog. In spring, the young shoots first grow vertically out of the Sphagnum layer that overgrew them the previous year and then lay down on the moss surface. The older shoots are pressed together kinkily by the compaction of the peat (after Grosse-Brauckmann, modified from Walter 1968).

The trees (pine, spruce) that have the most difficulty are those that are unable to relocate their trunk base and show only slight height growth on the poor substrate (◘ Fig. K-28). Often, only the uppermost branch tips protrude from the bog hummocks. Forest raised bogs are therefore only found where, as a result of the dry climate, the growth of peat mosses is low. As soon as the bogs are drained and the growth of the *Sphagnum* mosses comes to a standstill, a rapid heathland formationoccurs, i.e. the dwarf shrubs come to dominate. Soon, tree species such as birch, pine or spruce are added. Most peatlands in Central Europe are in this state, and this effect is intensified by the additional nitrogen input from the atmosphere.

It is striking that along the gullies or at the edge of the funnels often species of the minerotrophic soil grow, although the water is just as nutrient-poor as in the rest of the bog. It can be seen that flowing water or water moved by waves provides a more favourable supply of nutrients than still water, in which only diffusion of nutrients takes place. With the high water content of bog soils, they warm up very slowly. Bogs are therefore cold sites, and it is understandable that Nordic-Arctic floral elements, including many relicts of the glacial period, can persist on them; in addition, on raised bogs they are protected from competition from fast-growing demanding species.

◘ **Fig. K-28** An approximately 9-year-old spruce whose trunk is encased 20 cm deep by the peaty moss layer (after Bertsch, modified from Walter 1927).

With the exception of the Drosera species (or Utricularia in the bog ponds), which supplement their nitrogen supply by digesting insects caught on the leaves, all other species are xeromorphic, although water is available to them in abundance. This is attributed to a lack of nitrogen supply. It has generally been shown that xeromorphy is observed when the growth of plants is inhibited, for example by a lack of water, but also when there is an excess of water, i.e. a lack of oxygen in the soil, by low soil temperatures which make the uptake of nitrogen difficult, or by a direct lack of nitrogen. The seemingly xeromorphoses here are therefore deficiency symptoms; it is therefore more appropriate to speak of peinomorphoses.

A summary account of the peatlands in NW Europe was given by Overbeck (1975), a new overview by Succow & Joosten (2001).

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| Box K-8 Western Siberia - the largest bog on earth |
| 40% of the peat deposits of the whole Earth are located in the West Siberian lowlands. The peatlands, with over 100,000 peat lakes, store an amount of water said to be equivalent to the two-year runoff of the vast Ob-Irtysh River system. |

**9.2 The West Siberian lowlands, the largest marshland on earth**

This area with the Ob-Irtysh basin is a peinohelobiome of a scale difficult to imagine (Tanneberger et al. 2003). It extends from the forest tundra in the N to the steppe in the S over 800 km and from the Urals in the W to the Yenisey in the E over about 1800 km.

In this moorland area the settlements are located only along the rivers that serve the traffic. The actual marshland was explored in detail only by Popov (1971-75).

The causes of the peatlands can be called the topography, climate and hydrological conditions. The bogs have replaced the dark taiga.

The great basin is underlain by Meso-Neozoic strata. The Pleistocene ice ages had little effect. Deposition of alluvial sediments, some of which were impermeable to water, occurred, promoting waterlogging. Peat mosses (Sphagnum species) easily settle on the wetted nutrient-poor podsol soils, which initiate peat formation. The climate is humid with annual precipitation of 500 mm, as evaporation is only 240 to 300 mm and runoff 127 to 270 mm. In terms of temperature, the climate is very continental; the frost-free period is 174 days, yet the daily averages are above 10 °C on 100 days. Summers are therefore relatively warm and, as a result, plant production and peat growth are considerable. Even short hot droughts occur, so that forest fires are not necessarily excluded. The burnt areas easily become boggy.

However, the hydrological conditions are of particular importance. The little incised rivers meander strongly, which inhibits the discharge. The spring flood on the upper reaches of the Ob and Irtysh begins 1.5 months earlier than the snowmelt on the lower reaches, i.e. when the rivers are still covered by ice in the N. When the ice melts, high ice dams are formed; upstream of these, the water is additionally dammed. Since the sources of the Ob are fed by the glaciers of the Altai Mountains, the summer flood follows immediately, i.e. the high water level of the rivers (12 m above low water) lasts practically the whole Siberian summer. The low watersheds are also flooded and a single large body of water is formed together with the bog lakes.

The peatland formation already began in the subarctic period of the postglacial period. The starting point was formed by wide shallow depressions with water low in mineral salts. In them, Scheuchzeria bogs with Eriophorum vaginatum and various Sphagnum species developed. Corresponding mesotrophic Scheuchzeria peats are found at the base of the oldest 4 to 7 m deep peat profiles. The oligotrophic phase is indicated by the occurrence of the main peat moss species, Sphagnum fuscum. It begins in the middle postglacial. The peatlands bulged upwards and the water table was raised. This led to the wetting of the adjacent forests; Sphagnum species colonized under the dying trees, and the bogs spread rapidly in a horizontal direction. All the younger bog profiles, and they are the majority, have a peat thickness of 3 to 4 m and always have peats with a lot of pine and bark remains in the lowest horizon; just after that the oligotrophic phase with *Sphagnum f*uscum peat begins.

The bogs of western Siberia mostly are string bogs (◘ Fig. K-29, ► Fig. K-20) with an average inclination of only 0.0008 to 0.004°. On the more or less wide strings grow Pinus sylvestris (in the stunted form P. willkommii) and Ledum palustre as well as the dwarf shrubs Chamaedaphne calyculata, Andromeda polifolia, Oxycoccus microcarpus, scattered Rubus chamaemorus as well as Drosera rotundifolia. The moss layer consists of Sphagnum fuscum; patches with lichens (Cladonia spp., Cetraria) are rare.

In the hollows(schlenken) one finds *Eriophorum vaginatum* with *Sphagnum balticum* or *Scheuchzeria,* respectively *Carex limosa* with *Sphagnum majus,* but also *Rhynchospora alba* with *Sphagnum cuspidatum* occur.

The string bogs usually undergo regression on the wetted watersheds, leading to the formation of bog lakes (► Fig. K-22). This occurs particularly wherever recent tectonic movements are associated with subsidence. Recent aero-geological surveys showed subsidence of 0.07 to 0.25 mm per year in several areas. This is sufficient to disturb the very unstable equilibrium between strings and sinks and lead to increasing waterlogging. This excess water initiates the regression phenomena. It leads to oxygen depletion even in the upper peat layers and to the formation of methane gas.

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| Box K-9 The peatlands of Western Siberia |
| Thus, the rivers of Western Siberia do not drain the lowlands, but on the contrary, their waters become dammed, overflow them with water and promote bog formation |

◘ **Fig. K-29** Partially forested parts of the Wasjugan Marshes in W Siberia (photo: Succow).

When drilling in such places, the escaping methane gas causes fountains of liquid peat. When the gases escape naturally, the plant cover dies. Dead bog areas form, which become bog lakes. The lakes, which are small at first, merge into larger ones, where wave action causes the peat banks to collapse, resulting in the formation of ever larger bodies of water. The bog lakes of various sizes, together with the bog depressions, all form a single hydrological system - an ecological unit that, because it is low in nutrients (ash content of peat only 2 to 4%) and wet, we call the peinohydrobiome (► Fig. K-20, ► Walter 1977).

In places, the string bogs can also dry out if such a wetted area forms its own drainage system and the bog streams cut into the peat so that the banks are better drained. On such banks a narrow strip of forest can develop with pine, birch and the stone pine (Pinus cembra ssp. sibirica).

The description of peatlands given here applies to the taiga zone. The peat thickness decreases towards the N because of the shortening of the vegetation period and the lower plant production. South of the taiga the types of peatlands change.

In the area of forest steppes, i.e. in Siberia in the ZE VII-VIII with birch-aspen forests, the Ca content of the groundwater is already high, and slightly domed eutrophic hypnaceous peatlands with *Carex* species (sedges) prevail. However, oligotrophic peatlands can also form on these forest peat islands ("Rryami"). Peat growth is almost inhibited by the greater aridity of the climate. In the S part there are only lowland peatlands in the lowest parts of the relief, especially in the wide river valleys. The ash content of the peat there can be very high (19%). Typical lowland bogs are often found, the hummocks consisting of old clumps of Carex caespitosa and C. omskiana. Such fens are helobiomes.

Even further S in the N steppe zone, the climate is semi-arid. In the Baraba lowlands no complete river system is formed, but like in the Pampas there are countless small drainless lakes, some of which are brackish. Around these one finds eutrophic mires or even halophytic swamps with salt plants, thus already transitions to a halo-helobiome (ZE VIII/VII).

10 **Man in the taiga**

The vast expanse of the taiga has not prevented it from being cut up in many places during this century, and large areas have even been destroyed, these days ever increasing. This is caused by large-scale oil and gas prospecting, pipelines and ore extraction and the land-intensive infrastructure required for this (◘ Fig. K-30). Exploitation has reached huge proportions; biodiversity has not been irreversibly destroyed, as in some tropical regions.

In past centuries, the Siberian taiga was a difficult area to access. Fur hunters and individual settlers roamed the area, which in many places, however, was also populated by original tribes on a small scale at wide intervals.

This original use of the taiga as a habitat for wandering nomads and widely scattered individual settlements has been sustainable in every respect. On the other hand, it must be noted that many large mammals survived the entire ice ages and only became extinct in the Late Glacial. There is much evidence to support that this was already an effect of the destructive influence of man. Today it is oil, gas, mining, iron, gold, diamonds, hunting, logging, timber!

11 **Zonoecotone VIII/IX (forest tundra) and the polar forest and tree line**

Similarly as the forest steppe inserts itself between forest and steppe as ZE VI/VII, we have also between the boreal forest zone and the treeless tundra as ZE VIII/IX the forest tundra, in which forest and tundra are macromosaic-like interlocked. At first, individual treeless patches occur in the forest area, mostly on elevations. They increase to the N until only individual islands remain of the forest, which finally consist only of bushy cripples. In the mountains this stunted zone is quite narrow, but here in the flat terrain it can extend for hundreds of kilometres. The tree species in the oceanic area are birches (◘ Fig. K-31), in the extremely continental area larches (◘ Fig. K-32), otherwise spruces.

As causes for the occurrence of the polar timberline we can assume the same as for the alpine timberline. The frost-drought are increased by the winter storms. The forest advances furthest on the slopes of river valleys, where it is protected from wind and snow, where the well-drained soils thaw more deeply in summer and the rivers coming from the S carry warmer water. However, lack of regeneration is also cited as a cause. At the N limit of distribution, trees rarely produce germinable seeds. In addition, most are eaten by animals. Storms can transport them (sliding on the snow surface) far N, where development is no longer possible.

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| Box K-10 The Destruction of the taiga |
| The encroachment and extent of destruction in the Siberian taiga sometimes exceeds that in the tropical rainforests. |

◘ **Fig. K-30** The Mirny diamond mine in Sakha (Yakutia) with a diameter of 1,200 m and a depth of 500 m as well as the associated infrastructure buildings with extensive overburden. Large-scale destruction of the taiga can be seen here (photo: Breckle).

◘ **Fig. K-31** The arctic-polar tree line with Betula tortuosa above Torneträsk (oceanic expression) in northern Sweden (photo: Breckle).

◘ Fig. K-32 The Arctic-Polar tree line with Larix gmelinii (extreme continental expression) in northeastern Siberia, wedging light forest in the Moma valley of the Chersky Range (photo: O. Agachanyanz).

◘ Fig. K-33 Cross-section through the trunk (just under 10 cm ᴓ) of a ( c.104-year-old) Larix gmelinii (= L. dahurica) from Arymas (72° 30′ N) with very narrow annual growth rings (photo: Agachanjanz/Breckle).

Also, dense lichen and moss cover is present in the forest tundra, which is an unfavourable germination bed. The importance of humans and their reindeer herds is very great (► Fig. K-4). In addition to damage by animals, timber logging is namely important, because the natural increment of woody plants is extremely low. In most cases, a tree seedling only succeeds in gaining a foothold if particularly favourable temperature conditions prevail for two years in succession. Even then, further growth is extremely slow. 20- to 25-year-old saplings hardly protrude from the herb layer; the annual height increase is 1 to 2 cm. Tree thickness growth shows a very close correlation to July temperatures. The northernmost true forests, a taiga of trees 2 to 5 m high, are now found on the Taimyr Peninsula, at Arymas, beside the Chatanga estuary at 72° 30′ N, with Larix gmelinii. Growth is very slow, for example, a 104-year-old trunk has a diameter of 9.5 cm (◘ Fig. K-33) (Walter & Breckle 1990).

The open areas in the forest tundra are mostly occupied by the dwarf tundra. This also forms the S subzone of the true tundra (► Fig. J-49).

The timberline was significantly further N during the postglacial warm period. The tree stumps trapped in the peat in today's tundra serve as evidence. The consequences of the Climate change that has been constantly taking place over the last millennia are particularly evident in the forest tundra.

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Striped tundra (Zonobiome IX) with espalier Salix species and frost heaps at the Finland-Norway border (Photo: Breckle)

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