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Alpine timberline in the High Sudetes

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Abstract

The alpine timberline is an essential boundary in mountain relief. In the High Sudetes, there are three mountain ranges rising above alpine timberline - the Krkonoše Mts. with largest and well diferentiated alpine area, Králický Sněžník, which is small, summit phenomenon effected enclave and Hrubý Jeseník Mts. with seven alpine areas of different extent. Using orthophotomaps and air photos we assesed such a characteristics of alpine timberline as its length, average height and extent of alpine belt. We also discussed a natural origin of an alpine belt in the High Sudetes. We have noticed many differences in synmorphology of alpine timberline between the Krkonoše Mts. and Hrubý Jeseník Mts.

Introduction

There are four different areas above the alpine timberline (ATL) in the mountains of the Czech massif. Three of them – Krkonoše, Králický Sněžník and Hrubý Jeseník Mts. are situated in the High Sudetes, last one is the highest peak of the Šumava Mts. – Velký Javor (Grosser Arber, 1456 m). We are going to point on the High Sudetes area, because of small and heavily man–degraded Velký Javor area. According to Jeník (1973), Krkonoše Mts. belong to group of mountains with well differentiated alpine belt, Hrubý Jeseník and Králický Sněžník Mts, aproximate to this group, Šumava Mts. belong to the group of mountains with slight features of alpine ecosystems.

Theoretical aspects of alpine timberline

The ATL is a fundamental boundary in the mountain relief from the geodynamics, microclimatic and phytocenologic point of view. It is fairly conservative system, which responds on the macro and mezoclimatic changes with longer delay than single specimens of trees (alpine tree species line respectively). In the case of passage ATL into dwarf shrubs, the essential boundary from floristic and sozologic point of view is the upper limit of dwarf shrubs (Ellenberg 1963).

ATL isn't a sharp line boundary, in reality it is a transition zone, which has its own two boundaries and they are in turn, also transition zones with their own boundaries, and so on endless (Paulsen, Weber et Körner, 2000). It is necessary for practical reasons to define convention criterions for its delimination. Differentiation of ATL and tree species line is caused by the ecotop conditions in the microscale (Körner 1999). High frequency of catastrophic events is another reason for its differentiation. We have recorded the abruptly ending ATL without so called „kampf" zone, only by the plantations or by geomorphologically influenced ATL (rocks and block of fields). As regards to the main factors induced establishing of ATL, the most probably reason is the insufficient incorporating of asimilates rising by photosynthesis into a cell structures, causing by low temperatures in vegetation period (globaly average temperatures 5,5 – 7°C at ATL). Often mentioned average july temperature 10°C (Plesník, 1971, Ellenberg, 1963) isn't predictive value on the global scale. There are big differences between average july temperatures at ATL even across the Europe. Tree growth isn't limited by low intensity of photosynthesis (Körner 1999). Tranquilini (1979) and also Körner (1999) suggested significant meaning of mycorhiza. Besides above mentioned factors, there are, especialy in the middle mountains with intensive summit phenomenon, another stress factors: snow and ice injury, winter dessicitation and low germinating rates in the vegetation across ATL (*Deschamsia cespitosa, Avenella flexuosa, Nardus stricta, Calamagrostis villosa*).

Habitus of Norway spruce at ATL in the Krkonoše and Hrubý Jeseník Mts. is much more stressed by effected force of wind and ice injury compared with spruces in the Tatra Mts. or the Alps, where a rate of such injured spruces is lower. It is caused by more intensive summit phenomenon, because ATL runs near summits. Such a summit phenomenon hasn't changed throughout the Holocene, nor by oscillations of regional (and global) temperature conditions, that's why there is no reason for significant natural oscillations of ATL.

Present-day ATL is ecologicaly stabilized system, which course is a result of climatic proceses in several last centuries (Körner 1999). There are generaly accepted mild movements of ATL throughout the Holocene. Wick et Tinner (1999) mentioned for the central Alps rate of oscillation 150 m. There haven't been recorded considerable natural changes of ATL course in the middle mountains of the central Europe, where the cold oscillations haven't been forced by oscillations of snowline and glaciers (Hüttemann et Bortenschlager 1987). Such a mild changes of ATL cohere with strong effect of summit phenomenon.

The ATL in some studied regions across the Europe displays remarkably increasing tendention, either as continuing of this tendention from last periods (Wick et Tinner 1997, central Alps) or as deviation from generally decreasing trend (Kullman et Kjällgren 2000, the Scands).

Presence of closed canopy forest in the summit areas (present-day situated above ATL) isn't probably until melting of permafrost (cca 8000 BP, Czudek 1997). The only cold oscillation recorded by decrease of ATL in the Krkonoše Mts. is paralleled by Hüttemann et Bortenschlager (1987) with cold event Oberhalbstein (8000 - 7500BP uncal.). After this oscillation the ATL had increased slightly above its present-day level (average cca 26m, Jeník et Lokvenc, 1962) and hadn't showed significant oscillations until the man induced changes started happen. It means in the Krkonoše Mts. the time span cca 1100 AD (Speranza et. al., in print) - cca 1500 AD (Hüttemann et Bortenschlager 1987).

There is asumed the same evolution of ATL course in the Hrubý Jeseník Mts, however, there is lasting presence of an alpine belt throughout the Holocene cast doubt on absention of dwarf pine. Jeník (1973), Jeník et Hampel (1991) suggested similar rate of human induced decrease of ATL as in the Krkonoše Mts., moreover, they mentioned some localities where carried out temporary artificial increas of ATL.

The vegetation indicated natural origin of an Alpine belt in the High Sudetes

We consider plant communities, which presence is caused by climatic extrems on deflation summits of highest peaks, where „periglacial“ phenomenons occures (pipcrake, cryosegregation, soli(geli)fluction, deflation), as an indicator of original natural alpine area. On those ecotops there are wind blown alpine grasslands (Chytrý et al. 2001) of alliance Juncion triffidi (as. *Carici-rigidae-Juncetum trifidi* Šmarda 1950 and *Cetrario festucetum supinae* Jeník 1961) with arcto-alpine species (*Carex bigelowii, Juncus trifidus, Diphassiatrum alpinum, Hieracium alpinum*, and abundant lichens and mosses – *Cetraria* sp., *Cladonia* sp.) and alpine heatlands of the same association. Occurence of mentioned plant communities coheres with cryo-eolian zone sensu Soukupová et al. (1995).

Communities strictly limited by extreme snow deep or periodical avalanche activity, solifluction and snow drift are the another sort of plant communities, which occurence is limited on the unforested ecotops, in this case in the cirques and nivation hollows. Such a plant communities are represented by alliances of snow beds vegetation - *Salicion herbaceae*, species rich communities of alliance *Calamagrostion arundinaceae* Luquet 1926, Jeník 1961, subalpine shrubs of alliance *Adenostylion*, as. *Salicetum lapponum* Zlatník, 1928 and alliance *Salicion silesiacae* Rejmánek et al. 1971.

Methods

We used definition and criterions for determinating ATL published by Jeník et Lokvenc (1962): „The alpine timberline is such a vegetation line which joins all of empiricaly ascertainable highest limits of forest". It is generally accepted definition, however there are differences in the standarts, how to comprehend forest. It is determinated by many authors as growth of trees with minimal height, minimal density of canopy and minimal area.

Table 1 Standarts for determination of the alpine timberline by various authors

Author	Minimal canopy	Minimal height	Minimal area	Other criterions
Vincent (1933)*	> 0.5	8m	1ha	Stem density > 0,5
Sokolowski (1928)*		8m		
Somora (1958)*		8m		
Jeník et Lokvenc (1962)	> 0,5	5m	1ar	Distance of isolated forest eclave included in continuous ATL<100m
Plesník (1971)	> 0,5	5m	10a	
Zientarski (1989)	> 0,4	8m	10a	
Ellenberg (1963)	> 0,3-0,4	> 2m		
Körner (1999, 2000)		> 3m		

*cited in Jeník et Lokvenc (1962)

From geoecological point of view, there is sufficient criterion of Ellenberg (1963) and Körner (1999), whose defined tree as an upright woody plant with single above-ground stem, that reaches a height of at least 3m. This height assures that such a tree would have closely coupled to prevailing atmospheric conditions and protrudes above deep snow where snow occurs. However, in the central Europe there is ussualy occured at the ATL Norway spruce, which is by the minimal canopy 0,5 always higher than 5m. That's why we consider choosen criterion for minimal height of tree for conditions of the middle european mountains as acceptable. Moreover, there is ensured possibility to compare height of timberlines in different regions, because the main criterion is density of canopy and height of trees isn't such important.

Many authors don't state minimum area as a characteristic of forest. The proposes of Jeník et Lokvenc (1962) - 1a and Plesník (1971) - 10a are the basic standards. According to using airphotos and orthophotomaps, we choose criterion proposed by Jeník and Lokvenc, which enable more detailed maping of ATL course. Next criterion is the minimum horizontal length of an alpine vegetation lobes. We maped all of lobes apprehensible in scale 1:4000, it means cca 10m broad, same value we used for maximum distance of outpost growths included into continous ATL. Those criterions were getting bigger by subsequent generalisation. For calculation of an average height of ATL we used formula, published by Jeník et Lokvenc (1962):

$$H = \frac{\sum^1 i_1 l_1 + i_2 l_2 + i_3 l_3 + \ldots\ldots + i_a l_n}{\sum^1 l_1 + l_2 + l_3 + \ldots\ldots\ldots + l_n}$$

i_1 , i_2 ….i_n - middle height of an interval (m)

l_1 , l_2 ….l_n – length of ATL in an interval (km)

The ecotone of forest passage into alpine belt, so called „kampf" zone, we determinated as an area, which upper limit is the line joining all of Norway spruce groups with minimum area of 0,5a and lower limit is the ATL. We used orthophotomaps and air photos for mapping ATL. Because of eliminating errors rising from „kampf" zone width identification, we sorted inclination into seven classes: 0 – 5, 5 – 10, 10 – 15, 15 – 20, 20 – 25, 25 – 30, 30 and more degrees, based on digital model of relief and inclination map respectively. We identified width of „kampf" zone in certain class and multipled with relevant inclination coeficient using ArcView script.

We used GPS for determinating position of maped phenomena. Multicriterial analysis were made in GIS ArcView and Topol.

Results

The Krkonoše Mts.

Characteristics

The Krkonoše Mts., consider to extent of an alpine belt, are largest of High Sudetes. Extent of the alpine area is 5465 ha altogether, 3178 ha in the east part of the Krkonoše Mts. and 2286 ha in the west part of the Krkonoše Mts. Average height of ATL in the Krkonoše

Mts. is 1230 m a. s. l. In the eastern part (Fig. 2), the ATL is situated higher (1245 m a. s. l.) than in the western part (Fig. 1) of the Krkonoše Mts. (1207 m a. s. l.). From total length 124 km, there is 74 km in the eastern part and 50 km in the western part. 92,5 km of ATL belongs to the Czech part of the Krkonoše Mts. and 31,6 km to the Polish part. 21,5 km of ATL course runs around avalanche tracks and 5,1 km around scree habitats. Minimal height of ATL is 960m on the bottom of the Labský důl valley, maximum elevation is reached on the west slope of Růžová hora Mt. – 1340 m.

Origin of alpine belt

Jeník (1961) and Jeník et Lokvenc (1962) convincely proved natural origin of alpine belt in the Krkonoše Mts. based on the theory of anemo-orographical systems. Such an opinion was confirmed also by subsequent palynological analyses (Bortenschlager et Hüttemann 1987).

We consider as crucial proofs of natural origin of an alpine belt the occurence of such a periglacial phenomena (active, conserved and fosile) as recently developing nivation hollows (Modrý důl valley, Bílé Labe valley), nivation benches, pasive morains (Obří důl valley), solifluction blocks (whole alpine treeless region), patterned grounds (whole alpine treeless region above 1300 m a.s.l., esspecialy planation surfaces), avalanche acumulations and above described plant communities. Those phenomena occure on the summit platforms of etchplain and in the cirques and nivation hollows, where presence of unforested area throughout the Holocene is assumed. Vegetated patterned grounds occure on the planation surfaces even 50 m above the ATL.

Except areal abundant solifluction blocks, which occure strictly above ATL, other phenomena are predisponed and limited by rock structure or orientation and exposition of surface. That's why, we don't consider the distance of mentioned phenomena from ATL as remarkable feature.

For other parts of area (especially lower situated slopes) we have only the informations from published historic researches. There are needed further palynological studies and macrofossils dating for reconstruction of former course and oscillations of ATL.

Recent tendences and historical evolution

A historical evolution of man-induced changes of the ATL was in detail elaborated by Jeník et Lokvenc (1962), Lokvenc (1978) and Lokvenc et al. (1992). Average anthropogenic decrease of ATL is estimated at 20m at Czech part and 13m at Polish part of the Krkonoše

Mts. Highest rate of decrease is observed in surroundings of mountain chalets - former farms. An afforestation which was carried out in the end of 19th. century and start of 20th. century didn't generally reached the level of ATL (except dwarf pine afforestation).

There is remarkable increasing tendention of ATL position in the last century: (a) in the localities further exploated by pasture and gras mewing (Stoh Mt., 1315 m, Svorová hora Mt.,1410 m), (b) on the formerly active avalanche tracks (northern oriented slopes of Zadní Planina Mt., 1422 m) and (c) on the small block of fields, where a forest has increased by joining small groups of trees, which present-day shadow over dwarf pines (south slope of Kozí hřbety hogbacks, sotheast slopes of Svorová hora Mt.). There is evident decrease of ATL on south slope of Železný vrch Mt. (1320 m) and north slope of Stoh Mt. in consequence of timber exploatation after imision injury. Where the exploatation didn't carry out, the ATL in consequence of imisions didn't decrease, however, there is recorded a decrease of upper tree line in some localities (northern slopes of Malý Šišák Mt., 1439 m).

Local characteristic, synmorphology

The ATL is situated in two different sections, shorter western part and eastern part. In the the eastern part of the Krkonoše Mts. there is besides main alpin area also one alpine enclave on the summit of Železný vrch Mt.

Table 2 Characteristics of the alpine timberline ecotone („kampf" zone) in the Krkonoše Mts.

Width of „kampf" zone (m)	Length of ATL* (km)/%		
	Total	W Krkonoše	E Krkonoše
0 - 50	29,8/**37,3**	11,4/36,0	18,4/36,9
50 - 100	14,0/**17,5**	5,4/17,4	7,6/15,1
100 and more	37,8/**47,2**	14,1/46,6	23,7/48,0
Total	80,6/**100,0**	30,9	49,7

Table 3 Length of ATL on the scree habitats and avalanche tracks in the Krkonoše Mts.

	Length of ATL section* (km)/%		
Stressed factor	Total	W Krkonoše	E Krkonoše
Avalanche tracks	21,5/**22,6**	5,6/18,1	15,9/32,4
Block of fields	5,1/**5,4**	0,8/2,6	4,3/8,8

*It is valid for the Czech part of the Krkonoše Mts. only, there are not included lengths of human influenced ATL (Krkonoše Mts total: 12 km, west part: 2,7 km, east part: 9,3 km.

Generally in the Krkonoše Mts. at localities, where the avalanche tracks, block of fields, former pasture and gras mewing (surroundings of chalets) absent, in such places, there is prevailed the ATL with ecoton broader than 100 m (Photo 2). This is very significant, especially in the eastern part of the Krkonoše Mts., where this ecoton, except avalanche tracks and blocks of fields, clearly dominates. The thinnest ecoton (until 50 m) is supplied in the eastern part of the Krkonoše Mts. only on the avalanche tracks and block of fields, in the western part of the Krkonoše Mts. The thinnest ecoton takes place also besides those habitats. Middle ecoton (50 – 100 m) exists only as a passage between thinnest and widest one, that's why the ATL, which such a sort of ecoton, is in the Krkonoše Mts. the shortest one.

Hrubý Jeseník and Králický Sněžník Mts.

Characteristic

Average height of ATL is in the Hrubý Jeseník Mts. 1310 m a. s. l. and in the Králický Sněžník 1305 m a. s. l. Maximum elevation of ATL is reached on the northwest slope of Praděd – 1405 m a. s. l., minimum takes place on the bottom of Velká kotlina cirque – 1100 m a. s. l. Total length of ATL is in the Hrubý Jeseník 44 km, in the Králický Sněžník 4,1 km. An extent of alpine area reaches 1048 ha in the Hrubý Jeseník Mts. and 65 ha in the Králický Sněžník Mts.

Origin of an alpine belt

The natural origin of alpine belt in the highest positions of the Hrubý Jeseník Mts. and Králický Sněžník Mts. was regulary casting doubt. That is the reason, why we suppose, that it is necessary comprehensively discuss this problem. Many related opinions have its origin in palynological analyses of Salaschek (in Jeník et Hampel, 1991) and Firbas (1949, 1952). Mentioned authors didn't consider pollen influx from lower positions as important, how refered Jeník et Lokvenc (1962). Müller et Salaschek in Jeník et Hampel (1991) came to conclusion, based on pollen analyses from peat bogs on Vysoká Hole and Velká Máj, that ridges of the Hrubý Jeseník Mts. hadn't been forested before a start of the man induced changes.

The natural absention of dwarf pine (*Pinus mugo*) in the Králický Sněžník Mts. and Hrubý Jeseník Mts. is often discused topic. This phenomenon is often considered as possible proof of former presence of closed forest on summits of Eastern Sudetes. Mentioned mountain ranges are islands without dwarf pine among the Krkonoše Mts., the Alps and the Babia hora Mt. The absention of dwarf pine as a proof of forest presence is cast doubt, because of occurence another heliophil indicator – *Juniperus nana*. However, there is possibility of its plantation by „german beutifiing clubs" because of an increase of *juniperus* sp. pollen in recent (Rybníček, oral communication). There were no findings of dwarf pine macrofossils. Found pollen of pine belonged to Scotch pine (*Pinus sylvestris).*

Absention of natural dwarf pine growths displays in synmorphology of the ATL and also in composition of plant communities above it. Jeník (1973) put recent species abundance in direct connection with florogenetic absence of dwarf pine. There are many similar localities in the Krkonoše Mts. such are Petrovy kameny and Tabulové kameny rocks, but the species abundance of those localities is much lower. Absention of dwarf pine (and natural absence of similar edificators such as *Duschekia viridis, rododendron* sp., nanophanerophyts, which in the other alpine regions ensure passage of a forest into a tundra) is also displayed in specific conditions for vegetation graduality and richness of alpine hemicryptophyts and chamaephyts, include many endemits and relicts (Jeník, 1972). The ATL is here situated relatively high, because of absention dwarf pine, considering temperature conditions (Plesník, 1972).

There are conserved patterned grounds (Vysoká hole, Kamzičník, Velká Máj, Praděd, Mravenčník) and thufurs (Keprník) at summits of the Hrubý Jeseník and Králický Sněžník Mts. Those phenomena clearly show, that at places where it occures, there haven't existed throughout the Holocene trees with closed canopy. The blocks of fields haven't been also forested (Břidličná and other smaller localities).

As the another evidence of natural origin of an alpine belt, we consider species rich plant communities in the cirques and nivation hollows of the alliance *Calamagrostion arundinaceae* (Velká, Malá Kotlina, Králický Sněžník). Evolution of such communities is joined with periodical avalanche activity and regular avalanche activity couldn't be possible in the case of forested summits. Similar features shows some alliances of *Calamagrostion villosae,* e.g. association *Avenastro planiculmis - Poetum chaixii,* (eastern slopes of Petrovy kameny, Velká, Malá kotlina, Králický Sněžník) and snow patches communities of alliance *Salicion herbaceae* (Velká Kotlina). Communities of deflation summits are also suitable indicators of natural alpine belt. There are alliances *Juncion trifidi* (as.*Cetrario - Festucetum supinae, as. Empetro hermaphroditi - Juncetum trifidi*) and *Nardo-Caricion rigidae*: Praděd, Petrovy kameny – Břidličná, Keprník, Šerák, Červená hora, Králický Sněžník, Mravenečník. Subalpine tall-forb vegetation of alliance *Adenostylion* (wind lee-ward positions of localities Petrovy kameny-Jelení hřbet, Praděd, Králický Sněžník), subalpine springs vegetation of alliance *Swertio-Anisothecion squarrosi* (northeast slopes of Petrovy kameny, Praděd, Velká and Malá Kotlina) and arcto-alpine bogs (Velký Máj) also surly proves natural origin of alpine belt in places, where mentioned plant communities occure.

Besides plant communities there are another idicators of natural origin of alpine belt, especially indication group of the arcto-alpine species of butterflies, because of their low vagility. Its presence indicates a primary unforestation of their habitat. Species composition on investigated habitats is poor but with remarkable domination of typical alpine species (Beneš et al. in Banaš, Lekeš et Treml 2001). All of autochton butterflies species of alpine belt are glacial relicts limited on arcto-alpine tundra (cenobiont species, Kuras in Banaš, Lekeš et Treml 2001).

Recent tendences and historical evolution

We can say, based on historical research (Hošek in Jeník et Hampel 1991, Banaš, Lekeš et Treml 2001), that general tendention of ATL in last centuries in the Hrubý Jeseník Mts. was until the end of 19th. century decreasing in consequence of a pasture and a grass mewing, localy also a timber exploatation. Later, in the end of 19th. and beginning of 20th. century, the ATL was increased by artificial afforestation, localy above its natural (climatical) level (Keprník). Majority of growths across ATL are plantations. There haven't been noticed any localities with natural increasing tendention of the ATL.

Local characteristic, synmorphology

In the Hrubý Jeseník Mts. there is ATL located in six different areas (Figs. 3, 4). The largest one is the section Vysoká hole (1464 m a. s. l.) – Pecný (1334 m a. s. l.), followed by the Praděd (1492 m a. s. l.) area, Malý Děd (1355 m a. s. l.), Mravenečník (1343 m a. s. l.), Červená hora (1337 m a. s. l.), Keprník (1423 m a. s. l.) and Šerák (1351 m a. s. l.). Forest transition into arcto-alpine tundra usually displays as abrupt passage into soliters (Photo 1), which could be very distant from position of ATL.

Table 4 Characteristic of the ecoton of the alpine timberline („kampf" zone) in the Hrubý Jeseník Mts.

Width of „kampf" zone (m)	Length of ATL section* (km)/%
0 - 50	17,6/**40,4**
50 - 100	13,1/**30,3**
100 and more	12,6/**29,3**
Total	43,3/**100,0**

Table 5 Length of the ATL on the avalanche tracks and block of fields in the Hrubý Jeseník Mts.

Stressed factor	Length of ATL section* (km)/%
Avalanche tracks	2,6/**6,0**
Blocks of fields	1,1/**2,6**

*It isn't included 0.7 km of ATL at Mravenečník area, destroyed by building of water dam

ATL with thinnest ecoton mostly occures in the Hrubý Jeseník Mts., even after including of ATL length on the avalanche tracks and blocks of fields. Both wider ecotons occure equable, consider its length. The widest ecoton (over 100 m) is often enlarged by occurence of small groups of Norway spruce distant from the ATL.

Králický Sněžník

In the southeastern part of summit region of the Králický Sněžník, there are Norway spruce plantations at ATL On southern and southeastern slopes, there is ATL limited by blocks of fields. On the northwestern and western side, the ATL passages into low spruces with dense canopy. Dwarf pine plantations aren't very extensive (Fig. 5).

Summit plant communities are composed in contradistinction to the Hrubý Jeseník Mts. from dominant *Festuca supina. Avenella flexuosa* and *Nardus stricta* are less abundant. Those plant communities belong to the wind swept alpine grasslands, as. *Cetrario-Festucetum supinae* Jeník 1961 from association *Juncion trifidi* Krajina 1933. There is quite abundant indicator of arcto-alpine plant communities *Carex bigelowii* and patterned grounds also occure on the summit plateau (especialy NW direction, on the cryoplanation terraces). There is significant decrease of ATL in the Morava river valley, where avalanche track takes place. This avalanche track isn't so species rich as those of the Hrubý Jeseník Mts. (prevailing by *Calamagrostis villosa* and at the bottom *Athyrium* sp.). We take flat bottom of Morava valley at the altitude 1150 – 1200 m with avalanche and debris avalanche acumulations as a proof of regular activity of intensive slope processes and permanence of unforested area, where those processes work.

Discussion

There are three mountain ranges rising above ATL in the High Sudetes – the Krkonoše Mts. with largest and well diferentiated alpine area, Králický Sněžník, which is small, by summit phenomenon effected enclave and Hrubý Jeseník Mts. with seven alpine areas, of different extent. Maximal elevation of ATL is in the Hrubý Jeseník 60 m higher than in the Krkonoše Mts. It confirms well known fact of increasing continentality gradient.

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Table 6 The basic characteristic of the alpine timberline in the High Sudetes

	Krkonoše Mts.	Králický Sněžník Mts.	Hrubý Jeseník Mts.
Average height of ATL (m)	1230	1305	1301
Maximum elevation (m)	1370	1340	1430
Total area (ha)	5465	65	1091
Total length (km)	124	4,1	42,0
Width of „kampf“ zone:	*km/%		km/%
a) 0 – 50m	29,8/37,3		17,2/40,4
b) 50 – 100m	14,0/17,5		12,9/30,3
c) 100 a více	37,8/47,2		11,9/29,3

* it is valid for the Czech part of Krkonoše Mts. only, for 94,5 km length of ATL

In the Krkonoše Mts., the course of ATL is more tortuous compared with Hrubý Jeseník and Králický Sněžník Mts (Photos 1, 2). It's caused by higher altitude, relief energy and higher rate of slope proceses (avalanches, debris avalanches).

In all of the mentioned mountain ranges there are many geomorphological signs of natural origin of the alpine belt. Above all, there are fosile or conserved patterned grounds, recent nivation hollows with active solifluction proceses, solifluction blocks, avalanche and debris avalanche acumulations. Special plant communities are the second possible indicator of natural presence of an alpine belt. There are two groups of those communities – the first one, which presence is caused by climatic extrems on deflation summits of highest peaks. Such a communities are represented by wind blown alpine grasslands (Chytrý et al. 2001) of alliance Juncion triffidi (as. *Carici-rigidae-Juncetum trifidi* Šmarda 1950 and *Cetrario festucetum supinae* Jeník 1961). The second sort of communities is strictly limited by extreme snow deep or periodical avalanche activity, solifluction and snow drift (snow beds vegetation - *Salicion herbaceae*, species rich communities of alliance *Calamagrostion arundinaceae* Luquet 1926, Jeník 1961, subalpine shrubs of alliance *Adenostylion*, as. *Salicetum lapponum* Zlatník, 1928 and alliance *Salicion silesiacae* Rejmánek et al. 1971.). The communities of alpine butterflies could be also significant sign of regional presence of natural alpine belt (but it isn't proof of natural origin of that treeless locality, where those butterflies occure).

In the Sudetes, there are many localities, where above mentioned signs take part: western part of the Krkonoše Mts., eastern part of tho Krkonoše Mts., summit of the Králický Sněžník Mt., summits of the Šerák Mt., Keprník Mt., Červená hora Mt., Malý Děd Mt., Praděd Mt., summit area of Mravenčník Mt. and the southern part of the main ridge of Hrubý Jeseník Mts. in section Vysoká hole – Pecný.

We consider the places, where described phenomena (periglacial phenomena and special plant communities) occures as natural treeless, that means those places had been treeless before the man induced changes have started happen. However, lower trees with thin canopy could there occure. We suppose, that besides the Krkonoše Mts., also the highest summits of the Králický Sněžník Mt. and Hrubý Jeseník Mts. have been unforested throughout the Holocene. It is proved by areal presence of well conserved periglacial phenomena on the planation surfaces of summits.

In the Krkonoše Mts., the main tendention of the 20th. century is an increase of ATL on the places formerly effected by pasture and gras mewing and on the little block of fields. There have been noticed oscillations of ATL position on the avalanche tracks. On some of them, the ATL has decreased, because of imisions. The alpine treeline localy decreased too, as a result of imisions injuries. In contrary, in the Hrubý Jeseník and the Králický Sněžník Mts. there was the ATL artificially increased in large areas by afforestations and also because of terminating pasture.

The Krkonoše Mts. differ a lot from the Hrubý Jeseník and Králický Sněžník Mts. by width of „kampf“ zone. In the Krkonoše Mts. the ecoton over 100m in width prevails, the thinnest ecoton occurs on the avalanche tracks and blocks of fields only, middle width ecoton acts as a passage between both above mentioned. On the contrary, in the Hrubý Jeseník and Králický Sněžník Mts. the thinnest ecoton is typical and the middle one sheres also quite significantly on the total length of the ATL. The thinnest ecoton is charasteristic for plantations, iclude the highest situated „price plantations“. In our opinion, such a synmorphology of ATL results from more intensive human impacts (ATL region is generally better accessible) and natural absence of dwarf pine, which is the crucial difference of the ATL course in the Hrubý Jeseník and Králický Sněžník Mts. related to the Krkonoše Mts.

Acknowledgments

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Resumé

Alpinská hranice lesa se ve Vysokých Sudetách nachází ve třech pohořích, a to v Krkonoších s největší plochou bezlesí a dobře vyvinutou alpinskou oblastí, dále na Králickém Sněžníku, kde se jedná o malou, vrcholovým fenoménem ovlivněnou enklávu a konečně v Hrubém Jeseníku s přibližně pětinovou plochou alpinského bezlesí ve srovnání s Krkonošemi. Maximální elevace alpinské hranice lesa je v Hrubém Jeseníku o cca 60 m výše než v Krkonoších, což potvrzuje známý fakt vzrůstajícího gradientu kontinentality.

Hranice lesa je v Krkonoších členitější, než v Jeseníkách a Králickém Sněžníku, což je způsobeno větší nadmořskou výškou a reliéfovou energií Krkonoš a s ní spojenými procesy (např. laviny a mury). Ve těchto pohořích se nachází geomorfologické doklady o dlouhodobé přítomnosti bezlesí, např. fosilní a více či méně recentně probíhajícími mrazovými procesy konzervované strukturní půdy. Zarostlé strukturní půdy se nachází na zarovnaných površích již 50 m nad alpinskou hranicí lesa. V Krkonoších probíhají i dnes ve větší míře procesy známé z periglaciálních oblastí. Kromě plošně se vyskytujících putujících balvanů, jejichž výskyt je omezen od linie hranice lesa vzhůru, jsou ostatní jevy strukturně, orientačně a expozičně podmíněny, takže jejich odstup od hranice lesa je pouze orientačním ukazatelem.

Dalšími doklady o přirozenosti bezlesí jsou rostlinná společenstva vyfoukávaných alpinských trávníků a endemická vysokostébelná společenstva karů.

Na základě výskytu výše uvedených jevů lze ve Vysokých Sudetách stanovit tyto přirozeně bezlesé lokality: vrcholová oblast Západních Krkonoš, vrcholová oblast Východních Krkonoš, vrchol Králického Sněžníku, Šerák, Keprník, Červená hora, Malý Děd, Praděd, Mravenečník a jižní část hlavního hřebene Hrubého Jeseníku v úseku Vysoká hole – Pecný.

Domníváme se, že podobně jako nejvyšší polohy Krkonoš, tak ani vrchol Králického Sněžníku a nejvyšší oblasti Hrubého Jeseníku nebyly v celém průběhu holocénu pokryty zapojeným lesem. Důkazem pro toto tvrzení je výskyt zachovalých periglaciálních jevů, zejména strukturních půd.

Trendem dvacátého století je v Krkonoších vzestup alpinské hranice lesa na místech dříve ovlivňovaných budním hospodářstvím a na menších kamenných mořích. Na lavinových drahách dochází k oscilacím. V důsledku imisního odumírání stromů lokálně na některých lavinových drahách hranice lesa klesla. Důsledkem imisních spadů je lokální pokles hranice stromu. V Jeseníkách a na Králickém Sněžníku docházelo po odeznění hospodaření v nejvyšších polohách vysokohorským zalesňováním v posledním století k plošnému zvýšení hranice lesa.

Typickou šířkou ekotonu alpinské hranice lesa se Krkonoše výrazně liší od Králického Sněžníku a Hrubého Jeseníku. Převládá v nich ekoton širší než 100m, ekoton užší než 50m se vyskytuje zejména na lavinových drahách a kamenných mořích, střední ekoton je zpravidla přechodem mezi dvěma výše uvedenými. Naproti tomu v Jeseníkách a na Králickém Sněžníku převládá nejužší ekoton, relativně dlouhý je i úsek hranice lesa se střední šířkou ekotonu. Nejužší ekoton je typický pro prokazatelné výsadby, včetně nejvýše položených, tzv. cennových výsadeb.Toto uspořádání vysvětlujeme větším antropogenním ovlivněním hranice lesa v obou pohořích a navíc přirozenou absencí kleče.

Treml, V., Banaš, M. Alpine timberline in the High Sudetes Acta Universitatis Carolinae, Geographica, 35(2): 83-99.

Photo 1: Alpine timberline nearby Velká kotlina in the Jeseníky Mts. Air photo: AOPK ČR.

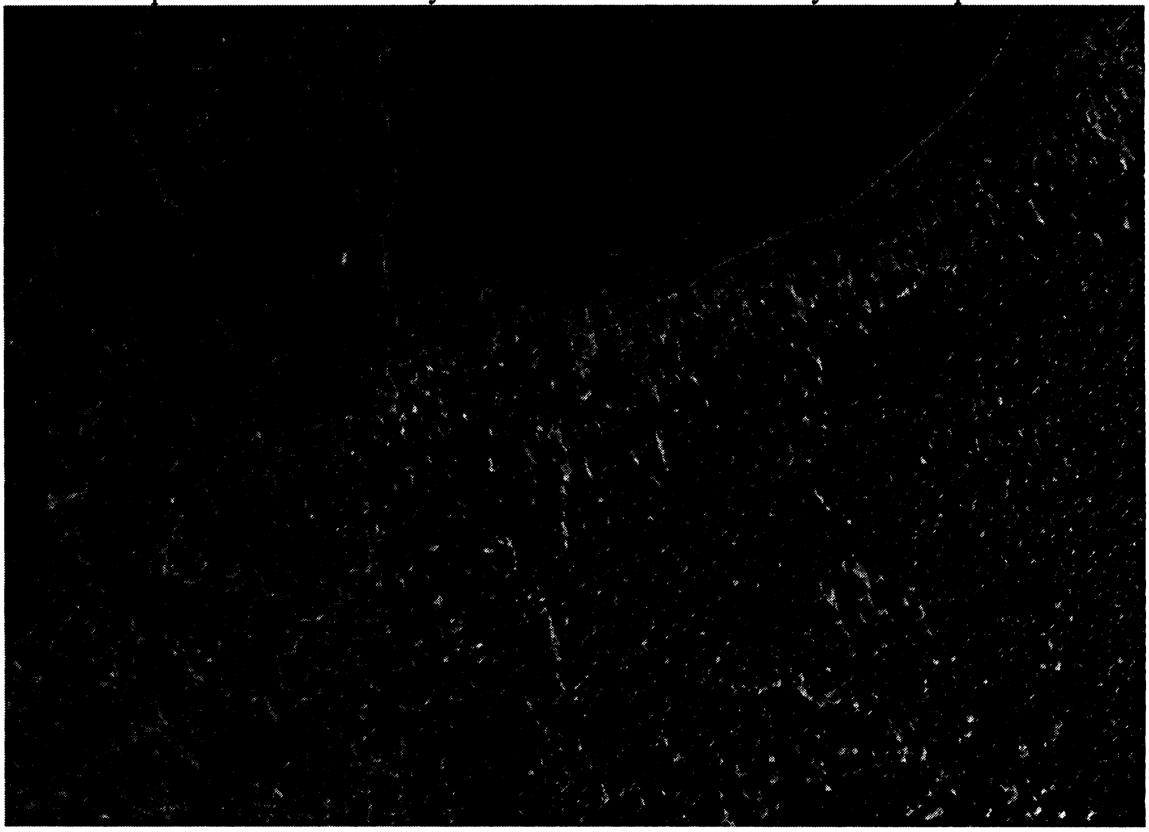


Photo 2: Alpine timberline in the Dlouhý důl valley, Krkonoše Mts. Air photo: AOPK ČR.

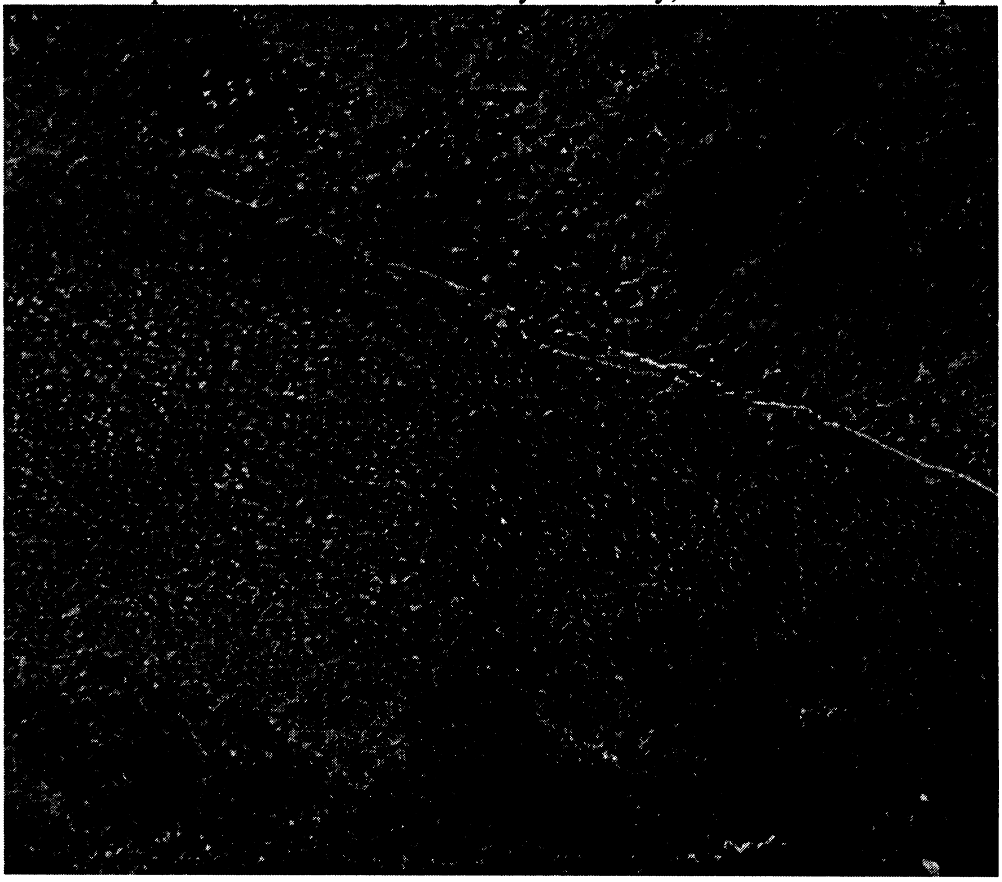


Fig. 1. Alpine timberline in the western part of the Krkonoše Mts.

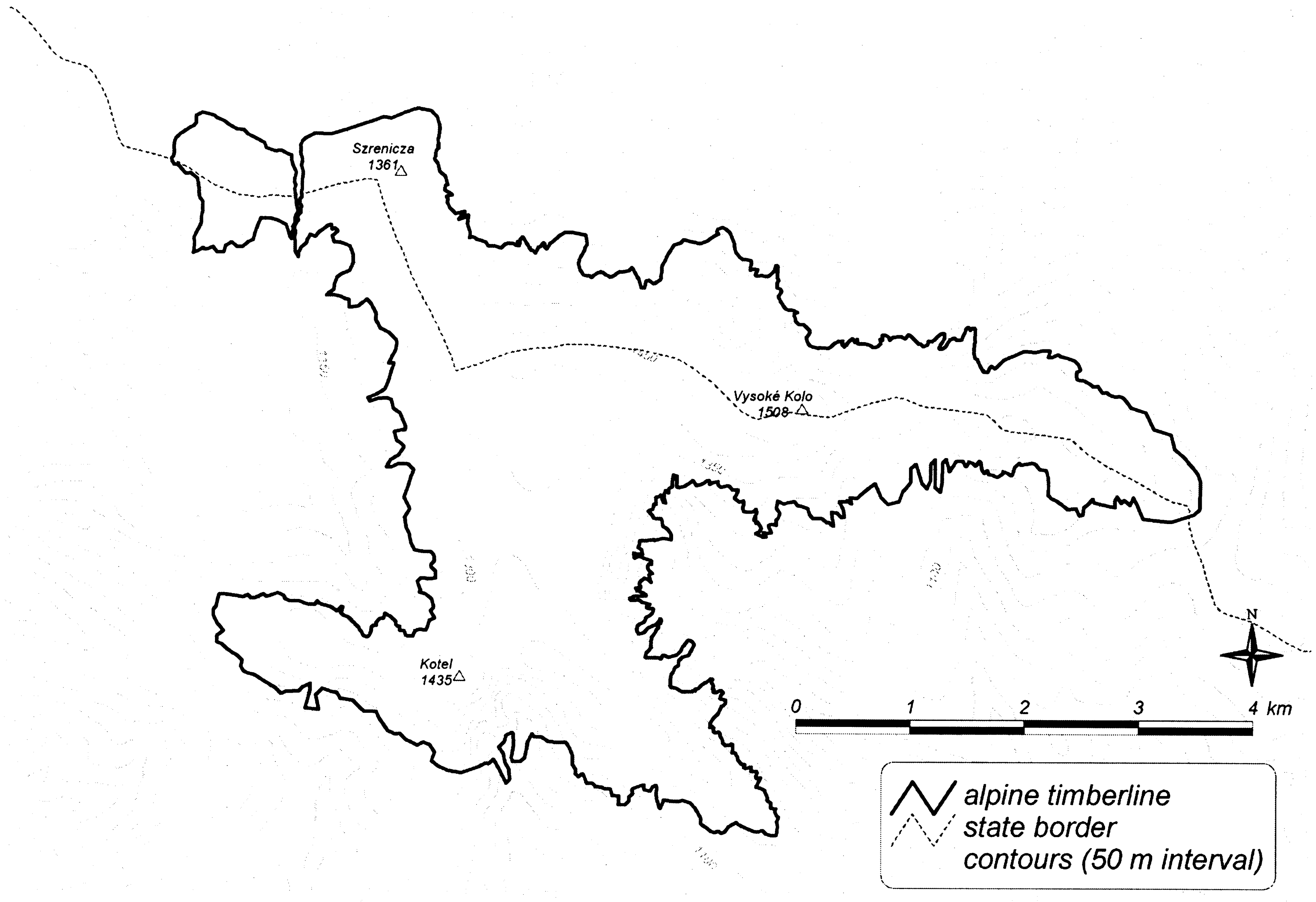


Fig. 2. Alpine timberline in the eastern part of the Krkonoše Mts.

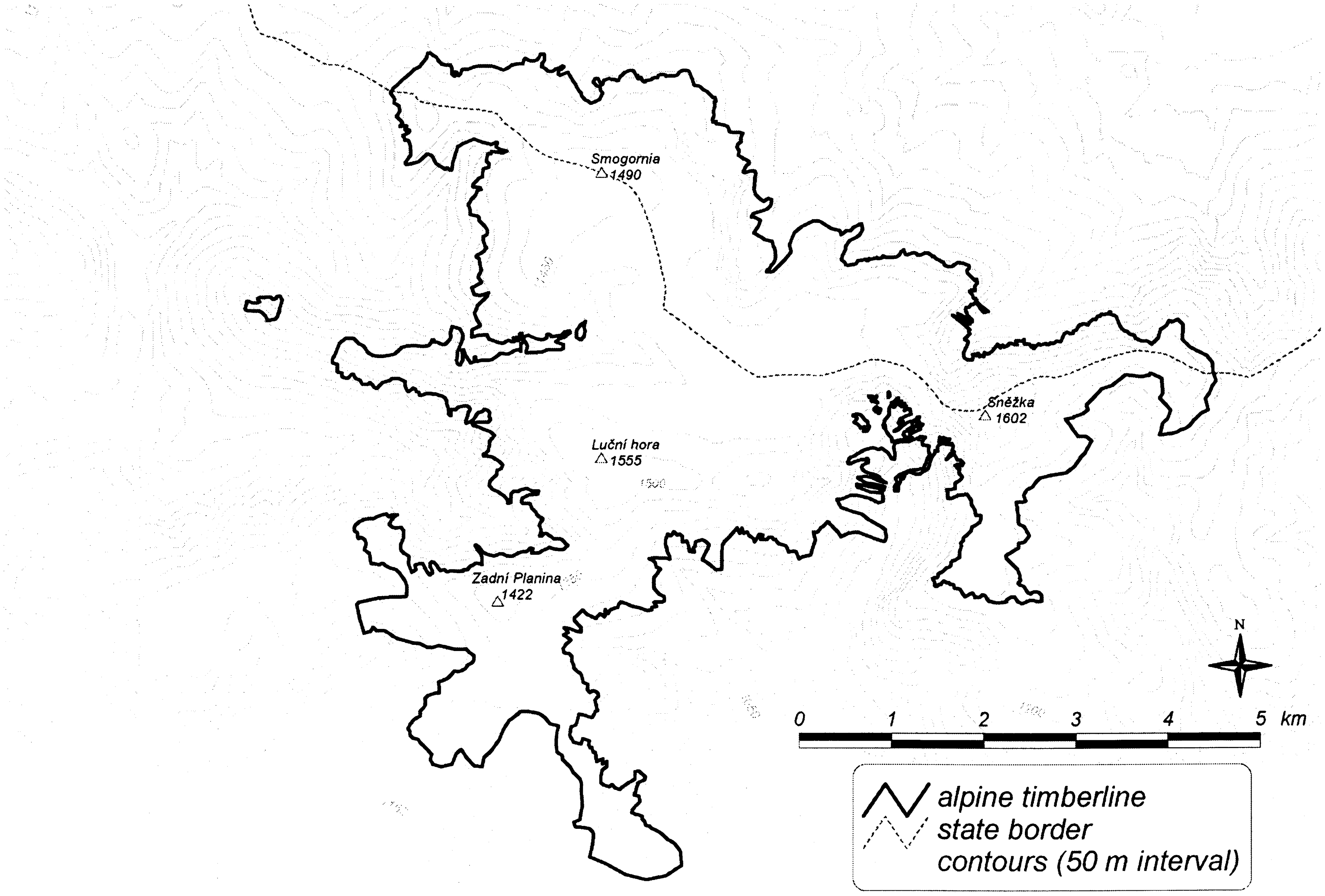
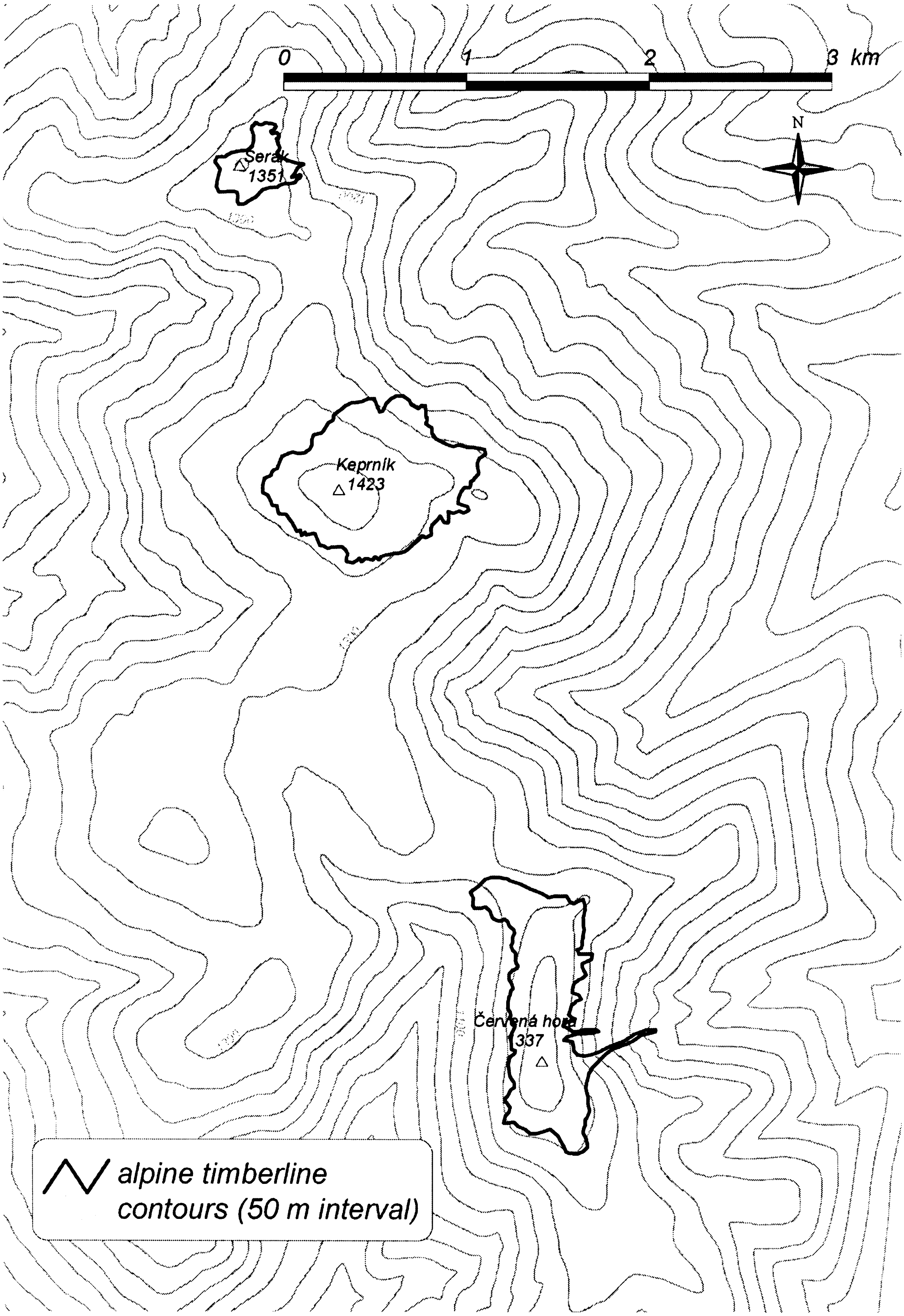
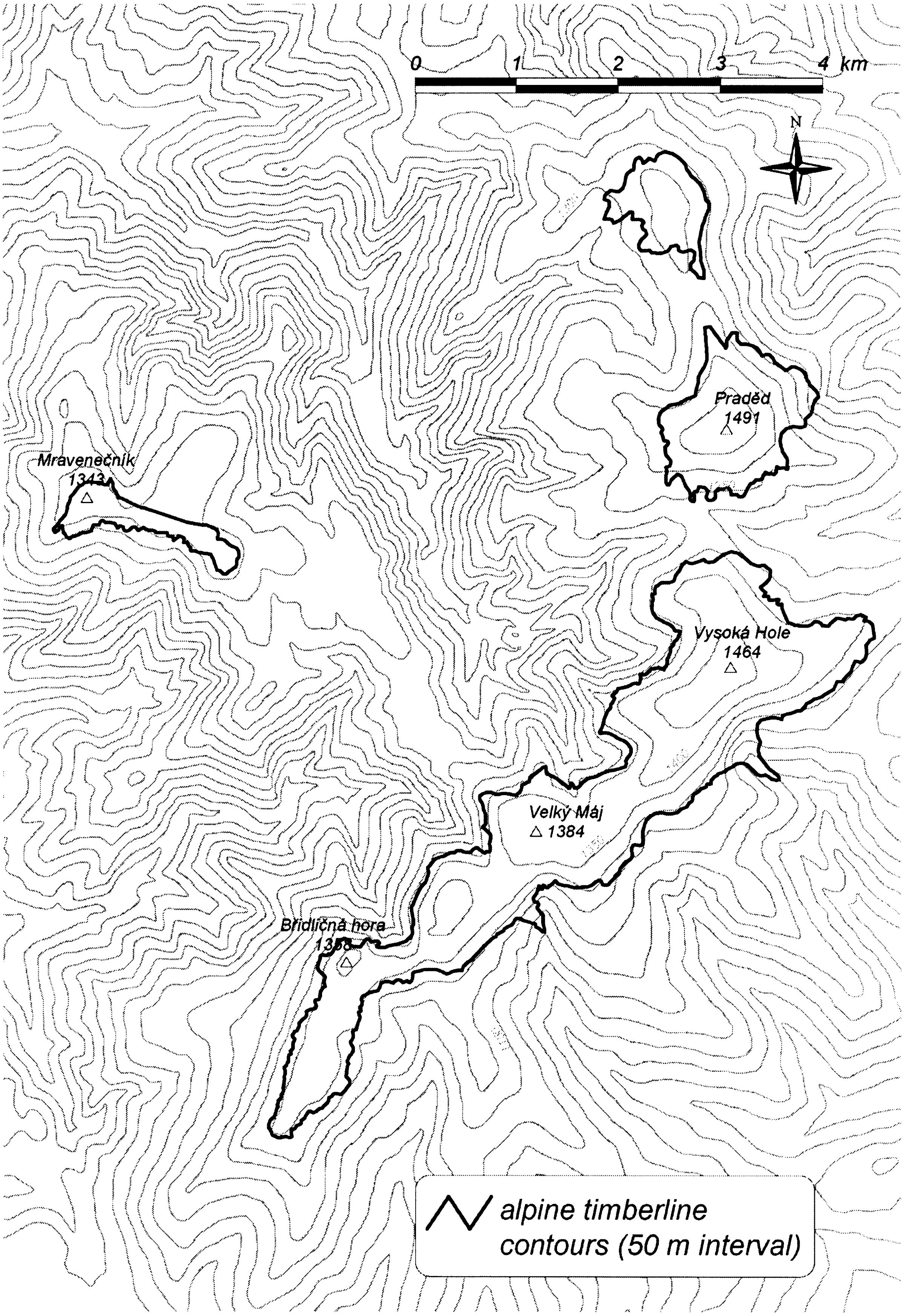


Fig. 3. Alpine timberline in the northern part of the Hrubý Jeseník Mts.



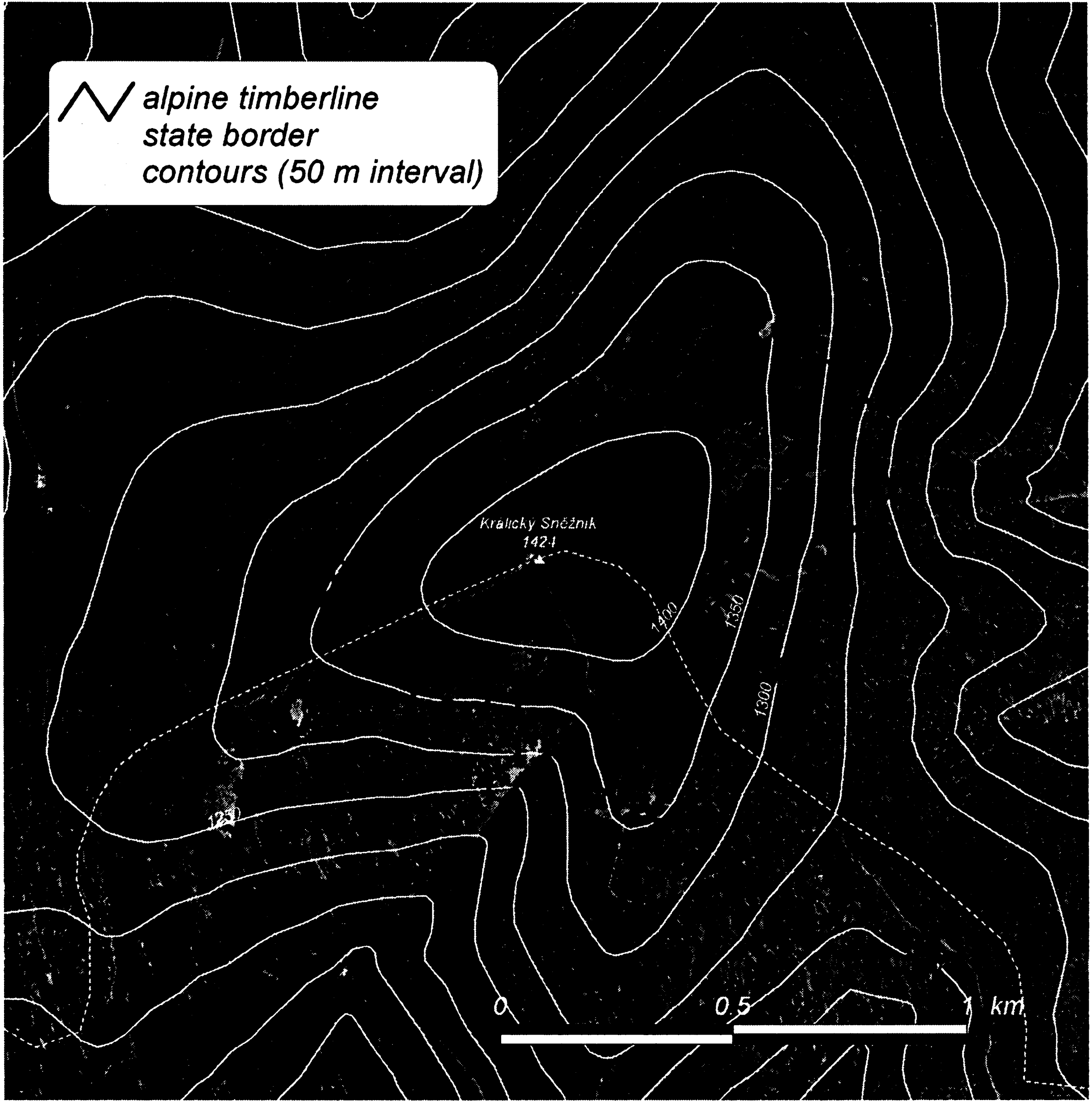
Treml, V., Banaš, M. Alpine timberline in the High Sudetes Acta Universitatis Carolinae, Geographica, 35(2): 83-99.

Fig. 4. Alpine timberline in the southern part of the Hrubý Jeseník Mts.



Treml, V., Banaš, M. Alpine timberline in the High Sudetes Acta Universitatis Carolinae, Geographica, 35(2): 83-99.

Fig. 5. Alpine timberline in the Králický Sněžník Mts., Air photo by AOPK ČR



Treml, V., Jankovská, V., Petr, L. Alpine timberline in the mid-mountains of Central Europe – evidence of its evolution during the Holocene. FENNIA (accepted).

Alpine timberline in the mid-mountains of Central Europe – evidence of its evolution during the Holocene

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Abstract

The study focuses on Central European Hercynian mountain ranges – Krkonoše Mts., Hrubý Jeseník Mts. and Vosges, Schwarzwald, Harz – that represent the only islands of alpine forest-free area between the Alps and Western Carpathians in the south and the Scandes in the north. Based on data from previously published pollen profiles and on newly taken cores, comparison of the development of the alpine timberline position is carried out. The Labský důl profile in the Krkonoše Mts. spans the whole Holocene, the Keprník profile in the Hrubý Jeseník Mts. brings information from ca 2500 BP to the present. An exceptional position of the Krkonoše Mts. in terms of permanent presence of alpine forest-free area throughout the Holocene was confirmed. In other mountain ranges the alpine forest-free areas probably vanished or were restricted only to the exposed peaks during the periods of positive temperature anomalies in the Middle Holocene. Then in the period 4000-500 BP forest free areas reappeared, nevertheless the contribution of climatic and anthropogenic causes to their formation remains questionable. Taking into account the supposed extent of temperature oscillations in the Middle and Upper Holocene and the existing pollen records the authors assume that the alpine timberline in the Hercynian mid-mountains of Central Europe varied rather slightly.

Treml, V., Jankovská, V., Petr, L. Alpine timberline in the mid-mountains of Central Europe – evidence of its evolution during the Holocene. FENNIA (accepted).

Introduction

The term alpine timberline stands for the ecotone between forest and alpine (sensu Körner 1999) belt or subalpine shrub formations. The factor determining the presence of the forest is the temperature decline related to the increasing altitude (Körner 1999). The alpine timberline ecotone presents the transition zone of varying width and structure (Armand 1992). The varying ecotone structure infers some differences in ecotone response to changing temperature conditions. In general the response of the alpine timberline to changing temperature conditions is usually delayed (Slatyer & Noble 1992, Paulsen et al. 2000). Its position is determined rather by long-term climatic trends than by actual temperature conditions (Paulsen et al. 2000). In contrast local or regional advances of treeline or tree-species line (for discussion about trees and lines see Körner 1999) as response to the short or mid-term temperature increase could be very rapid (e.g. Bugmann & Pfister 2000, Kullman 2007). Moreover, reactions to climatic changes are often opposing (ascent of the timberline due to higher temperature and its descent due to higher precipitation or drought – Wilmking et al. 2004).

A certain variation of the alpine timberline position due to climatic oscillations during the Holocene can be traced down. In Central Europe the fluctuation of the timberline position is supposed to reach up to 200 m (Tinner & Theurillat 2003). For the High Sudetes (Krkonoše and Hrubý Jeseník Mts.) and Western Carpathians, oscillations up to 400 m are quoted (Firbas 1952, Ložek 2001) though this question remains open.

The aim of this study is to summarize the development of the timberline position in the Hercynian mountains of Central Europe based both on interpretation of previously published data and pollen diagrams and on newly constructed pollen diagrams from Krkonoše and Hrubý Jeseník profiles.

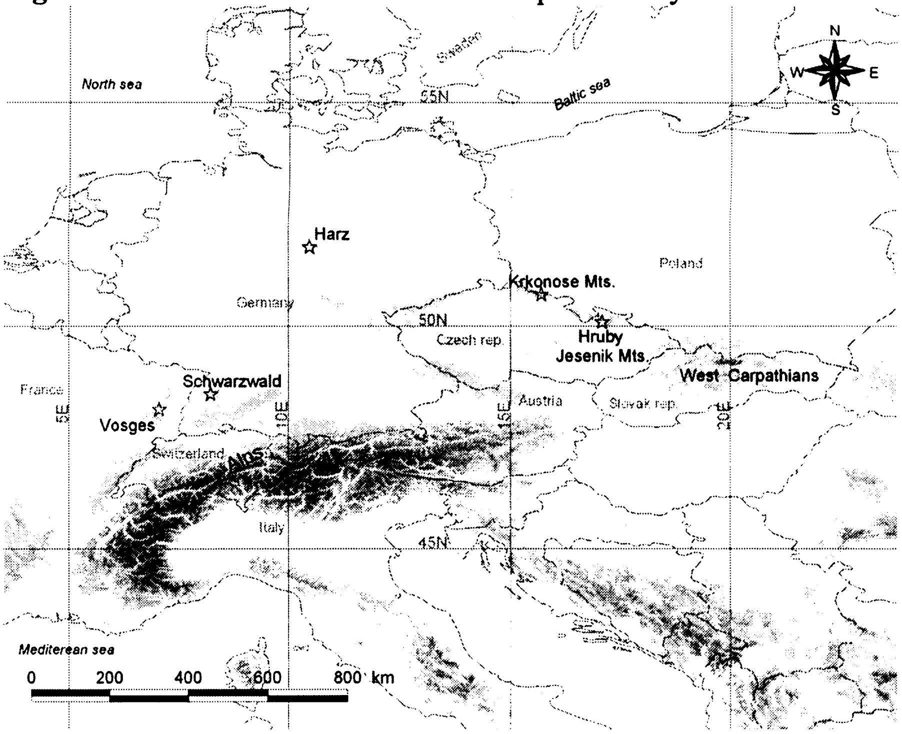
Methods

Study area

Hercynian mountain ranges of Central Europe with its primary forest-free areas represent the only alpine islands between the Scandes and the Alps and Western Carpathians (Jeník 1998). They include Vosges, Harz, Krkonoše Mts. (~ Giant mountains/Karkonosze/Riesengebirge) and Hrubý Jeseník Mts. (Fig. 1). Large forest-free area has developed also in the Schwarzwald Mts. but it is probably of secondary origin (Friedmann

2000). The same holds true for the forest-free area on the top of the Šumava (Bayrischer Wald) mountain range. All these mountains are characteristic by relatively high rainfall (from 2200 mm in the highest parts of the Vosges Mts. to 1500 mm in the Hrubý Jeseník Mts.). The average July temperatures range from 8,7 °C in the highest parts of the Krkonoše Mts. (Sněžka 1602 m asl) to 11,5 °C in the Vosges Mts. (Hohneck, 1363 m asl). Apart from the Vosges, where European beech (*Fagus sylvatica* L.) is present, the timberline is formed by Norway spruce (*Picea abies* [L.] Karst.) The extent of forest-free area has been strongly influenced by man who increased it in the past by deforestation in all the mentioned mountain ranges (Jeník & Lokvenc 1962, Jeník & Hampel 1991, Friedmann 2000, Schwartz et al. 2005).

Fig. 1: Position of described central European Hercynian mid-mountains.



Pollen analysis and sedimentology

This study presents two new pollen profiles that bring information about history of the alpine belt in the the Krkonoše and Hrubý Jeseník Mts. Pollen records come from the Labský důl valley (Krkonoše Mts.) and Kepmík Mt. (Hrubý Jeseník Mts.). The locality Labský důl is situated in the lake of glacial origin filled with deposits (Engel et al. 2005). This profile provided the longest pollen record ever analyzed in Krkonoše – from late glacial period to the present. The locality lies close to the timberline which is lowered here by avalanches. The 1283 cm deep profile (cirque bottom, 990 asl, 50°45'N, 15°33'E) was taken up by Russian peat sampler. Except the upper layer of peat character the profile contained mainly inorganic matter. The part of the profile between 810 and 830 cm was contamined during the sampling.

The profile from Mount Kepmík (1429 m asl, 50°10'N, 17°07'E) was taken from a pit dug in an earth hummock. The organic sediment had a peat character with sedge remains. The locality is situated on the plateau in the northern part of the mountain range at a distance of 200 m (60 m of altitude) above the timberline.

The samples for pollen analysis were processed with standard acetolysis method (Moore et al. 1991). Pollen grains were determined using the guides (Beug 2004). Pollen diagrams including stratigraphic zones were created using TILIA (Grimm 1992) software. The sediment from Labský důl was analysed also in terms of the proportion of organic matter (determined by loss-on-ignition) and particle size distribution (determined by wet sieving). Based on those two indicators the segments of the profile with similar characteristics (particle size distribution, organic matter proportion, colour) – so called litostratigraphic units – were determined. Radiocarbon dating was carried out by laboratories in Erlangen, Poznan (accelerator mass spectrometry /AMS/ ^{14}C) and at the Faculty of Science of Charles University in Prague (conventional ^{14}C) (Tab.1). Absolute data are expressed, if not indicated otherwise, as uncalibrated radiocarbon years BP. Linear age-depth model ($R^2 = 0,98$) from uncalibrated radiocarbon data was, in the case of Labský důl, created for the depth ranging from 205 to 963 cm. Chronostratigraphic zones are used according to Lang (1994).

Tab. 1: Radiocarbon data from Labský důl and Kepmík sites.

Site	Depth (cm)	Lab. No.	Dated material	14C Age (uncal. BP)	Laboratory
Labský důl	205	ERL 6295	peat	4080±49	Phys. Inst. der Uni. Erlangen
Labský důl	230-250	CU 1916	peat	4380±148	Radiocarbon Laboratory Charles University
Labský důl	354	ERL 6318	peat	5024±53	Phys. Inst. der Uni. Erlangen
Labský důl	438	ERL 6319	wood fragment	5272±57	Phys. Inst. der Uni. Erlangen
Labský důl	547	Poz-13708	wood fragment	5780±60	Poznań Radiocarbon Laboratory
Labský důl	797	ERL 7380	plant macroremain	8216±94	Phys. Inst. der Uni. Erlangen
Labský důl	963	ERL 6184	plant macroremain	9572±54	Phys. Inst. der Uni. Erlangen
Kepmík	50-51	Poz-13744	peat	2090 ± 35	Poznań Radiocarbon Laboratory

Interpretation of the alpine timberline altitudinal shifts

When interpreting the pollen diagrams in relation to the timberline position, emphasis was placed namely on the proportion of herbs and woody species (AP/NAP). This proportion enables to determine, although not precisely, whether forest or forest-free area dominated in the vicinity of the profile. Macroscopic remains of plant species provide better information about the timberline position (Tinner & Theurillat 2003). In the case of Kepník site the sedge and *Vaccinium* sp. remains were present, stomata were counted in Labský důl core. Unfortunately, macroremains of plant species were not mentioned in the majority of discussed studies, so the AP/NAP percentage had to be stressed when interpreting the timberline shifts.

Concerning the AP/NAP rate, critical arboreal percentage was considered to be 70-80 %, which is approximately the value of woody species proportion in the central European profiles situated in the area of timberline or just below (eg. Gouillé Rion, Gouillé Loéré, Grande Tsa – Tinner & Theurillat 2003, Tinner et al. 1996, Wright et al. 2003, northern side of Vysoké Tatry Mts. - Obidowicz 1993). In the case of variations of AP/NAP, it was always taken into account whether the change of the value was not due only to the change of dominant species with different (higher or lower) pollen production. If the timberline was constituted by spruce at the time, then proportion of spruce pollen ≥ 50 % was also considered as indicator of the closed stands at the locality (Obidowicz 1993).

Results

Krkonoše Mts.

The profile that is crucial for the reconstruction of the timberline position namely at the beginning of the Holocene comes from the locality Labský důl. The simplified pollen diagram (Fig. 2) shows data from Late Glacial period to ca 8000 BP which correspond to the profile depth 1283 cm to 790 cm. According to the analyses of pollen samples from the deeper parts of the profile, the markedly different composition of pollen spectra between 810 and 830 cm (Jankovská 2004) is due to contamination by peat sediment from the upper parts (cca 500-650 cm). Pollen curves of *Salix*, *Juniperus*, *Betula nana* type, *Ephedra distachya* and *E. fragilis* type and also the presence of the pollen of *Pinus* haploxylon type (i.e. *Pinus cembra*) delimit clearly the forest-free stage in the profile. Higher pollen curve of *Pinus sylvestris* type is produced by pollen from local *Pinus mugo* stands or by influx of *P. sylvestris* from lower altitudes. Combination of both factors is probable. In this period (i.e. before ca 9500 BP) alpine timberline was probably situated clearly bellow the investigated site. The first significant oscillation of AP/NAP curve is recorded around 1200 cm of profile depth (LD1). Before this period (early stage after deglaciation), closed pine forests have probably not occurred in the vicinity of the lake and thus regional (climatic) rather than local driving factor is suggested.

At around 9600 BP (LD2) a markedly lower proportion of arboreal pollen was recorded, nevertheless it is not clear whether the decrease of AP curve was caused by local disturbance events or by climatic influence.

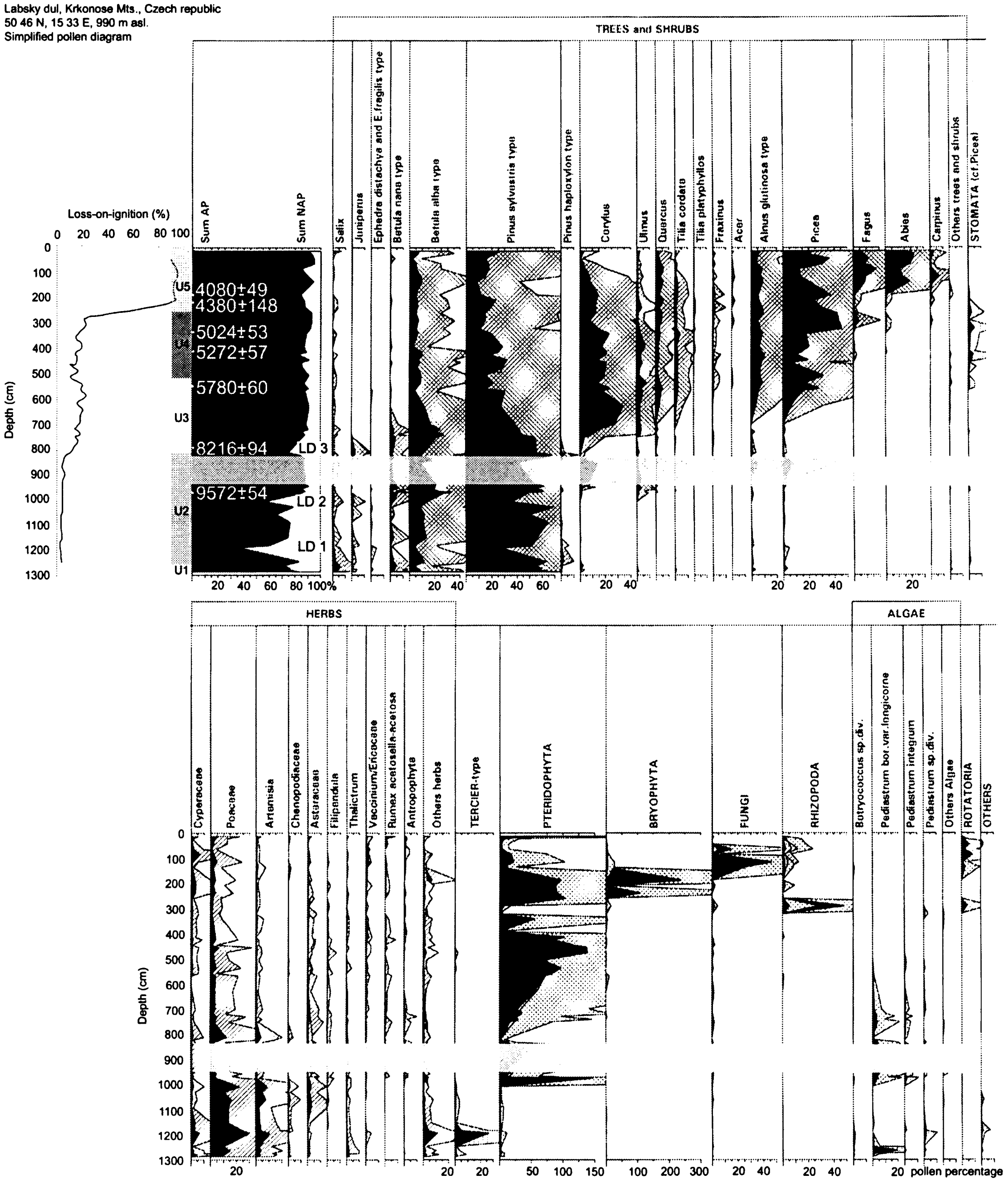
During the following period till 8200 BP the AP curve approaches and then, after 8200 BP, passes constantly 80 %. At the same time the proportion of organic matter in the lake sediment rises (from 7-9 % to 20-25 %). Apparently the timberline passed the level of Labský důl profile as late as around 9200-8800 BP. At that time it was composed of pioneer woody species (*Pinus, Betula*).

At 8200 BP another decrease of woody species pollen percentage (LD3) can be detected. It is set off by resedimentation of the matter below this part of the profile. Even other parameters (increase of the pollen of *Betula nana* type, *Juniperus*, lower proportion of organic matter in the sediment) probably indicate the increase of forest-free area either due to local disturbance or due to climatic event.

From above mentionted AP/NAP oscillation, only minor wiggles of AP/NAP curve in the range from 85 to 95 % arboreal pollen domination could be detected. Slight shifts in AP/NAP curve reflect probably only local vegetation changes and/or avalanche events. Hence more elevated localities can give more evidence about the alpine timberline position during the most part of Middle and Upper Holocene.

Norway spruce as a timberline forming species since Atlantic period (Jankovská 2004) has been sporadically present at the Labský důl site according to stomata since 7500 BP, in great number from 6800 BP.

Fig. 2: Simplified pollen diagram, radiocarbon data, loss-on-ignition and litostratigraphic units (U1-U5) in the "Labský důl" core. Light rectangle across pollen diagram indices contamined part of profile (810 – 830 cm depth).

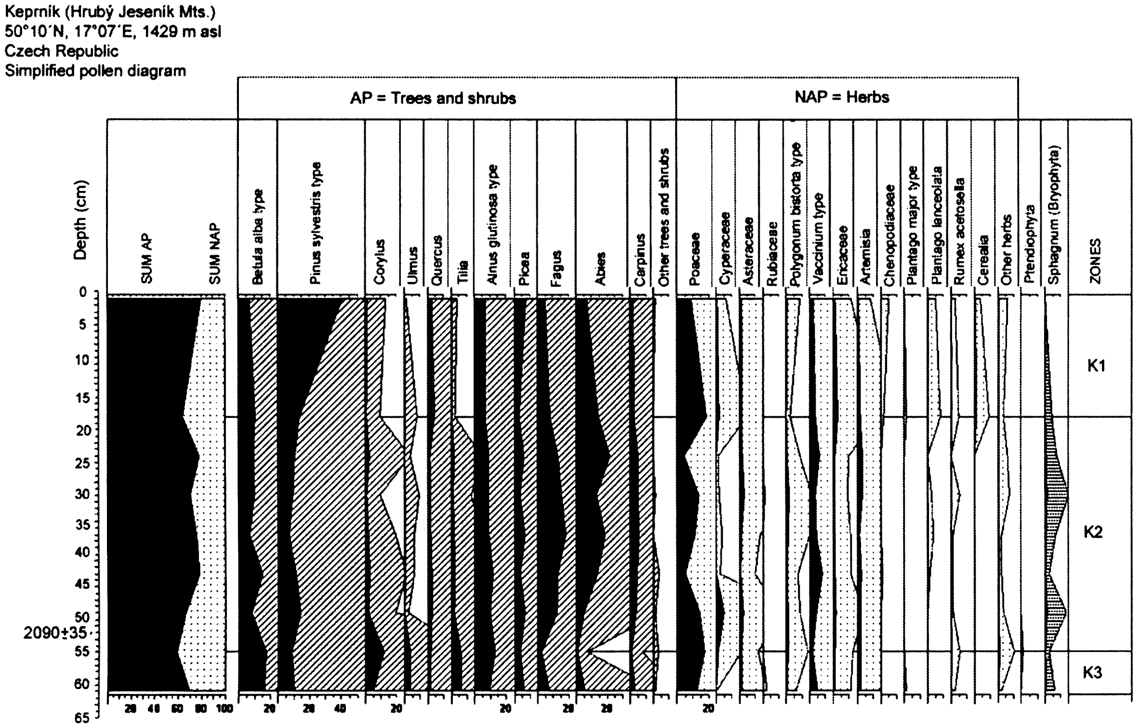


Hrubý Jeseník Mts.

The investigated pollen profile taken from an earth hummock at the summit of the Kepmík Mt. covers the time span since ca 2500 BP, so it records similar period as other pollen profiles analysed in the Hrubý Jeseník Mts. (Rybníček & Rybníčková 2004).

At the summit of Mount Kepmík the AP proportion in the mentioned time period was between 70 and 80 % (zone K1, K2, Fig. 3). At the same time no woody species stomata were found in the investigated profile. The profile shows regression of woody species typical for mixed oak forests and progression of beech and fir in the K2 zone. Direct indicators of human activities are present in the uppermost layers (K3). In the whole profile, there are only minor shifts in NP/NAP curve. With respect to the absence of spruce stomata remnants and AP percentage lower than 80 % (in exposed windy position with potentially high pollen influx from lower areas), it could be concluded that closed forest has not been established in the summit area of the Keprník Mt. during the last 2,5 kA. Other evidence for suggested development of the investigated locality could be found in occurrence of earth hummocks since at least 2090 BP. Those landforms are usually quickly destroyed as they are colonised by trees (Treml & Křížek 2006).

Fig. 3: Simplified pollen diagram, summit of Mt. Kepmík (1429 m asl).



Discussion

Evolution of the alpine timberline in the Krkonoše Mts. and the Hrubý Jeseník Mts.

As a starting point of the alpine timberline reconstruction in the Krkonoše Mts. its position in the Younger Dryas could be taken. During this period the timberline position can be estimated at 500-600 m of altitude (according to equilibrium line altitude, which lied at approximately 1200 m asl). It follows that the timberline reached the upper locations with a certain time lag which corresponds to the relatively late deglaciation (Bourlés et al. 2004). Three distinct oscillations of AP/NAP curve had been detected before the timberline finally passed the Labský důl cirque bottom. It is suggested that the first of them (LD1) is rather climatically driven timberline descent than the result of local disturbances (see Results). The second significant oscillation of AP/NAP curve (LD2) seems to have also more probably regional than local cause. Before this period timberline had still remained bellow the Labský důl site, therefore local disturbance in closed pine-birch forest would not be significantly manifested in AP/NAP curve. The third oscillation (LD3) could be, if climatically caused, correlated with the central European oscillation CE 2 (Haas et al. 1998), which was recorded also in the High Tatra Mts. (Kotarba & Baumgart-Kotarba 1999).

While the Labský důl profile brings the valuable information about the timberline position from the beginning of deglaciation till ca 8000 BP, other pollen profiles from the summit areas of the Krkonoše Mts. (Fig. 4) give evidence of alpine timberline evolution since 7600±130 BP, which is the time span of the Pančava peat bog profile (Huettemann & Bortenschlager 1987). This peat bog is situated on an exposed highly elevated planated surface and thus it is supposed that its pollen composition does not represent only local vegetation development, but the prominent part of pollen is brought by wind from windward valleys (Jeník 1998). High proportion of pollen belonging to herbs or dwarf shrubs species was detected (25-30% - Gramineae, 10 % - *Calluna*) at the basis of this profile (Huettemann & Bortenschlager 1987). It means that at given time (~ 7600 BP) either the timberline had not yet reached the Pančava peat bog (1300 m asl) or that it had already been lowered below its level. In the following period (after 7400 BP according to Huettemann & Bortenschlager 1987) the alpine timberline reached at least the level of the Pančava peat bog and then apparently it varied only a little. Nevertheless according to Speranza et al. (2000) there was a colder period between 2640±60 and 2480±35 BP but there is no evidence for a timberline shift due to this oscillation.

In the following period no marked trend in forestation or deforestation of the region was detected in the highest parts of the Krkonoše Mts. At less elevated Pančava peat bog the woody species percentage reaches 90 % of the pollen spectrum (Jankovská 2001), at Úpa peat bog (1430 m asl) it reaches approximately 80 % (Svobodová 2004). Considerable proportion (20-30 %) of the pollen spectrum belongs to pine pollen which comes mainly from local *Pinus mugo* stands.

While at the Pančava peat bog Picea pollen represents during 4000 – 800 BP about 10 - 20 % of pollen spectra (Jankovká 2001, 2004), at Úpa peat bog it reaches only 5 -15 % (Svobodová 2004). It is probably the consequence of longer distance of the Úpa peat bog from timberline during mentioned period. Moreover, the both Pančava and Úpa peat bog pollen profiles show significantly lower percentage of *Picea* pollen, compared with sites recently surrounded by spruce forest (Labský Důl, Barborka). It indicates, that at least Úpa peat bog had to be situated above the alpine timberline during 4000 – 800 BP. Man-induced changes in vegetation are recorded in the above mentioned pollen profiles since Middle Ages (Jankovská 2004).

Based on existing data it is not possible to determine the exact level that the closed forest reached in the climatic optimum of the Holocene. Most likely a closed tall-trunk stand cannot be expected at locations with occurrence of well developed sorted patterned ground (approximately above the level of 1430-1450 m asl). If these landforms are overgrown by trees, they usually lose their raised centre morphology, which is not the case of the above mentioned patterned ground (Sekyra et al. 2002). The maximum elevation of the closed forest could therefore be only by about 100 m higher than today.

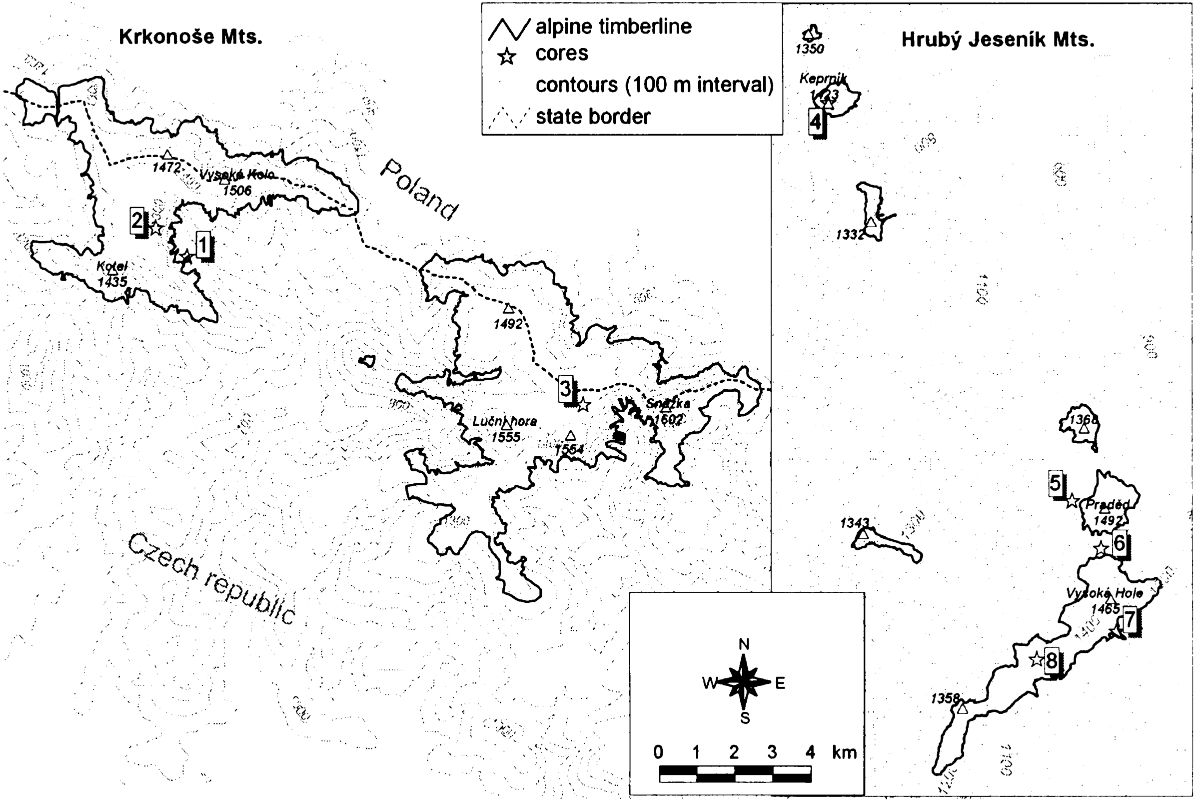
Profiles from the Hrubý Jeseník Mts. (Fig. 4) that were analyzed in terms of pollen composition contain record from 4620 BP to the present. High representation of hazel pollen indicates hazel stands at the summit locations (about 1300 m asl) during the period 4620 – 3500 BP (Rybníček & Rybníčková 2004), nevertheless there is no direct evidence in form of macroscopic remains to support this hypothesis.

At localities that are forest-free at present, relatively low proportions of woody species pollen were recorded during the period 1945-800 BP – approximately 60 % at Velká Máj (peat bog on the summit plateau) and also at Velká kotlina (peat bog on the cirque bottom), where the oscillations of AP/NAP curve were more pronounced (Rybníček & Rybníčková 2004). That indicates the existence of the permanent forest-free area at given localities in this period. Significant local changes in timberline position probably happened in the area of the Velká kotlina cirque. Proportion of arboreal pollen was higher in the case of Mt. Keprník (70-80%) compared to both above mentioned sites. However we take the presence of earth hummocks since at least ca 2100 BP as a proof of permanent forest-free area at the summit of Keprník. Such landforms could not persist in the closed forest canopy because tree roots would physically degrade them (Treml & Křížek 2006). The similar landforms of the same age occure also on the summit of the Praděd Mt. (1492 m asl, Treml et al. 2006).

At localities that are forested at present (Barborka, Velký Děd, Rybníček & Rybníčková 2004), the AP proportion fluctuates around 85 % between 3700 and 800 BP. A noticeable decrease of representation of woody species pollen, namely beech and fir, was recorded in most profiles at around 500 BP (zone K3 in the case of Keprník). This can be ascribed above all to the influence of human activities. Nevertheless, apart from the strong influence of man on the uppermost locations of the Hrubý Jeseník Mts. during the last 800-500 years (Hošek 1972), the synergic action of the last Little Ice Age could be involved.

With respect to all mentioned pollen profiles it could be concluded that in the Hrubý Jeseník Mts. the alpine timberline did not reach the most exposed summits (e.g. Keprník Mt., Velký Máj Mt.) during the period ca 2000-800 (500) BP and that forest free areas also persisted on steep slopes of the Velká kotlina cirque. Nevertheless the rest of the recent forest-free area remained covered with trees and was deforested as lately as after 800-500 BP.

Fig.4: Positions of described pollen profiles within the Krkonoše and Hrubý Jeseník Mts. (1) Labský důl; (2) Pančava peat bog (Huetteman & Bortenschlager 1987, Speranza et al. 2000, Jankovská 2001); (3) Úpa peat bog (Svobodová 2004); (4) Keprník; (5) Velký Děd; (6) Barborka; (7) Velká kotlina; (8) Velký Máj (5-8 - Rybníček & Rybníčková 2004).



Alpine timberline in the neighbouring mid-mountains - Vosges, Schwarzwald and Harz

The extent of alpine forest-free area in the neighbouring Hercynian mid-mountains is quite limited (Tab. 2, 3). In the Vosges Mts. the present alpine forest-free area is probably of natural origin only in the highest exposed parts of the summit plateaus (Carbiener 1963). Larger part of the area previously called "chaumes primaries" originates from deforestation during the Iron Age (Schwartz et al. 2005). The altitude of the timberline in the Younger Dryas is estimated at 500 m (Schloss 1979). Then in the early Holocene the timberline, constituted at that time by pine and birch trees, ascended rapidly to at least 1100 m (Schloss

1979, Edelman 1985). At the beginning of the Boreal period (according to Lemée 1963, ca 9000 BP), it reached altitude around 1200 m asl (Lemée 1963). Nevertheless in the Vosges Mts. the early Holocene could be affected by mesoclimatic effects of some valleys with glaciation relics (Mercier et al. 1999).

Around 8000 cal. BP (ca 7200 uncal. BP), according to Schwartz et al. (2005), Tilia platyphyllos occurred at an altitude of 1060 m (its present occurrence does not pass 900 m). This fact documents warmer climate at that period compared to the present. During the climatic optimum (8000-4500 BP), even the highest parts were forested. After ca 4500 BP beech stands in the highest parts thinned down and the timberline reappeared (De Valk 1981). At the most exposed locations it held there until the beginning of summer farming at such localities, which resulted in timberline lowering (1400-1200 BP, Schwartz et al. 2005). Due to farming (pasture, hay making, forest clearance), the majority of the present forest-free areas was created (Schwartz et al. 2005).

In Schwarzwald the altitude of the timberline in the Younger Dryas is estimated at 750 m (Lang 2006). During the early Holocene it increased rapidly to the level of the highest peaks where closed stands of pine and birch established. Present forest-free area is probably secondary and originates from the period of expansion of the summer farming to the highest parts (around 1000 AD Bogenrieder 1982, Friedmann 2000).

In the Harz Mts., the summit of Brocken Mt. (1141 m asl) was forested during the period of climatic optimum of the Holocene (e.g. Atlantic chronozone sensu Lang 1994) (Firbas 1952, Beug et al. 1999). Four treeless periods are documented in the summit area of Brocken (Younger Dryas – 9700 BP, ca 5700 – 5300 BP, 2900 – 2800 BP and after 500 BP, Beug et al. 1999). Existence of last period of forest-free area is documented from the 16th century, i.e. before the rise of intense human influence (Tackenberg et al. 1997). However, the assumptions about natural origin of the forest-free area at the Brocken summit are based mainly on floristic (Hauepler 1970) and historical evidences (Schade, cit in Tackenberg et al. 1997). No direct proofs (archaeological findings, soil charcoals) of previous anthropogenic impacts have been found; nevertheless a certain contribution of man to forest-free area formation at the Brocken summit can not be excluded (Beug et al. 1999).

Tab. 2: List of sources and sites which were used for reconstruction of alpine timberline position.

Mountain Range	Site/Source	Age start of record	Proxy used for treeline reconstruction	Author of study
Vosges	Gazon de Faing, 1230, 1290 m	only relative biostratigraphic dating – since Boreal	pollen	Lemée 1963
Vosges	Altenweiher 926 asl, Moselotte 1290	ca 8000 BP resp. 2500 BP	pollen	De Valk 1981
Vosges	Sewensee 500 m	late glacial	pollen	Schloss 1979
Vosges	Rossberg 1190 m	7600 BP – the oldest charcoal	charcoals – soil profiles	Schwartz et al. 2005
Vosges	Goutte Loiselot 850 m	late glacial	pollen	Edelman 1985
Vosges	several sites on Hautes Chaumes (above 1200 m)		soil profiles	Carbiener 1963
Schwarzwald	9 sites (654 – 1280 m)	late glacial	pollen	Lang 2006
Harz	Brocken summit area		historic data	Tackenberg et al.1997
Harz	Brocken summit area		floristic data	Hauepler 1970
Harz	several sites in Brocken area (highest 1100 m)	late glacial	pollen	Beug et al. 1999
Krkonoše	Labský důl 990 m	late glacial, first ^{14}C date 9200 BP	pollen, stomata	this study
Krkonoše	Pančavské rašeliniště 1325 m	7600 BP	pollen	Huettemann & Bortenschlager 1987
Krkonoše	Pančavské rašeliniště 1320 m	3100 BP	pollen, pollen concentration	Speranza et al. 2000
Krkonoše	Pančavské rašeliniště 1325 m	3995 BP	pollen	Jankovská 2001
Krkonoše	Úpské rašeliniště 1420 m	3440 BP	pollen	Svobodová 2004
Krkonoše	summit plateaus (above 1430-50 m)	persisted from late glacial	soils	this study
Hrubý Jeseník	Velký Máj 1350 m	1945 BP	pollen	Rybníček & Rybníčková 2004
Hrubý Jeseník	Velká Kotlina 1400 m	ca 1700 BP	pollen	Rybníček & Rybníčková 2004
Hrubý Jeseník	Barborka 1315 m	ca 3700 BP	pollen	Rybníček & Rybníčková 2004
Hrubý Jeseník	Velký Děd 1395 m	4600 BP	pollen	Rybníček & Rybníčková 2004
Hrubý Jeseník	Keprník 1423 m	2090 BP	pollen	this study
Hrubý Jeseník	Keprník 1415 - 1423 m, Praděd 1450 – 1490 m	2100 BP	earth hummocks - soils	this study, Treml et al. (2006)

Extent of the alpine belt during the Holocene

With respect to the present vertical extent of the alpine belt in various Hercynian mountains of Central Europe (Tab. 3) it can be assumed that the alpine forest-free areas most “endangered” during the Holocene were situated in the Harz and Vosges Mts. At least in the second half of the Holocene, when woody species constituting the timberline today were already present in the Harz and Vosges Mts., no areas were probably naturally treeless during periods 0,5-1 °C warmer than today. Such positive temperature anomalies are likely, considering the recent Holocene temperature estimates from Central Europe (Haas et al. 1998, Hieri et al. 2003).

This hypothesis is supported also by results of the pollen analyses. They show that during the Holocene the alpine timberline in Hercynian mountain ranges of the Central Europe developed in different ways. In the Krkonoše Mts. large forest-free areas were present throughout the Holocene. In the Harz and Vosges Mts. even the uppermost locations (except for steep slopes, rocks, block fields or exposed peaks) were forested during the climatic optimum (De Valk 1981, Beug et al. 1999). The alpine forest-free areas in the Vosges reappeared after 5000 BP (De Valk 1981). In the Hrubý Jeseník Mts. according to recent temperatures and Holocene temperature estimates (e.g. Hieri et al. 2003) the alpine forest-free area had probably only a very limited extent during the warmer periods of the Holocene and it expanded most likely before 2000-2500 BP, which is the age of the part of the pollen profile documenting forest-free areas at summit localities (Velký Máj, Velká Kotlina – Rybníček et Rybníčková 2004, Kepník). Presence of treeless areas at the summits of the Hrubý Jeseník is also proved by an earth hummock rise around 2100 BP. In the Schwarzwald Mts. the actual relatively large forest-free area is of anthropogenic origin (Friedmann 2000).

The history of alpine areas can be related to biodiversity. For example the butterfly communities of the Krkonoše Mts. differ greatly from those present in the Harz, Hrubý Jeseník and Králický Sněžník Mts. They are more similar to those of the West Carpathian mountain ranges (Mařák & Kuras 2006). This fact could confirm the notable distinctions of the forest-free area development in the Krkonoše Mts. compared to other mentioned Hercynian mountain ranges. The presence of many plant species and diversified communities dependent strictly on forest-free areas in all those mountain ranges (Jeník 1961) indicates that the forest-free enclaves had to exist in the long term. Nevertheless the presence of those forest-free patches depended rather on soil conditions, water regime or slope inclination than on temperature.

Tab. 3: Recent vertical extent of the alpine belt in Hercynian mid-mountains of central Europe – difference between elevation of the highest peak and uppermost outposts of the timberline. Values in the brackets correspond to the average height of natural nondepressed alpine timberline (Treml & Banaš 2000).

	Maximal elevation of the alpine timberline (m asl)	T** (°C)	Vertical extent of the alpine belt (m)	Corresponding gradient of summer temperature (°C)
Vosges	1360	8,0	60	0,3-0,4
Harz	1125*	7,8	20	0,1-0,2
Krkonoše	1370	7,1	210 (300)	1,2-1,3 (1,8)
Hrubý Jeseník	1430	7,2	60 (140)	0,3-0,4 (0,8)

* ... sensu Tackenberg et al. (1997)

** ... average temperature IV – IX (vegetation period, 1981-1990) at the maximal elevation of the alpine timberline, calculated from data published by Migala (2005), with temperature lapse 0,6°C/100 m.

Rate of timberline fluctuation

The maximum extent of timberline oscillations in central European mid-mountains is influenced by their low altitude and a very limited space between their uppermost parts and the timberline. In the Krkonoše Mts. the presence of a closed forest cannot be expected at sites with well developed sorted forms of patterned ground at altitudes above 1450 m asl. Sorted forms of patterned ground were formed here at the end of the last glacial stage (Traczyk & Migoň 2003). Maximum difference in the timberline position compared to the present was therefore less than 100 m. In other Central European Hercynian mountain ranges the timberline ascended to the highest locations. Minimum difference in the timberline position ranged therefore from 25 m (Harz Mts.) to 40-150 m (Hrubý Jeseník Mts.). However, it is possible that during some of the cold oscillations recorded in the Central Europe (for example CE 8, Haas et al. 2003) the timberline could be situated lower than today and the total fluctuation would therefore be several tens of meters. As for the Vysoké Tatry Mts., Obidowicz (1993) argues that during the climatic optimum the alpine timberline was only by 50 or 100 m higher than today. The above mentioned lower rates of the timberline oscillations correspond to temperature reconstructions (Haas et al. 1998, Hieri et al. 2003) that estimate the extent of summer temperature oscillations in Middle and Upper Holocene to 1 °C. Nevertheless the changes of the timberline position in this period could not be as vigorous as at the very beginning of the Holocene (Tinner & Kaltenrieder 2005) because of the already formed stable communities that were strongly influenced by competition. This can be seen in the Krkonoše Mts. even today – as temperature increases the timberline ascends first at disturbed localities with low herb cover (old debris flow tracks) and thus the sites with higher rates of seedling establishment (Treml 2004).

Conclusions

In the Holocene, Harz, Vosges, Schwarzwald and Hrubý Jeseník Mts. were more prone to disappearance of forest-free area during the periods with favourable climatic conditions. Most likely, the temperature dependent alpine belt did not exist there during the climatic optimum of the Holocene. A large alpine area was maintained throughout the Holocene only in the Krkonoše Mts. In the Hrubý Jeseník Mts. a temperature dependent forest-free area existed at least since 2000 BP to the present.

In the Krkonoše Mts. alpine timberline gradually advanced from 500-600 m in the Younger Dryas to 1000 m (9200-8800 BP). After 7400 BP timberline ascended at least to 1320 m, which is the altitude of the Pančava peat bog. Maximum timberline position in the Krkonoše Mts. had not been situated higher than at 1450 m asl (lower limit of well developed sorted patterned ground formed in the late glacial). It had therefore passed the present maximum by 60 m and the average positions of the natural timberline by 150 m. During 4000 – 800 BP alpine timberline was situated probably below Úpa peat bog (1420 m asl.). In the Labský důl profile three distinct oscillations of AP/NAP curve were recorded during the Lower Holocene, of which at least two (LD1 and LD2 – 9600 BP) are supposed to be caused by climatic factors rather then by local events (disturbances). Both come probably from a timberline descent.

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Holocene dynamics of the alpine timberline in the High Sudetes

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Abstract

The study focuses on the High Sudetes that represent the most distinctive islands of alpine forest-free area among hercynian mid-mountains of Central Europe. Based on data from newly taken cores and previously published pollen profiles, comparison of the development of the alpine timberline position is carried out. The first of the analysed pollen profiles - the Labský důl core in the Krkonoše Mts. spans the whole period of the Holocene, the Keprník and Mezikotlí profiles in the Hrubý Jeseník Mts. bring information from the Subboreal/older Subatlanticum turn to the present. An exceptional position of the Krkonoše Mts. in terms of permanent presence of the alpine belt throughout the Holocene was confirmed. Three oscillations of the alpine timberline during the Lower Holocene were detected in the profile from the Labský důl site. In the Hrubý Jeseník Mts. a temperature dependent forest-free area existed at least since Subboreal to the present.

Key words: alpine timberline, High Sudetes, Krkonoše Mts., Hrubý Jeseník Mts., Holocene.

Introduction

The term alpine timberline (defined according to Körner 1999) stands for the ecotone between forest and alpine belt or subalpine shrub formations. A fundamental factor determining a gradual decline of forest with increasing altitude is the temperature decrease

(Körner 1999). Recently, many forest advances to higher elevations are recorded as a reaction to temperature increase (Holtmeier & Broll 2005, Kullman 2007). Nevertheless, the general upward shift of the alpine timberline is determined rather by long-term climatic trends than by actual temperature conditions (Paulsen et al. 2000). Moreover, reactions to climatic changes are often opposing (ascent of the timberline due to higher temperature and its descent due to higher precipitation or drought, Wilmking et al. 2004).

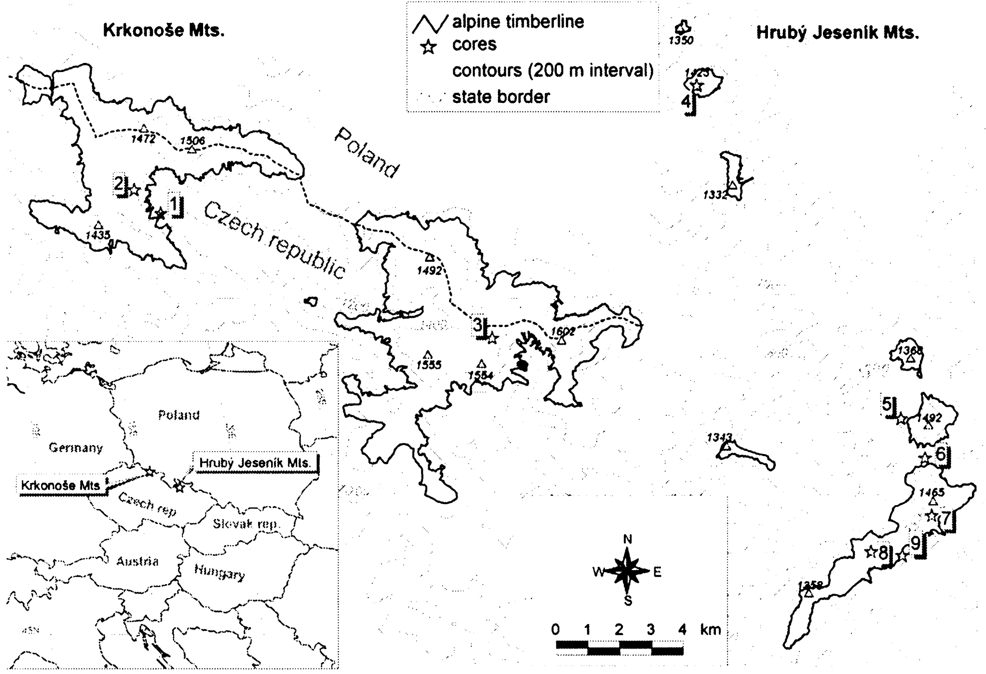
A certain variation of the alpine timberline position due to partial climatic oscillations during the Holocene can be traced down. In the Central Alps the fluctuation range of the timberline is supposed to reach up to 200 m (Tinner & Theurillat 2003). For the High Sudetes (Krkonoše and Hrubý Jeseník Mts.) and Western Carpathians, oscillations up to 400 m are quoted (Firbas 1952, Ložek 2001) though this question remains open. Recently, some new cores have been taken in the Krkonoše Mts. and Hrubý Jeseník Mts. and thus new information about formation of the alpine timberline ecotone throughout the Holocene can be presented. The aim of this study is to describe the newly constructed pollen diagrams from the High Sudetes with respect to the alpine timberline position and to discuss the development of the alpine forest-free area extent during the Holocene.

Methods

Study area

The High Sudetes with its primary forest-free areas are supposed to be the best developed alpine areas among central European hercynian mid-mountains (Jeník 1961). They include the Krkonoše Mts. (~ Giant Mountains/Karkonosze/Riesengebirge), the Králický Sněžník and the Hrubý Jeseník Mts. (Fig. 1). The study area is characteristic by relatively high precipitation (around 1500 mm per year). The average annual temperatures range from 0,1 °C in the highest parts of the Krkonoše Mts. (Sněžka 1602 m asl) to 1,1 °C in the Hrubý Jeseník Mts. (Praděd, 1493 m asl). The alpine timberline is formed by Norway spruce (*Picea abies* [L.] Karst.). The timberline ecotone grades either into dwarf pine (*Pinus mugo* Turra) growths in the Krkonoše Mts. or into alpine grasslands (Krkonoše and Hrubý Jeseník Mts.). The actual alpine timberline position is situated on average at 1230 m asl in the Krkonoše Mts. and at 1310 m asl in the Hrubý Jeseník Mts. (Treml & Banaš 2000). The extent of the forest-free area has been strongly influenced by man who increased it in the past by deforestation (Jeník & Lokvenc 1962, Jeník & Hampel 1991).

Fig. 1: Study sites in the High Sudetes. 1 – Labský důl, 2 – Pančava peat bog (Huettemann & Bortenschlager 1987, Speranza et al. 2000a, Jankovská 2001) 3 – Úpa peat bog (Svobodová 2002), 4 – Kepmík, 5 – Velký Děd, 6 – Barborka, 7 – Velká kotlina, 8 – Velký Máj (5-8, Rybníček & Rybníčková 2004), 9 – Mezikotlí.



Pollen analysis and sedimentology

This study presents three new profiles that bring information about the history of the alpine belt in the Krkonoše and Hrubý Jeseník Mts. Pollen records come from the Labský důl valley (Krkonoše Mts.), Mount Kepmík and Mezikotlí (Hrubý Jeseník Mts.). The locality Labský důl (cirque bottom, 990 m asl, 50°45'46"N, 15°33'08"E) is situated in a fossil lake of glacial origin filled with deposits (Engel et al. 2005). This profile provided the longest pollen record ever analysed in Krkonoše – from late glacial period to the present. The locality lies close to the timberline which is lowered here by avalanches. Except the upper layer of peat character the 1283 cm deep profile contained mainly inorganic matter. A part of the profile between 810 and 830 cm was contaminated by peat sediment from the upper parts (ca 500-650 cm) during the sampling. It is proved by markedly different composition of the pollen spectra (Jankovská 2004). According to pollen composition, sediment properties and radiocarbon data, the other parts of the profile were not contaminated.

The profile from the Mount Kepmík (1429 m asl, 50°10`15``N, 17°06`57``E) was taken from a pit dug in an earth hummock. The organic sediment had a peat character with sedge remains. The locality is situated on the summit plateau in the northern part of the mountain range at a distance of 200 m (60 m of altitude) above the timberline. The third pollen profile comes from Mezikotlí (1250 m asl, 50°02'46"N, 17°58'46"E), which is the bottom of a nivation hollow. A small peat bog with lagoons is situated directly at the alpine timberline lowered here due to athropogenic impacts and avalanches. The analysed 125 cm deep profile has a peaty character with frequent fine clasts (sediments of slope wash) on the base.

The cores were sampled every 5 cm (Keprník, Mezikotlí) or every 10 cm in the case of Labský důl. The samples for pollen analysis were processed following the standard acetolysis method. The pollen diagrams including stratigraphic zones were created using TILIA software (Grimm 1992). The sediment from Labský důl was analysed also in terms of proportion of the organic matter (determined by loss-on-ignition) and particle size distribution (determined by wet sieving). Based on those two indicators the segments of the profile with similar characteristics (particle size distribution, organic matter proportion, colour) – so called lithostratigraphic units – were determined. Radiocarbon dating was carried out by laboratories in Erlangen, Poznan (accelerator mass spectrometry ^{14}C) and at the Faculty of Science of the Charles University in Prague (conventional ^{14}C). All the absolute data are expressed as uncalibrated radiocarbon years BP. Chronostratigraphic zones are used according to Lang (1994).

Interpretation of the alpine timberline altitudinal shifts

When interpreting the pollen diagrams in relation to the timberline position, emphasis was placed namely on the proportion of arboreal and non-arboreal pollen (AP/NAP). This proportion enables to determine, although not precisely, whether forest or forest-free area dominated in the vicinity of the profile (Obidowicz 1993). Nevertheless, a comparison of the recent pollen record and vegetation composition had to be made to avoid misinterpretations resulting from specific local conditions. Concerning the AP/NAP rate, the critical arboreal pollen percentage fluctuates generally within the range of 70-80 % in the area of the timberline or just below (Tab. 1). In the case of the variations of AP/NAP, it was always taken into account whether the change of the value was not caused by a change of the dominant species with different (higher or lower) pollen production. Also the changes of the *Poaceae* pollen percentage were regarded as an indicator of the forest advance or retreat. Pollen percentage of *Poaceae* usually varies more notably between forest and forest-free area than AP/NAP or the *Picea* pollen percentage (Obidowicz 1993, Beug et al. 1999, Table 1).

Macroscopic remains of woody species which provide better information about the timberline position (Tinner & Theurillat 2003) were analysed in the Mezikotlí profile, stomata were counted in the Labský důl and Mezikotlí cores. In the case of the Keprník site, neither macroscopic remains of woody species nor stomata were present in the processed samples.

Table 1: Recent pollen percentages below and above the alpine timberline (ATL) in the High Sudetes, High Tatras and Harz, taken from the uppermost (0 cm) samples of pollen profiles or from the pollen analysis of surface samples.

Site name	Position	Elevation (m asl)	Arboreal pollen (%)	Picea pollen (%)	Poaceae pollen (%)	Author
Barborka (Hrubý Jeseník)	peat bog ca 50 m below ATL in a closed forest	1315	75	35	10	Rybníček & Rybníčková 2004
Velký Děd (Hrubý Jeseník)	peat bog ca 50 m below ATL in open forest stands	1395	65	12	15	Rybníček & Rybníčková 2004
Černá hora (Krkonoše)	peat bog below ATL in a closed forest	1190	70-80	35	20	Speranza et al. 2000b
Černá hora (Krkonoše)	peat bog below ATL in a closed forest	1105	90	20	5	Svobodová 2002
Labský důl (Hrubý Jeseník)	peat bog in open forest stands close to avalanche tracks, ca 50-100 m below the alpine timberline	990	85-90	25-30	5	this study
Brocken (Harz)*	closed forest 25 m below the alpine timberline	1080	65-55	30	25-30	Beug et al. 1999
High Tatra*	montane forest		79-91	37-69	2-8	Obidowicz 1993
Pančavské rašeliniště (Krkonoše)	peat bog with frequent *Pinus mugo* growths and scattered *Picea abies* idividuals (≤ 6 m), ca 50 m above ATL	1320	98-90**	10	5	Speranza et al. 2000a
Pančavské rašeliniště (Krkonoše)	peat bog with frequent *Pinus mugo* growths and scattered *Picea abies* individuals (≤ 6 m), ca 50 m above ATL	1325	60-80**	10	20-40	Jankovská 2001
Velký Máj (Hrubý Jeseník)	spring bog surrounded by *Poaceae* grasslands and *Picea abies* groups, (height ≤ 7 m), ca 50 m above ATL	1350	60	15	25	Rybníček & Rybníčková 2004
Velká Kotlina (Hrubý Jeseník)	spring bog, surrounded by *Poaceae* grasslands and *Vaccinium* sp. shrubs, scattered *Picea abies* individuals, (height ≤ 5 m), ca 100 m above ATL	1400	60	12	20-30	Rybníček & Rybníčková 2004
Úpské rašeliniště (Krkonoše)	peat bog with frequent *Pinus mugo* growths and scattered *Picea abies* individuals (≤ 5 m), ca 130 m above ATL	1430	40-50**	5-10	5-10	Svobodová 2002
Úpské rašeliniště (Krkonoše)	peat bog with frequent *Pinus mugo* growths and scattered *Picea abies* individuals (≤ 5 m), ca 130 m above ATL	1430	70**	5	10	Svobodová 2002
Úpské rašeliniště (Krkonoše)	peat bog with frequent *Pinus mugo* growths and scattered *Picea abies* individuals (≤ 5 m), ca 130 m above ATL	1430	50-60**	10	15-20	Svobodová 2004
Keprník (Hrubý Jeseník)	earth hummock covered with *Vaccinium myrtillis* and *V. vitis idaea*, surrounded by *Pinus mugo* growths and *Picea abies* idividuals (height ≤ 3 m), 50 m above ATL	1423	75**	8	10	this study
Mezikotlí (Hrubý Jeseník)	peat bog directly at the ATL lowered by human impact (height of *Picea abies* at ATL ≤ 15 m)	1250	65-75	35	10-20	this study
Brocken (Harz)*	forest-free area ca 50 m above ATL	1120	45-30	30	35-70	Beug et al. 1999
High Tatra*	subalpine belt		60-70**	8-20	10-28	Obidowicz 1993
High Tatra*	alpine belt		42-74**	7-16	15-45	Obidowicz 1993

* pollen analysis of surface samples; ** including *Pinus mugo* pollen

Results

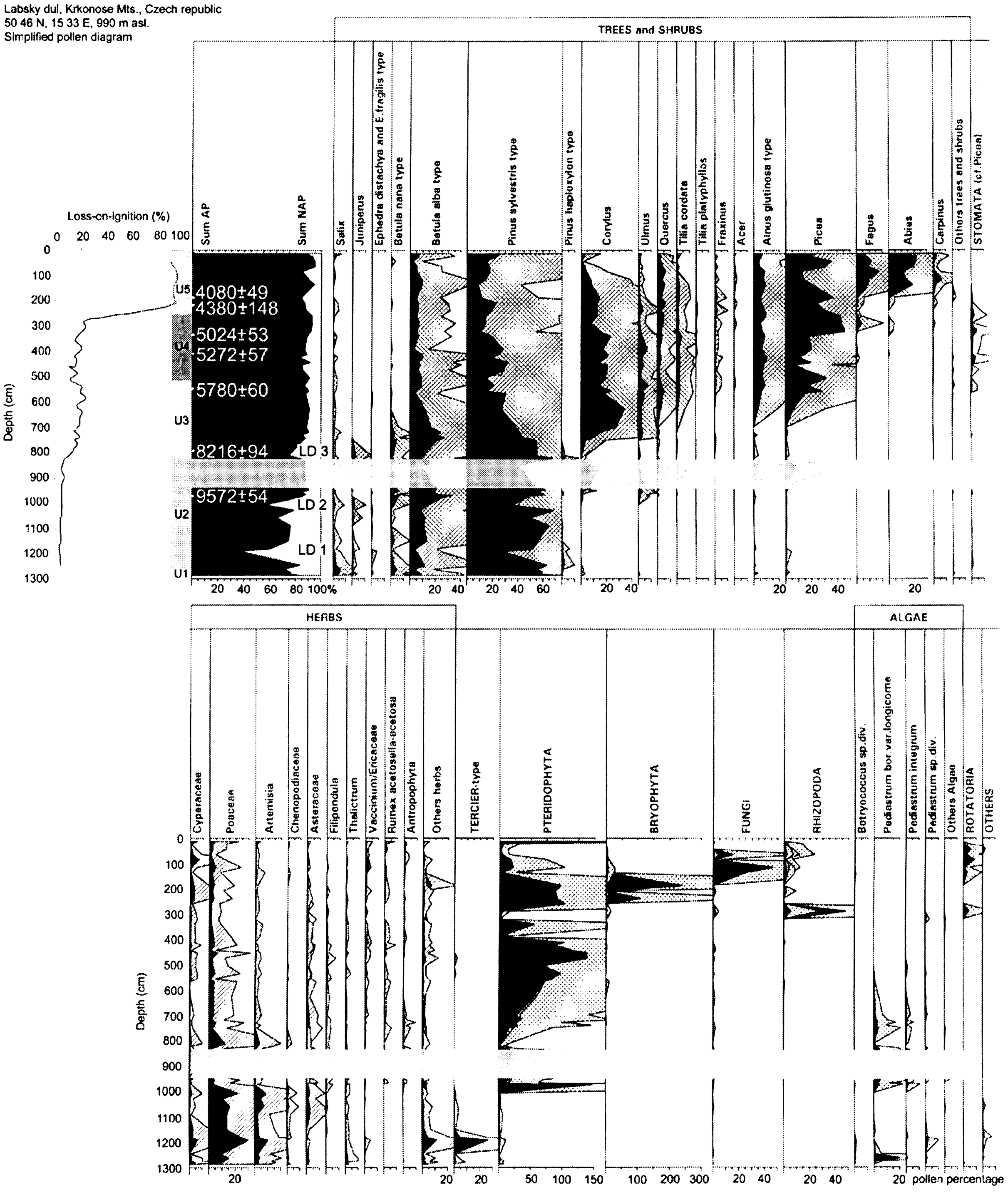
Labský důl profile

The profile that is crucial for the reconstruction of the timberline position in the Krkonoše Mts. at the beginning of Holocene comes from the locality Labský důl. The simplified pollen diagram (Fig. 2) shows data from Late Glacial period to Boreal which correspond to the profile depth 1283 cm to 790 cm. Pollen curves of *Salix* sp., *Juniperus* sp., *Betula nana* type, *Ephedra distachya* and *E. fragilis* type and also the presence of the pollen of *Pinus haploxylon* type (i.e. *Pinus cembra*) delimit clearly the forest-free stage in the profile. The higher pollen curve of *Pinus sylvestris* type is produced by pollen from the local *Pinus mugo* stands or by influx of *P. sylvestris* from lower altitudes. Combination of both factors is probable. The organic matter content is very low (8 % on average). Together with the particle size distribution (silty sand) and the presence of algae (*Pediastrum boryanum* var. *longicorne* and *Pediastrum integrum*), it shows the lake phase of the profile. At the base of the U2 lithostratigraphic unit (LD1) and around 9500 BP (LD2) a markedly lower AP percentage was recorded. Both above mentioned AP curve depressions are combined with the increase of the *Poaceae* pollen. In this period the alpine timberline was still situated below the Labský důl site, hence both recorded pollen composition changes (LD1, LD2) should probably be interpreted rather as a general forest retreat than as a local disturbance of forest.

In early Boreal the AP curve approaches and then passes constantly 80 %. After ca 8200 BP the proportion of organic matter in the lake sediment rises (from 7-9 % to 20-25 %). Thus the timberline passed the level of Labský důl profile as late as at the beginning of Boreal. At that time it was composed of pioneer woody species (*Pinus* sp., *Betula* sp.). It follows that the timberline reached the upper locations with a certain time lag which corresponds to relatively late deglaciation (Engel et al. 2005). A notable decrease of the arboreal pollen rate could be detected in the Labský důl profile around 8200 BP (LD3). It is set off by contamination of the matter below this part of the profile. Even other parameters (an increase of the pollen of *Juniperus* and *Betula nana* type, a lower proportion of organic matter in the sediment) probably indicate that forest-free area had expanded in the Labský důl. Nevertheless, it is not clear, whether this expansion was caused by large-scale disturbance or by climatic oscillation.

After this event, the AP percentage has oscillated only weakly in the range of 80-90 %. It is suggested that a similar state of forested and unforested areas as today was established and it has been preserved due to frequent disturbances (avalanches, debris flows). The Norway spruce as a recent timberline forming species has occurred at the locality since at least 7000 BP according to the stomata record.

Fig. 2: Simplified pollen diagram, radiocarbon data, loss-on-ignition and litostratigraphic units (U1-U5) in the "Labský důl" core. Light rectangle across pollen diagram indicates the contaminated part of the profile (810 – 830 cm depth).



Kepmík profile

At the summit of the Mount Kepmík the AP proportion in Subatlanticum zone was held between 70 and 80 % (zone K1, K2, Fig. 3). At the same time no woody species stomata were found in the investigated profile. The profile shows the regression of woody species typical for mixed oak forests and the progression of beech and fir in the K2 zone. Direct indicators of human activities are present in the uppermost layers (K3). The time scope of the profile is Subboreal and Subatlanticum. With respect to the absence of spruce stomata remnants and the AP percentage lower than 80 %, very low *Picea* pollen sum (in exposed windy position with high pollen influx from lower areas), it could be concluded that the alpine timberline has not reached the summit area of Keprník Mt. since Subboreal/Atlanticum turn. It is proved also by occurrence of the earth hummocks since at least ca 2090 BP. Those landforms are usually quickly destroyed as they are colonised by trees (Treml & Křížek 2006).

Mezikotlí profile

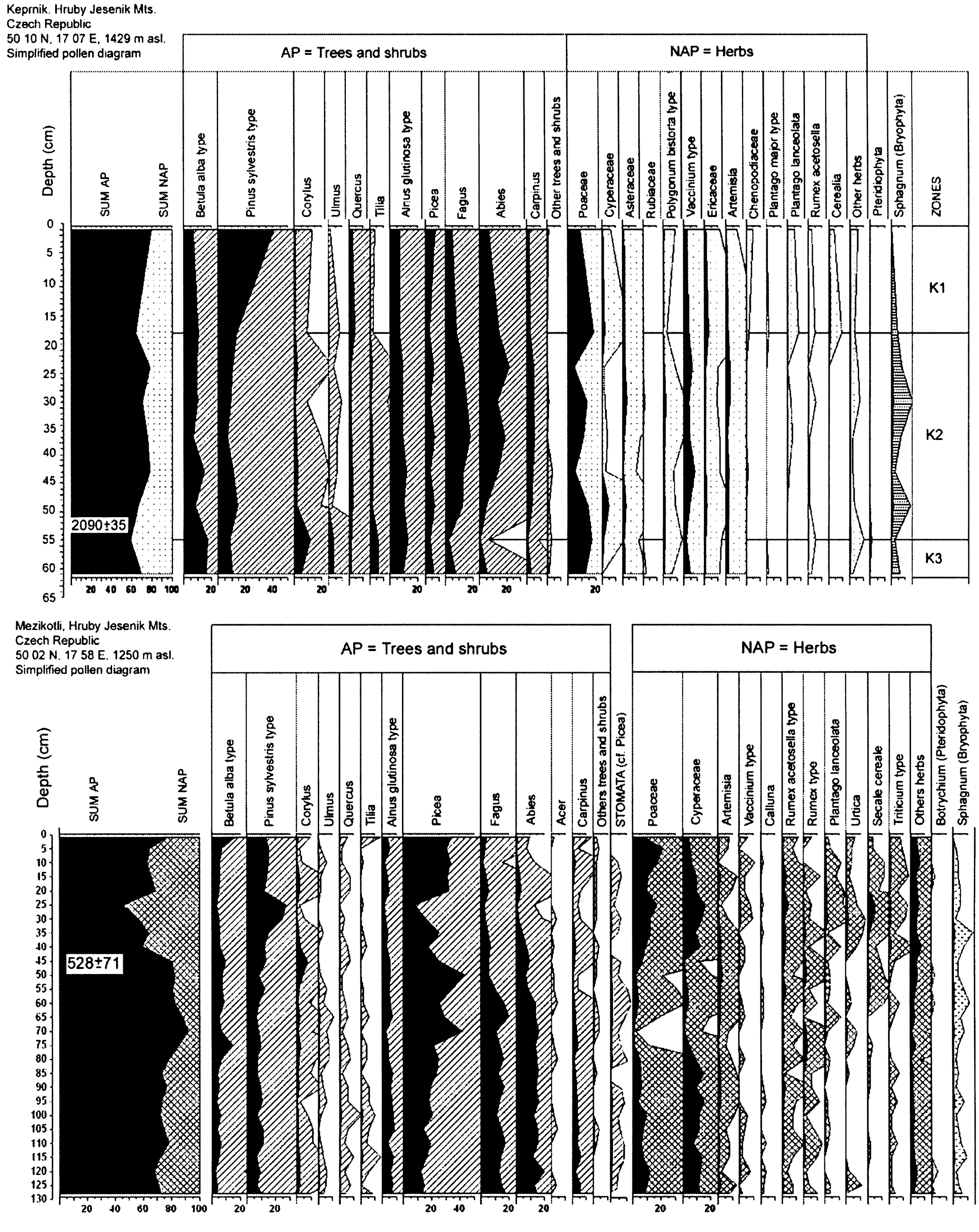
According to pollen composition the pollen profile from the Mezikotlí site spans the period from Late Subatlanticum till present (Fig. 3). The Pollen composition between base and the depth of 85 cm probably reflects fir-beech forests which extended to higher elevations than today (the nearest specimens of *Fagus sylvatica* recently occur 100 m below the analysed site). Stomata of *Picea* were abundant in all samples of this part of the profile and therefore the occurrence of the Norway spruce directly at or above the site is evident.

During the following period (profile depth 75-50 cm – till ca 530 BP) dynamic changes of vegetation composition are recorded. Fir, beech and hornbeam gradually declined, while the proportion of *Picea* and *Pinus* pollen increased. *Picea* pollen reached as much as 45 % of pollen spectra, at the same time the amount of the arboreal pollen oscillated between 80-90 %. In this period the upper limit of closed forest was certainly situated above the level of the Mezikotlí site.

Pinus pollen rate significantly increased after 530 BP (profile depth 40-20 cm), which could be a consequence of the decrease of local woody species pollen numbers. During this period *Pinus sylvestris* could constitute early succession stages of forest on forest clearances in lower elevations. At the same time the *Picea* pollen curve sharply decreased and also stomata of *Picea* were not detected in the 40-35 cm part of the profile. The AP/NAP rate decreased even below 50 % and the pollen curve of *Poaceae* increased up to 15-20 %. A distinct decline of the alpine timberline due to anthropogenic impacts is suggested to be the reason of the recorded changes in the pollen composition. From 50-40 cm depth of the profile the pollen curve of direct human indicators (Cerealia, weeds) as well as indirect human indicators (*Chenopodiaceae*, *Artemisia* sp., *Rumex acetosella* and *Plantago lanceolata*-type

/which is undistinguishable from *Plantago alpinum* naturally occurring in the Hrubý Jeseník Mts./) started to increase.

Fig.3: Simplified pollen diagrams and radiocarbon data (marked with the white rectangles within the AP curve), summit of the Mt. Kepmík (1429 m asl) and the Mezikotlí site (1250 m asl).



Discussion

Timberline fluctuations in the Krkonoše Mts.

In the Labský důl profile, three distinct oscillations of arboreal pollen curve were detected (LD1, LD2, LD3). While LD1 and LD2 were most probably caused by a general downward shift of the alpine timberline, the third oscillation (LD3) could be induced by a large-scale disturbance as well. The alpine timberline was situated at or above the Labský důl site before this oscillation, hence the disturbance event could be displayed in pollen spectra in similar way as a general forest retreat.

After the mentioned oscillations, the timberline definitively passed the Labský důl site. A cold oscillation (7600±130 BP), which was probably expressed in the timberline dynamic, is documented by Huettemann & Bortenschlager (1987) from neighbouring Pančava peat bog (cca 900 m W from Labský důl site, 1320 m asl), based on high proportion of pollen belonging to herbs or dwarf shrubs species (25-30 % - *Poaceae*, 10 % - *Calluna* sp.). This means that at given time (~ 7600 BP) either the timberline had not yet reached the Pančava peat bog or it had been already lowered below its level. In the following period during the Atlanticum and Subboreal the alpine timberline reached at least the level of Pančava peat bog and apparently it varied only a little – the percentage of AP at Pančava peat bog fluctuates around 90 % (Huettemann & Bortenschlager 1987, Speranza et al. 2000a, Jankovská 2001). Nevertheless according to Speranza et al.(2000a) there was another colder period between 2640±60 and 2480±35 BP. However, there is no evidence which would substantiate the decrease of the ATL position due to this cold oscillation.

Also in the period of Older Subatlanticum no marked trend in forestation or deforestation of the region was detected in the highest parts of the Krkonoše Mts. At less elevated Pančava peat bog the woody species percentage reaches 90 % of the pollen spectrum (Jankovská 2001), at Úpa peat bog (1430 m asl, east Krkonoše Mts.) it reaches approximately 80 % (Svobodová 2004). A considerable proportion (20-30 %) of the pollen spectrum belongs to pine pollen which comes mainly from local *Pinus mugo* stands.

Based on existing data it is not possible to determine the exact level that the closed forest reached in the climatic optimum. Most likely a closed tall-trunk stand cannot be expected in locations with occurrence of well developed sorted patterned ground with distinctly raised centres (approximately above the level of 1430-1450 m asl, Křížek 2007). Those landforms usually change their morphology into the flat-topped patterned ground after the colonisation of trees or shrubs (Sekyra et al. 2002). The highest current positions of the timberline are situated at altitudes 1350-1390 m asl (Treml & Banaš 2000). The maximum difference in the timberline position compared to the present was therefore less than 100 m. The above mentioned lower rate of the timberline oscillation corresponds to the temperature reconstructions (Hieri et al. 2003) that estimate the extent of long-term summer temperature oscillations in the Middle and Upper Holocene to 1 °C.

Development of the alpine timberline in the Hrubý Jeseník Mts. during the Upper Holocene

The profiles from the Hrubý Jeseník Mts., that have ever been analysed in terms of pollen composition contain the record of the period between the Atlanticum/Subboreal turn and the present. High representation of *Corylus avellana* pollen (Rybníček & Rybníčková 2004) indicates the hazel stands in the summit locations (about 1300 m asl) at the beginning of Subboreal, nevertheless there is no direct evidence in form of macroscopic remains to support this hypothesis.

At localities that are forest-free at present, relatively low proportions of arboreal pollen (approximately 60 %) and high percentage of *Poaceae* (10-15 %) were recorded in the Older Subatlanticum, notably at Velký Máj (Rybníček & Rybníčková 2004, summit plateau, 1350 m asl) and also at Velká kotlina (cirque headwall, 1400 m asl), where the oscillations were more pronounced (10 – 30 % of the *Poaceae* pollen). That indicates the permanent forest-free area at given localities in this period, although it could oscillate at avalanche tracks in the area of the Velká kotlina cirque. A slightly higher AP proportion in the Older Subatlanticum zone was recorded at the summit of the Keprník Mt. (70-80 %), however a forest-free area is documented here by occurrence of earth hummocks in this period (Treml et al. 2006). According to Mezikotlí profile, the alpine timberline was situated above 1250 m asl during this period.

At localities that are currently forested (Barborka, Velký Děd - Rybníček & Rybníčková 2004), the AP proportion came up to 90 % since the Atlanticum/Subboreal turn and the pollen percentage of *Poaceae* fluctuated around 5-8 %. A noticeable decrease of representation of arboreal pollen, mainly beech and fir, was recorded in most profiles at around 500 BP (zone K3 in the case of Keprník, before 528 BP in the case of Mezikotlí profile). This can be ascribed above all to the influence of human activities (Jeník & Hampel 1991).

Thus, it is suggested that a very limited treeless space occurred at the Atlanticum/Subboreal turn in the Hrubý Jeseník Mts. However, this area must have been consecutively extended during Subboreal because there is evidence of treeless area from Kepník, Velký Máj and Velká kotlina sites during the Older Subatlanticum.

With respect to the present vertical extent of the alpine belt in the High Sudetes it can be assumed that in the Hrubý Jeseník Mts. the alpine forest-free area was more "endangered" during the Holocene than in the Krkonoše Mts. As far as positive long-term temperature oscillations 0,5-1°C for Central Europe are considered (Haas et al. 1998, Hieri et al. 2003), the temperature dependent forest-free areas had to disappear almost entirely in the Hrubý Jeseník Mts. By contrast, in the Krkonoše Mts. large forest-free areas were present throughout the Holocene. Nevertheless, the occurrence of many plant species and diversified communities dependent strictly on forest-free areas (Jeník 1961) indicates that the forest-free enclaves in the High Sudetes had to exist in the long term. However the presence of forest-free patches in the Hrubý Jeseník Mts. depended rather on soil conditions, water regime or slope inclination than on temperature.

Acknowledgments

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Recent tendencies of alpine timberline shifts in the Krkonoše (Giant) Mts., High Sudetes

VÁCLAV TREML

Abstract

Field observations and comparison of three generations of aerial photographs (1936, 1964, 2000) revealed an ascending trend in 16 sections of the alpine timberline (merely 5% of its total length) dominated by *Picea abies*. Dendrological measurements conducted downhill across the timberline (transects of 15 x 15 m sample plots in five selected areas) disclosed either facilitation or competitive factors responsible for the upward shift or stabilised position of the timberline. However, objective correlation of the timberline dynamics to the centennial 0.6 °C rise of air temperature could not be detected.

Introduction

The alpine timberline (ATL) is one of the basic biogeographic boundaries. The positions of alpine tree, forest and/or timberlines (for discussion see Körner 1999) are generally correlated to average temperature of the growing season. The generally accepted relation of the alpine timberline to the air temperature (Tranquillini 1979, Körner 1999) implies that the forest limit ecotone could change in response to the current increase in temperatures. The ATL ecotone must be considered a conservative system, which responds to climatic changes with a certain delay (Armand 1992). The response in the alpine timberline can manifest in two basic manners. First, by increased radial increment and increased length of internodes on the current alpine timberline, second, by establishing of new growth above the current timberline, resulting in its ascent. The latter form of manifestation can be observed in the age composition of stands, showing presence of young trees and seedlings. In investigation of the response of alpine timberline ecotone to the recent increase in temperatures and lengthening of the growing season, the conditions of the alpine timberline in the studied area must be taken into account, i.e. species composition of the alpine timberline, position of the timberline in relation to summit areas, human influence, plant competition and geomorphological conditions.

In Central Europe, there is a marked gradient of descending alpine timber/tree/line in the direction southeast – northwest, due to increasing oceanity. The Giant Mountains mountain

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range (Krkonoše Mts., highest summit Sněžka, 1602 m a.s.l.) is the culminating and the westernmost point of the mountain system of the High Sudetes. It is the highest Hercynian mountain range in Central Europe with the best developed alpine belt (for details see Jenik 1961, 1998). The extent of alpine area is 5465 ha, the average elevation of the alpine timberline in the Giant Mountains is 1230 m a.s.l., the maximum elevation then 1340 m a.s.l. (Treml et Banaš 2000). Average temperatures on the uppermost summits range from 1°C (Sněžka, 1602 m a.s.l., eastern Giant Mts., Glowicki 1997) to 2°C (Szrenicza 1362 m a.s.l., western Giant Mts., Migala et al. 2002). The last 100 years has seen prolongation of the growing season in the Giant Mountains (increased number of days with average temperatures above +5°C), by approximately 9 days, compared to the period at the beginning of the last century, as well as an increase in sum of temperatures above +5°C during the growing season by 86°C (the average sum of temperatures exceeding +5°C during the growing season between years 1991-1999 was 726, Dubicka et Glowicki 2000).

Position and synmorphology of the alpine timberline in the Giant Mountains is fundamentally affected by the following factors: 1) Alpine timberline is formed by Norway spruce *Picea abies*; 2) There are extensive summit etchplain plateaus, the alpine timberline is usually directly beneath; 3) The alpine timberline is topped by stands of *Pinus mugo* ssp. *pumilio* and grasslands dominated by *Nardus stricta* and *Calamagrostis villosa*. Regeneration of the spruce is quite slow in such communities; 4) the Giant Mts. have been under human influence since the 12th century. The average human-induced lowering of the timberline is estimated at 20 m on the Czech side of the Krkonoše Mts. (Jeník et Lokvenc 1962). In the 70s and 80s, the spruce stands below the timberline thinned due to air pollution. The pollution has had no apparent effects on the alpine timberline on the Czech side of the mountain range, however, the radial increments diminished (Brázdil et al. 1997) and the upper tree boundary lowered locally (Treml 2000); 5) The course of the alpine timberline is affected by the presence of frequent avalanche tracks (22 % of the ATL length on the Czech side of the Giant Mts.) and block fields (5.4 % of the ATL length on the Czech side of the Giant Mts.) (Treml et Banaš 2001).

Currently, the available amount of information on the dynamics of the alpine timberline in the Giant Mountains is rather limited. The fluctuation of the position of the alpine timberline within the avalanche tracks is particularly cited (Kociánová et Spusta 2000), as is the raising of the ATL in thinned spruce stands around former mountain cottages (Treml 2000). In the 70s and 80s an air pollution crisis on the Polish side caused elongating and lowering of the alpine timberline (Zientarski 1995). All data on changing radial increments of spruces for the last half century are strongly influenced by the effects of air pollution (Brázdil et al. 1997).

Data documenting the recent dynamics of the ATL in the Giant Mountains are significant with respect to understanding of the overall nature of biogeographic changes in European mountain ranges. While the current shift of the treeline upwards in Scandinavia follows the continuous decrease of treeline since the beginning of the Holocene (Kullmann et Kjällgren 2000, Kullmann 2002), in the Alps the current tendency of the ATL is indistinct and its position has fluctuated during the Holocene (Wick et Tinner 1997).

Methodology

Recent dynamics of the ATL has been assessed particularly in terms of changing position of the ATL during the last seventy years, and by the analysis of tree age structure at the timberline.

The ATL is a line connecting all uppermost altitudinal extremities of trees reaching the minimum height of 5 metres and minimum canopy of 0.5 (as defined by Jeník et Lokvenc 1962); small stands are included in ATL upon meeting the criterion of a minimum area of 1 ar (determined by comparison to a square of area of 1a in perpendicular coordinates). The cover degree of trees was determined either by projection of an aerial photographs onto a grid and identification of individual tree areas in software ArcView Spatial Analyst, or visually, in case of poor quality images.

Changes in the position of the alpine timberline were assessed using a series of aerial photographs made in 1936, 1964 and 2000. Images from years 1936 and 1964 were geo-referenced and orthorectified, ortophotos were used for the year 2000.

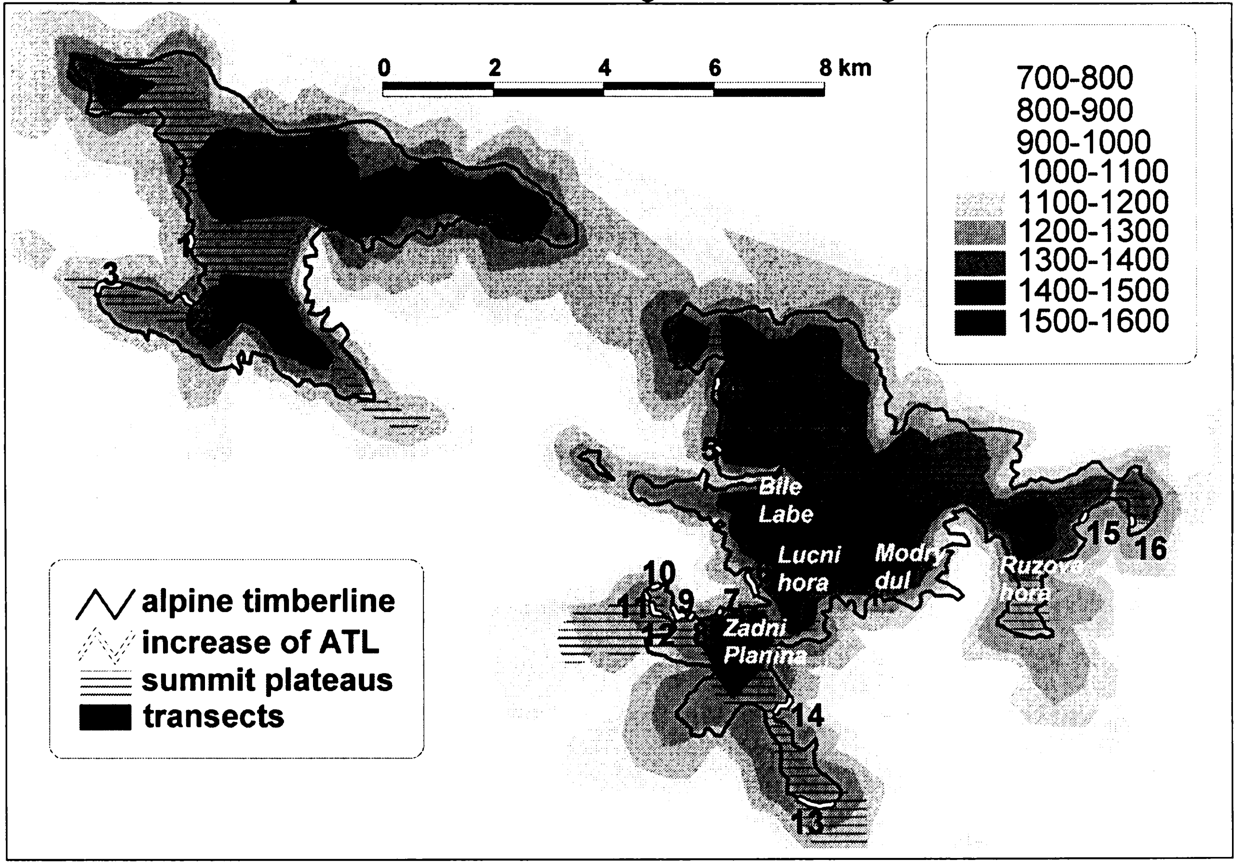
The selection of localities for detailed assessment of ATL shifts was made according their demonstrative value for various synmorphologic timberline types in the Giant Mts. The following limitations affected our selection:

- Some of the aerial photos from 1936 and 1964 were unavailable for the whole selected area or were of unsatisfactory quality.
- Referencing of aerial images was possible only in places with enough rectification points.

For the selected locations, dendrometric investigation was conducted in 15 × 15 metre sample plots arranged in three rows, intersecting the ATL ecotone gradient. The following parameters were identified for each square: coordinates and elevation above sea level of the square centre, concavity and convexity (using digital elevation model and checked against actual measurement of the terrain slope), surface heterogenity (3 grades), maximum tree height, average length of the apical shoots of five tallest trees, diameter of trunk of the tallest tree at 50 cm above ground, health condition of trees (3 grades), presence of tree groups originated from vegetative rejuvenation (yes, no), dominant species of the herb layer. Correlations of the elevation with tree height, diameter, terminal increment and other factors were evaluated in each transect. The following locations had been selected for assessment of the above factors: Zadní Planina, Luční hora, Důl Bílého Labe, Modrý důl, and Růžová hora (Fig. 1).

The upper tree species limit (maximum elevation of 5m height trees) was identified as well. Tree height was determined either by the Suunto tree-height meter or by a measuring rod. Tree age was determined by growth rings on bores acquired by the Suunto Pressler drill.

Fig. 1: The alpine timberline in the Krkonoše Mts., the numbers mark sites with detected increase of ATL, comp. also Tab. 1, white writing describes investigated transects.



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Results

Specification of locations with current ascending tendency of alpine timberline

Such places were identified based on presence of groups of young trees (up to 30 years of age) and seedlings above the current timberline. These spruce stands are charcterized by gradual closing of canopy. In the Giant Mountains, 16 such locations were specified with total ATL length of 3 717 metres (5 % of the total ATL length within the Czech territory). Length of timberline without significant human impacts and stress factors (avalanches, block fields) is 55 km; current raising tendency is therefore found on 7 per cent.

Table 1: Sites with detected increase of ATL.

Site Nr.	Elevation of ATL (m a.s.l.)	Tree height at ATL (m)	Length of ATL section (m)
1	1250 - 1270	6	207
2*	1225 - 1300	7-10	211
3	1250	7 - 13	492
4	1325	5 - 8	177
5	1300 - 1310	6	72
6	1220 - 1325	6 - 11	368
7*	1250	9	46
8	1280 - 1300	7 - 9	71
9	1260	11	336
10	1250	9	101
11	1300	8	85
12	1275 - 1300	8 - 14	270
13	1260 - 1275	8	622
14	1175 - 1270	11 - 13	407
15	1320	11 - 12	132
16	1275 - 1300	8	120

Note: Locations in bold letters have been strongly influenced by human activities before the year 1945 (pastures, haymaking; Lokvenc 1978). The locations marked by asterisk are found on former avalanche track (location 2) or on the margin of a current track (location 7).

In the cases of most locations, young tree stands of high density were adjacent to current timberline. In locations 8 and 9, these tree stands were found high above the current timberline, and there was a zone of sporadic tree occurence between the ATL and the determined tree stand.

The delimited locations with an ascending tendency of ATL can be divided by the age composition at the timberline itself into three groups. The first group includes trees up to 6 metres in height (locations 1 and 5). These timberline sections are composed of younger spruce trees (up to 40 years of age). The ascent progresses on, since younger stands above the timberline gradually are incorporating.

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The next group is represented by timberline segments with a relatively wide range of height and age of trees (locations 2, 3, 4, 6, and 12). Younger trees progress among solitary older treess or smaller groups of the latter. The timberline is thus formed both by younger and older trees.

The last group of locations is composed of ATL of old spruce stands (locations 7, 8, 9, 10, 11, 13, 14, 15, and 16), with new younger growths above them. These could not be determined as proper timberline stand due to low height and/or canopy lower than 0.5 cover degree.

Dynamics of alpine timberline

Zadní Planina location

It is a slope exposed to the north, with the alpine timberline running at elevations between 1260 and 1290 m a.s.l. The ATL is covered with trees of heights from 7 to 9 metres. The timberline grades into old dwarf pine stands. The upper tree limit runs at elevation of 1,405 m a. s. l. Available aerial photographs were made in 1964 and 2001.

Comparison between the two aerial photos yielded minor shifts in both directions (Fig. 4). The ascertained weak shifts may not exceed the possible errors in image rectification and determination of the timberline. Alpine timberline can therefore be declared stable in this location, influenced by partial disturbances only.

The transect is found in the western part of the location, at elevation from 1,240 to 1,410 a.s.l. The tree height within the transect does not correlate with the elevation (-0.11), the length of apical shoots correlates well with increasing elevation (-0.87), there is certain correlation even between elevation and the tree trunk diameter (-0.65). Remarkable decrease of tree numbers, tree height, length of the apical shoots and deterioration of health condition is found in the pronounced convex shape of the relief – boundary of the summit etchplain. It is most likely caused by the stress factor of wind (with resulting effects of greater snow accumulation, sliding of snow and grinding by snow and ice crystals).

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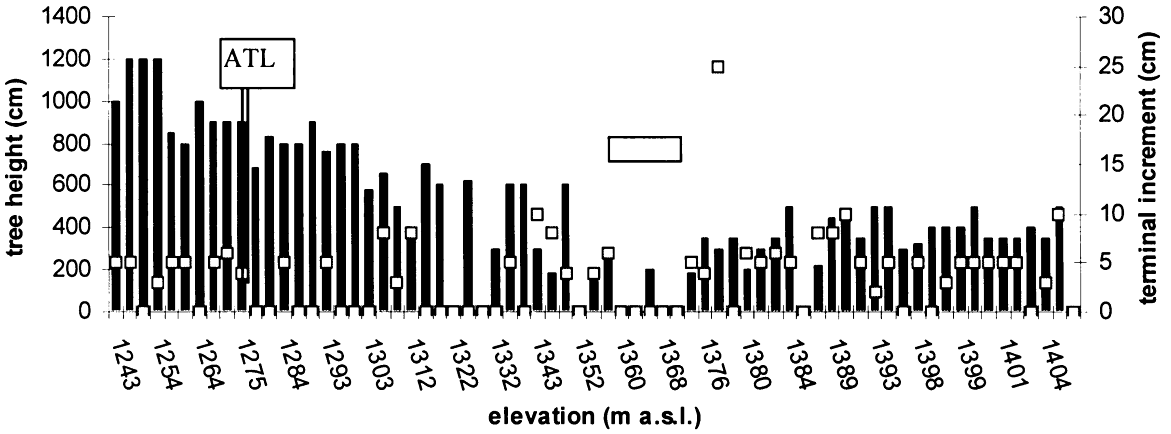
Fig. 2: Tree height (column) and terminal increment (point) in relation to elevation. The empty rectangle highlights the most convex part of slope.



Luční hora Mt.

It is a slope exposed to the south, with alpine timberline running at elevations of 1220 to 1325 m a.s.l. The ATL is covered with trees of heights from 11 metres in the lowest places to 6 metres in highest elevations. The timberline grades into thin dwarf pine stands and meadows with dominant *Nardus stricta, Deschampsia caespitosa* and *Calamagrostis villosa.* The upper tree species limit runs at elevations from 1390 to 1 400 m a.s.l. The slope incorporates an avalanche track and numerous debris flows released at the end of 19th century (Pilous 1975).

Available aerial photographs were dated 1964 and 2001. During this period, the location witnessed pronounced raise of the timberline (by approximately 50 to 100 metres). The age composition of the newly established stands (up to 50 years) demonstrates the shift having taken place during the last 40 years. The timberline is succeeded in the upwards direction by further gradually incorporating young growths of heights between 4 and 5 metres.

The transect is found within the elevation interval of 1,175 to 1,515 m a.s.l. The transect is marked with first steep, then gradual decrease in tree height (correlation coefficient for the tree height and elevation is -0.53). The boundary between the steep and gradual decrease of tree height is situated at the places, where the ATL was recorded in 1964. Those old trees (timber upwards of 100 years of age) pass into young spruce stands at the debris flow tracks (age interval up to 50 years). The length of the apical shoots correlates well with the elevation above sea level (-0.89).

Fig. 3: Tree height and terminal increment in relation to elevation. The empty rectangle highlights the most convex part of slope.

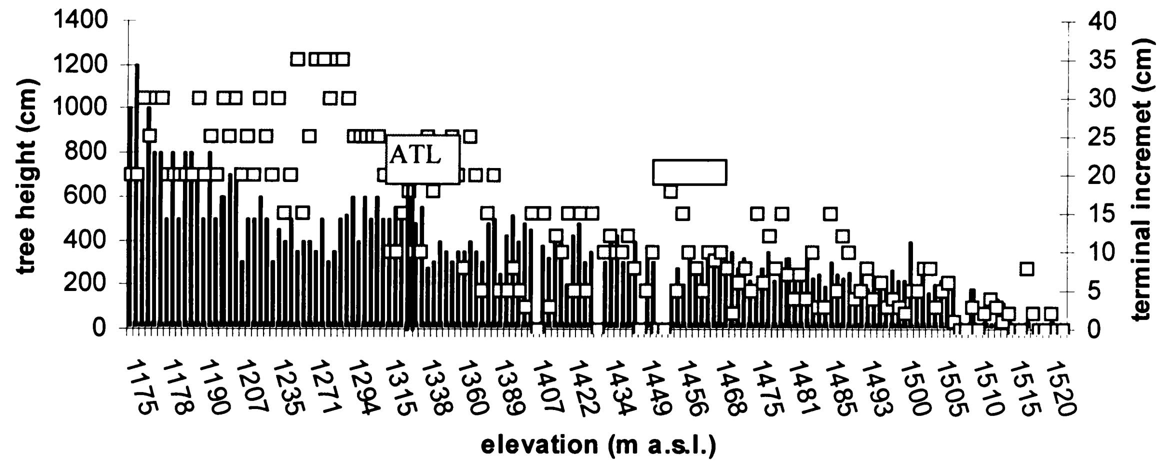
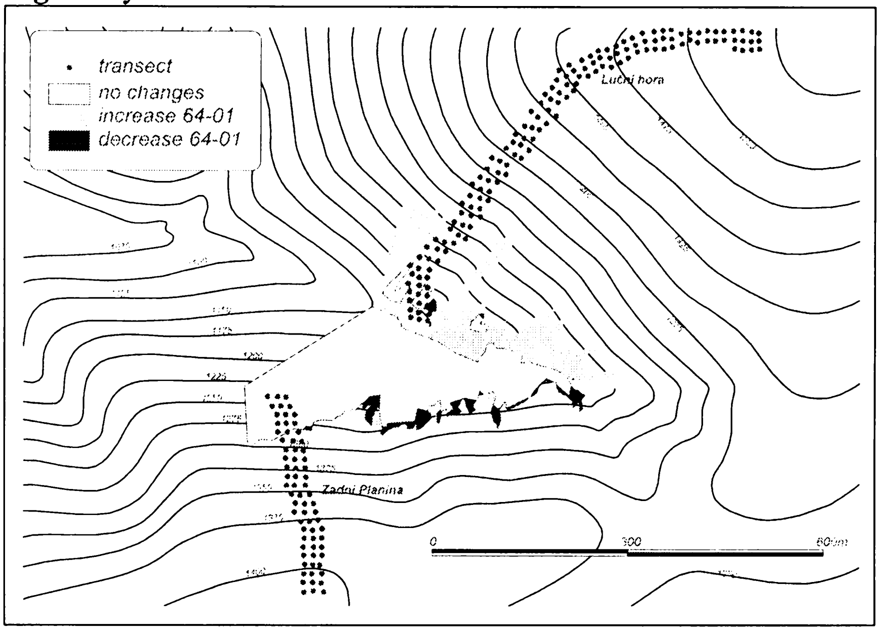


Fig. 4: Dynamics of ATL in the Zadní Planina and Luční hora sites.



Důl Bílého Labe location

The slope is exposed to the north, with alpine timberline running at elevations of 1,225 to 1,235 m a.s.l. The ATL is formed by trees from 10 to 12 m in height. The timberline grades into dwarf pine stands with deciduous component – *Sorbus aucuparia* and *Acer pseudoplatanus*. The upper tree species limit is found at 1380 m a.s.l. The slope in the lower portion is covered with polygenetic accumulations and frequent boulders. There are both avalanche tracks and debris flows from the end of the 19th century (Pilous 1975).

Available aerial photographs were dated 1964 and 2001. In the period specified, the ATL shifted upwards overall, yet without increasing its maximum elevation. The ascent resulted from connection of spruce stands in the avalanche tracks and gaps created by the debris flows.

The transect runs between elevations 1222 and 1449 m a.s.l. Within the transect, tree height does not correlates to the elevation (-0.25), since gradual decrease of tree height can be found from the middle of the transect upwards. Correlation of the length of apical shoots and the trunk diameter to elevation, on the other hand, is rather significant (-0.69 and -0.65 respectively). Sharp decrease of tree height was found above the ATL. Relative increase in tree numbers, height as well as terminal increments was recorded in distinctly convex relief (etchplain boundary). On the other hand, sharp decrease of both the tree height and length of apical shoots, and decrease of health condition of the trees, was recorded in the upper parts of the transect in distinctly convex edges of cryoplanation terraces.

The above features of the transect in Důl Bílého Labe location can be explained mainly by the presence of avalanche tracks and activities of sliding snow (in elevations of 1250 - 1340m a.s.l.). The avalanche break-off zones and areas of most intensive activity of sliding snow are found in the steepest part of transect (i.e. place of transition from convex to concave shape of relief). This worsens conditions for tree growth. A portion of the transect between 1,370 and 1,430 a.s.l. was strongly influenced by grazing in the past. This is reflected in dominance of *Nardus stricta,* which proves to be the significant obstacle of tree growth.

Fig. 5: Tree height and terminal increment in relation to elevation. The empty rectangle highlights the most convex part of slope, the dark one indicates the most concave part of slope.

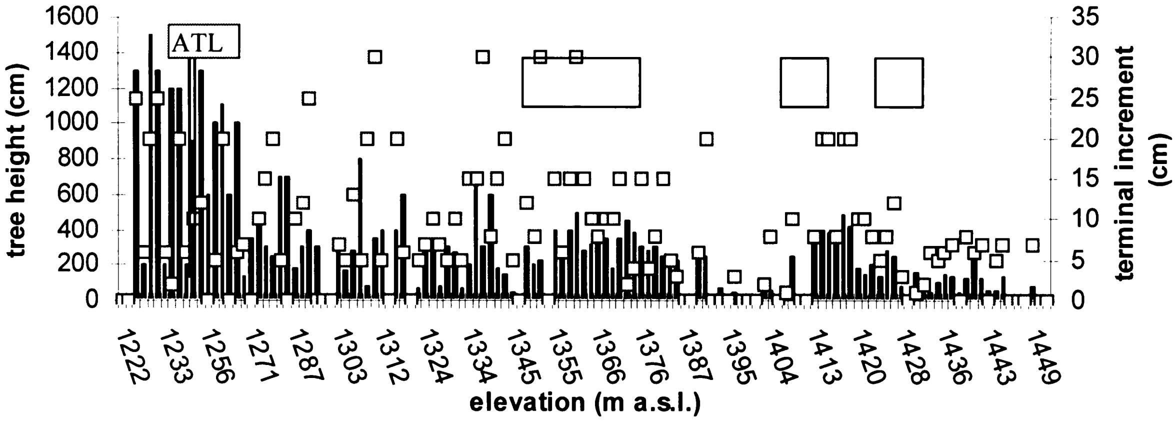


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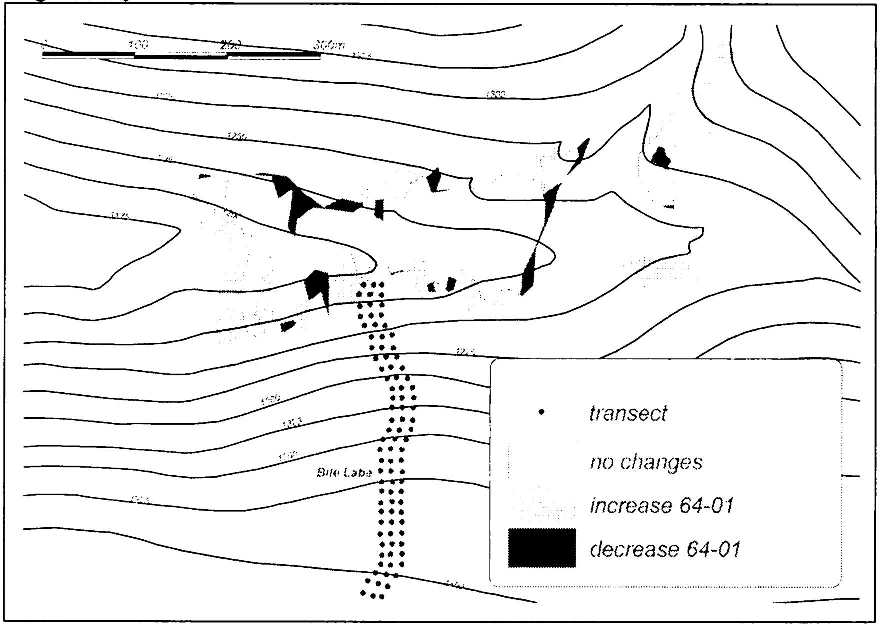
Fig. 6: Dynamics of ATL in the Důl Bílého Labe site.



Modrý důl locality

The slope is exposed to the south, with the alpine timberline running at elevations of 1,300 to 1,325 m a.s.l. At its maximum elevation the ATL is covered with trees about 7 metres in height and 12 metres in the lowest position. The timberline grades into loose dwarf pine stands on the western side and into block fields with dwarf pine on the eastern side. The upper tree limit runs at 1,380 – 1,320 a.s.l. The western side of the location is delimited by an extensive avalanche track. The ATL of this location is affected by smaller avalanches across the whole area.

Aerial photos were available from 1936, 1964 and 2001. The ATL of the location shows a generally raising trend, both in the period from 1936 to 1964, and in the period 1964 – 2001 (Fig. 8). The maximum elevation of the ATL, however, has not changed. Many places within the location show oscillations or even slight descend of the ATL. The timberline within the Modrý důl locality is dynamic, indicating rather strong effects of disturbances.

The transect runs between elevations of 1,255 and 1536 m a.s.l. It is marked gradual decrease of the tree height and trunk diameter, well correlated to the elevation (- 0.83 and - 0.85 respectively). More pronounced decrease in tree height can be found on the part of slope, where the ATL was determined in 1964. Length of the apical shoots does not correlates with the elevation so well (-0.58) – being constant on the transect up to elevations of 1,360 - 1,380 a.s.l., and steeply decreasing in places of convex relief (elevations 1405 – 1420 m a.s.l.).

Fig. 7: Tree height and terminal increment in relation to elevation. The empty rectangle highlights the most convex part of slope.

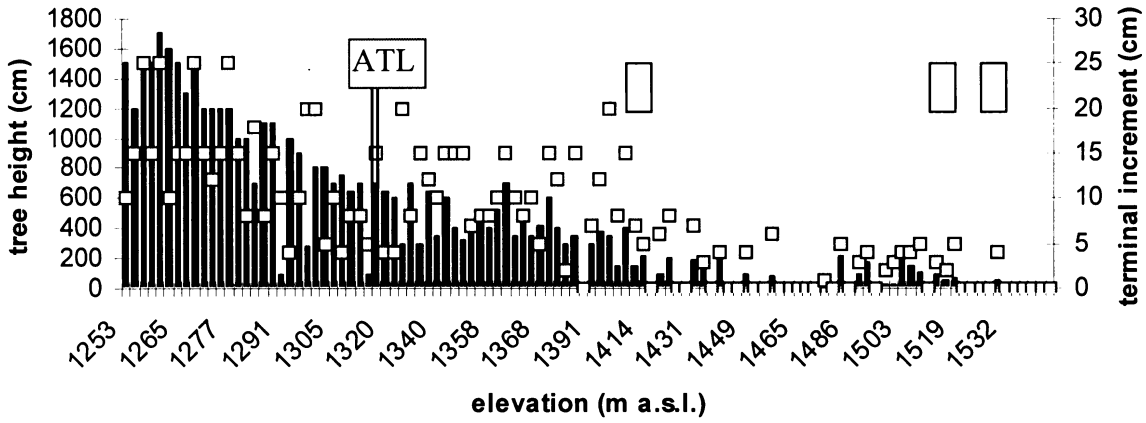
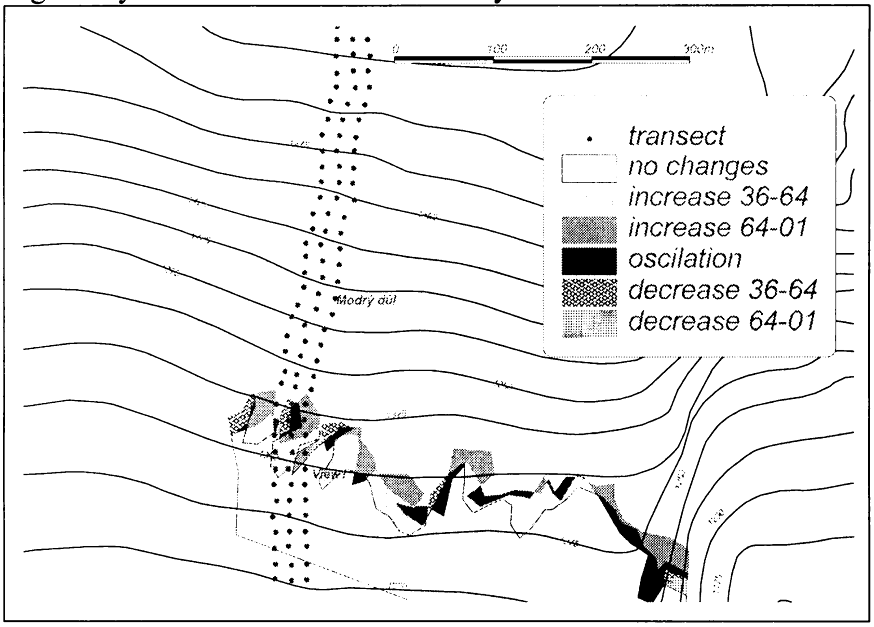


Fig. 8: Dynamics of ATL in the Modrý důl site.



Růžová hora locality

The slope faces westward, with alpine timberline running at elevations of 1 350 – 1 360 m a.s.l. Tree height at the ATL is up to 6 metres. The spruce stands pass into closed dwarf pine growths. Some trees below the ATL were planted at the beginning of the 20th century. The ATL is located just below the summit etchplain of the Ruzova hora mountain (1 370 – 1 390 m a.s.l.). Aerial photograps dated 1936, 1964 and 2001 were available for our study.

ATL of the locality shows no dynamics in the whole period of observation (Fig. 10). Slight shifts discovered do not exceed the possible errors of rectification and referencing of the aerial photos.

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The transect runs between elevations of 1,332 and 1,375 m a.s.l. None of the tree heights, nor terminal increments and trunk diameters correlate to the elevation (0.08, -0.12, -0.12 respectively). A gradual decrease of the measured dendrometric parameters along increasing elevation is strongly affected by the convex landform, where the influence of stress factors is intensified. The convex part of the transect (1,360-1,370 m a.s.l.) shows a strong decrease in the tree height, the terminal increments length and deterioration of health condition of trees. The vitality of trees above this part of transect increases again (increase of the tree height, lengthening of the apical shoots and improove of health conditions).

Fig. 9: Tree height and terminal increment in relation to elevation. The empty rectangle highlights the most convex part of slope.

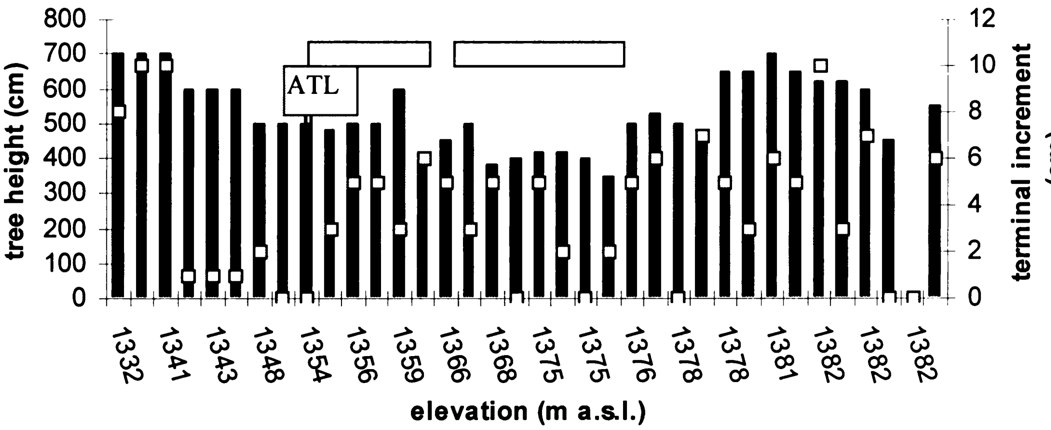
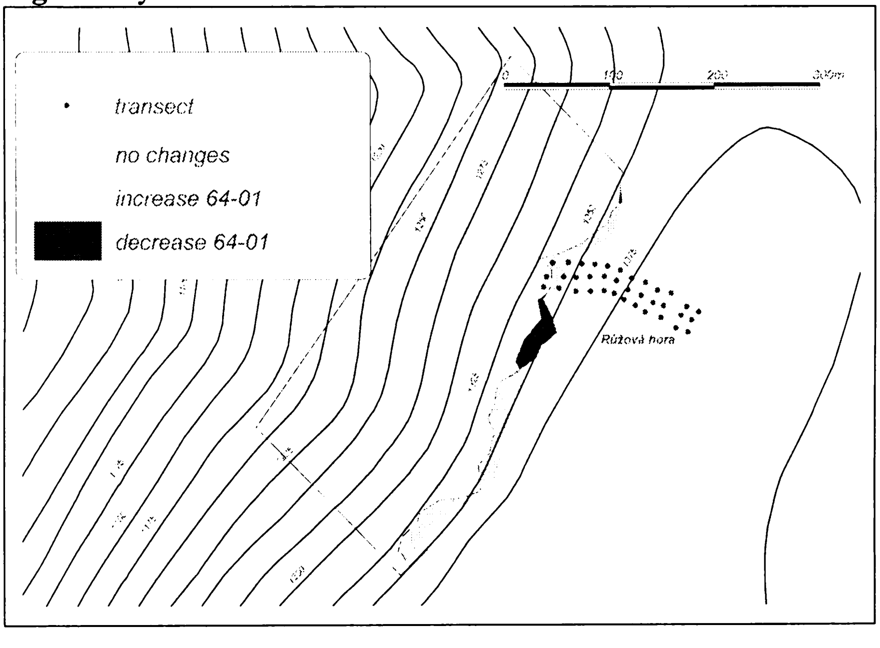


Fig. 10: Dynamics of ATL in the Růžová hora site.



Treml, V. 2004. Recent tendencies of alpine timberline shifts in the Krkonoše (Giant) Mts., High Sudetes. In: Drbohlav D, Kalvoda J & Voženílek V (eds.) Czech geography at the dawn of the millenium, 151-162. Nakladatelství Univerzity Palackého, Olomouc.

Discussion

As many as 16 localities with an ascending alpine timberline were detected. In most cases, they are situated in sections strongly affected by grazing and haymaking in the past, in two cases they include old avalanche tracks, in one case a location is strongly disturbed by debris flow. The ascending process in the ATL shows certain differences between individual locations. These include abrupt and long term increase of timberline, as in the case of locations 1 and 5, where only young trees form the timberline. In other cases, the alpine timberline progress is slower or happened in a shorter time span, creating timberline composed of both younger and older trees. Locations with the shortest existence of ascending tendency are distinctive in presence of a quantity of young spruces (trees up to 30 years of age including seedlings and saplings) above the ATL, however the ATL still remains formed by old closed spruce stands.

Otherwise, raising tendency of timberline was detected in close proximity to summit plateaus (within 50 meters of elevation below the breaking of slopes demarcating the etchplain). On such places, new spruce stands were found on the plateaus, having thus “skipped” the plateau edge. The above phenomenon is proven also by transects of dendrometric characteristics of trees. Tree height and length of the apical shoots correlate poorly or not at all to the elevation. Strongly convex parts of relief (plateau edges) show faster decrease of tree counts, tree height, length of the apical shoots, and deterioration of health condition. These indicators improve again on the summit plateau. The only exception in this respect is the transect of the Důl Bílého Labe, showing opposite tendency. It can be explained by specific conditions – presence of avalanche break-off zones and strong effects of grazing and haymaking on the summit plateau lasting well into the 20th century.

Also dedrometrical investigations and analysis of aerial photos in five selected localities show different dynamic of the ATL between localities with the ATL running in proximity of plateau edges and the ATL situated in lower section of slopes. Three locations showed raising tendency and two stagnation. The ATL running bellow summit plateaus did not show ascending tendency. These were always locations without apparent frequent disturbances, with closed old dwarf pine stands above the ATL. The alpine timberline in these locations was also stabilised by the necessity to “skip” the exposed edge of the plateau.

The ascent of the ATL in the remaining three locations occurred under different local conditions. The transects “Důl Bílého Labe” and “Modrý důl” are locations disturbed by avalanches. The increase of ATL in the location of Důl Bílého Labe was caused by gradual connection of gaps created by disturbance factors (avalanches, debris flows), the maximum elevation of ATL did not thus increase. The upwards shift of the ATL in such places can be explained either as a result of decreased frequency of disturbing factors, or (more likely) as oscillation of the ATL in comparably frequently disturbed area. In the case of Modry dul, the ATL ascended continually, with local oscillations, caused most likely by infrequent avalanches. The upward shift of ATL can be credited namely to the extinction of pasture and haymaking on the southern slopes of the Studniční hora mountain in the last sixty years.

The most pronounced ascent of the alpine timberline was recorded in the "Luční hora" site, where the ATL has shifted upwards by approximately 100 metres since 1964. It is a slope used for haymaking until the 40s of the 20th century (Lokvenc 1978). There are frequent debris flow tracks from the end of the 19th century (Pilous 1975). Plant communities of these areas do not cover the ground completely and therefore offer a better chance for generative rejuvenation of spruce stands better than the surrounding interconnected grassland with dominant *Calamagrostis villosa* and *Nardus stricta*. The above given conditions enable marked raising of the ATL. In locations Modrý důl and Luční hora, the ATL as determined in 1964 is correlated in terms of position to recorded intensive decrement of tree height and diameter (age) for the examined transects. It is therefore safe to assume that long-term established trees were rapidly topped by new growth.

With respect to the long lasting human influence exerted over the Giant Mountains, it cannot be specified to what degree, or whether at all, the trends discovered have been influenced by the increasing average temperatures and lengthening of the growing season in the Giant Mountains (Dubicka, Glowicki 2000). All investigated transects showed increased wood increments in the last decade (Treml, unpublished data). It is difficult to distinguish negative impact of air pollution between 1960 and 1980, judging by tree rings, from effects of temperatures, as indicated by Brázdil et al. (1997).

Summary

On the Czech side of the Giant Mountains, 3.7 kilometres of ATL with raising tendency was determined by the age composition of Norway spruce stands (5 per cent of ATL length on the Czech side, 16 locations). In the majority of cases, the locations had been affected by grazing and haymaking resulted in slightly decreased ATL (11 locations). The investigated sample transects, used for examination of the ATL dynamics, using a series of aerial

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photographs dated 1936, 1964 and 2001, showed ascending tendency even in places where the timberline shifts detected by the age composition were not be ascertained. It is therefore possible, that ATL might show upward shift even outside the locations specified in this paper. Despite the discovery of locations with a raising tendency of the ATL, the major part of the alpine timberline in the Giant Mountains remains stabilised, even with regard to terminated grazing, haymaking, logging and lengthening of growing season. It is most likely the result of the presence of strongly competitive dwarf pine growths and grasslands with dominating *Nardus stricta* and *Calamagrostis vilossa* unsuitable for germination of spruce. Besides the known factors named, the stability of ATL in the Giant Mountains is likely affected by the position of the ATL, often running parallel to edges of summit plateaus, exposed to more pronounced climatic stress. In case of the raised ATL above such distinct plateau edges, the new spruce stands establish on the plateaus, leaving the edge bare. The most rapid ascent of the ATL was found in places disturbed by debris flows. That seems to be another evidence of the strong negative influence of closed-canopy grasslands on germination of spruce. Based on the currently available data, the share of recorded changes in climate in the ascending tendency of the timberline cannot be determined with any degree of certainity.

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The effect of terrain morphology and geomorphic processes on the position and dynamics of the alpine timberline. A case study from the High Sudetes, Czech Republic.

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Abstract

The influence of a terrain morphology on the alpine timberline ecotone was investigated in the High Sudetes. The effects of slope inclination, relief curvature and profile curvature on the position of the alpine treeline were assesed using GIS tools. Alpine timberline dynamics were determined by means of comparison of aerial images from different time periods. Consequently, the dynamics of alpine timberline were analysed according to terrain morphology and the occurence of debris flows and shallow landslides. A dendrochronological approach was used to explain the influence of sporadic debris flow events on alpine timberline shifts. The possible effects of the alpine timberline position on a recent distribution of shallow landslides were analysed as well. It was concluded that the alpine treeline is lowered in valley bottoms even in old hercynian mountains with less deepened valleys, compared to alpine mountain ranges. The highest positions of the alpine treeline are reached on straight slopes without significant curvature, and in contrast the treeline is usually lowered on the most concave or convex landforms. The descending tendency of the alpine timberline was observed on the most convex part of slopes, due to the increase of stress factors in second half of 20. century. The highest rates of upward shifts of the alpine timberline are related to the presence of old debris flow tracks. Lower competition pressure of graminoids enabled a massive establishing of trees on such sites. At first, the lateral ramparts of debris flows were colonised, and subsequently, with a certain time lapse, trees also started to grow on releasing zones. The occurence of shallow landslides depends particularly on well known factors (slope inclination, lithology and catchment area). Nevertheless the alpine timberline position modifies the strength of their influence.

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Key words: alpine timberline, alpine treeline, High Sudetes, Krkonoše Mts., Hrubý Jeseník Mts., timberline dynamics

Introduction

The term alpine timberline (ATL) stands for the ecotone between forest and alpine belt (sensu Körner 1999) or subalpine scrub formations. In reality, ATL is not a sharp boundary, but a transition zone (Armand 1992). ATL is understood as a principal boundary from the microclimatic, phytosociological, edaphic and geodynamics point of view (Holtmeier 2003).

What are the main differences regarding geoecological conditions on both sides of the ATL ecotone? Absence of the stabilisation function of roots is the first factor, which should be considered. Above the ATL ecotone, it results in higher rates of soil creep and snow sliding as well as higher frequency of mass wasting processes. Also more intensive deflation, rill erosion and slope wash occur above ATL, compared to in closed forest (Parzóch, Migoň 2004). For example, annual rates of soil creep above ATL in the Central European mid-mountains range from 8 to 9 mm, while there were almost no soil movements recorded in montane forests (Jahn 1989, Auzet, Ambroise 1996).

Different microclimatic changes can be found on both sides of ATL. Tundra above ATL ecotone is characterised by a more extreme near-ground temperature regime, higher precipitation (there is no interception), more intensive evaporation, higher rates of wind speed and direct radiation compared to forest below ATL (Holtmeier, Broll 2005). Mentioned contrasts are usually reduced if montane forests grade into krummholz communities (in Central European mountains mostly dominated by *Pinus mugo* or *Rhododendron* sp.). Higher elevation of alpine tundra alone results in increased precipitation supply compared to lower forest stands. Thicker snow pack usually accumulates within the ATL ecotone because of snow drifting from treeless areas (Štursa et al. 1973). Irregular distribution of windswept snow above ATL also leads to frequent occurrence of the processes connected with deep snow pack (avalanches, snow sliding, solifluction, Jeník 1961).

The actual position of ATL is primarily the result of temperature conditions of the given site (Körner 1999). However, local temperatures are modified in meso and microscale by relief shaping and topography (Holtmeier 2003). Also, catastrophic slope processes often predetermine the position of ATL in heavily dissected alpine mountains (Plesník 1971, Holtmeier 2003). ATL lowering on valley heads is a commonly observed phenomena, especially in glacially remodelled deep valleys (so-called „valley phenomenon“; Schiechtl 1967, Plesník 1971, Holtmeier 2003). Nevertheless a depressed timberline position also usually occurs in the surroundings of prominent mountain peaks in those localities where ATL runs near summits (so called „Gipfel phenomenon“, Scharfetter 1938, Holtmeier 1974). Microtopography often plays a decisive role affecting the position of the highest outposts of forest, because local terrain conditions influence soil moisture and snow distribution patterns (Hättenschwiller, Smith 1999). That is why landforms such as solifluction risers, isolated blocks, roche moutonnées or moraine ridges could predetermine the structure of the ATL ecotone (Holtmeier, Broll 1992, Walsh et al. 2003, Holtmeier 2003). Block fields are an other factor that can depress the ATL position to lower elevations (Treml, Banaš 2000, Autio, Colpaert 2005).

Even the slope inclination could manifest itself in the course of ATL. Timberline forest usually grades abruptly into alpine tundra on steep slopes, whereas in contrast the range of the ecotone is much wider on gentle slopes (Holtmeier 2003, Kjällgren, Kullman 1998).

The shape of the relief could, besides the ATL position, also influence the timberline dynamics. Recently, strong upward pressure of ATL is mentioned for the temperate mountain ranges as a consequence of ameliorated temperature conditions (Slatyer, Noble 1992, Paulsen, Weber, Körner 2000). The pattern of the ATL increase alone is often influenced by local geomorphologic conditions (Malanson et al. 2002, Holtmeier 2003). Faster upward shifts of ATL were observed on solifluction lobes with bare unvegetated patches (Walsh et al. 2003), while stable ATL positions are mentioned from localities where forests are edged with block fields (Treml 2000). The occurrence of prominent convex landforms immediately above ATL could result in a stable tendency of the forest boundary as well. In contrast, sporadic disturbances caused by catastrophic slope processes accelerate the ATL dynamics because they weaken competition with the herbal layer (Kociánová, Spusta 2000, Treml 2004).

Most of the above-mentioned facts were inferred mainly for alpine mountains or for limited areas. Relatively little emphasis has yet been put on the influence of concave or convex slopes on the overall ATL position (not only on the structure of the ATL ecotone alone). It is hypothesised that convexity or concavity of slopes could also remarkably affect the patterns of snow distribution and wind deflation in mesoscale, which are are considered to be decisive factors of the ATL position. The question of impact of weakly deepened valleys on the position of ATL in the old uplifted mountains has remained unsolved as well. While the range of the ATL ecotone (~ „kampfzone“) depends on slope steepness, the question is, whether the slope steepness and the shape of slope determine also the timberline dynamics. It is assumed that ATL dynamics are affected by seedling establishment and survival. Those characteristics are influenced by both the rate of disturbances which weaken competition with graminoids and microclimatic conditions. Occurrence of both disturbances and favourable microclimatic conditions is actually related to slope inclination (rate of slope processes) and shape (snow accumulation, deflation). Also the effect of sporadic catastrophic slope processes on the structure of the ATL ecotone seems to be an interesting question. It is supposed that some patterns of the ATL ecotone could be explained by previous debris flows or shallow landslide events.

This paper aims to at least partially answer the above mentioned questions. The presented study is focused on the influence of the relief and geomorphic processes on the ATL position and dynamics in the old hercynian mountains. This topic was researched using an approach based on analysis of an extensive number of ATL sections using GIS tools.

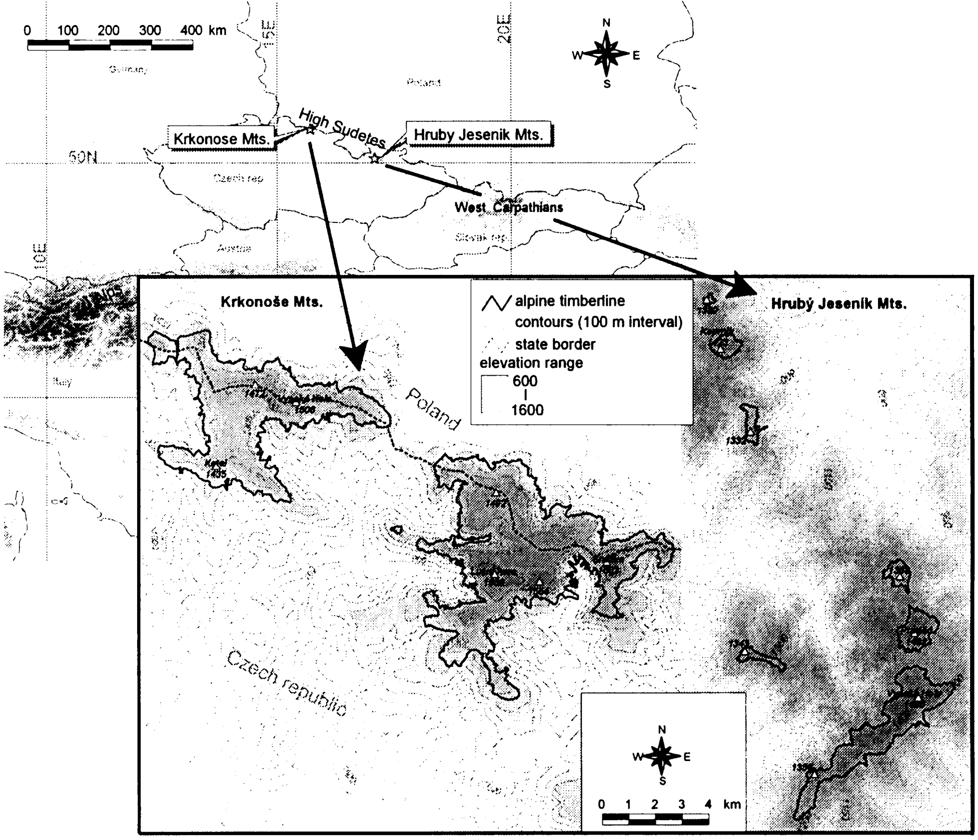
Study area

The hercynian mountain ranges of Central Europe with their primary forest-free areas represent the only alpine islands between the Scandes, Alps and Western Carpathians (Jeník 1998). They include the Vosges, Harz, Krkonoše Mts. (~ Giant mountains/ Karkonosze/ Riesengebirge) and Hrubý Jeseník Mts. (Fig. 1). The last two mentioned mountain ranges represent the most elevated parts of the High Sudetes mountain system. They are prominent because of the large extent of their primary forest free areas (more than 5500 ha in the Krkonoše Mts., 1600 ha in the Hrubý Jeseník Mts.).

Both the Krkonoše and Hrubý Jeseník Mts. are characteristic by high elevated planated surfaces. Valleys and cirques strongly remodelled by glacial activity occur in the Krkonoše Mts. In both mountain ranges the timberline is often limited by extensive block fields and avalanche tracks. In the Hrubý Jeseník the timberline is situated closer to the mountain tops (50–150 m below on average) compared to the Krkonoše Mts., where the forests diminish 200–300 m below the topmost peaks and ridges. The average height of the actual position of ATL is 1230 m ASL in the Krkonoše Mts. and 1310 m ASL in the Hrubý Jeseník Mts. (Treml et Banaš 2000).

Described mountains are characterised by relatively high precipitation (approximately 1400-1500 mm per year). The average annual temperatures range from 0,1 °C in the highest parts of the Krkonoše Mts. (Sněžka 1602 m ASL) to 1,1 °C in the Hrubý Jeseník Mts. (Praděd 1493 m ASL). Forests of upper montane belt and timberline ecotone are composed of Norway spruce (*Picea abies*). Alpine and subalpine communities are composed of dominant graminoids (*Nardus stricta, Calamagrostis villosa, Calamagrostis arundinacea, Avenella flexuosa*) and dwarf pine (*Pinus mugo*) growths. The extent of the forest-free area has been strongly influenced by man who increased it in the past by deforestation in both studied mountain ranges (Jeník, Lokvenc 1962, Jeník, Hampel 1991). Nevertheless, an extensive part of ATL is not disturbed by man regarding its position (but not as regards the structure of the ecotone, Jeník, Hampel 1991, Zientarski 1995, Treml, Banaš 2000). In addition, there has not been any distinctive direct anthropogenic impact on ATL in the High Sudetes during the last 60 years, since those areas were either abandoned by German inhabitants or strictly protected as nature reserves.

Fig. 1: Position of studied area.



Methods

Delimitation and characteristics of the alpine timberline and treeline

The recent ATL position was determined using thresholding of ortorectified aerial images (RGB, pixel 0,4m). ATL was defined as a line connecting all uppermost parts of forest/tree groups with canopy denser than 0,5 on 1a square. Squares were defined using JTSK coordinate system and thus this method tends to slightly „lower“ the ATL position on slopes parallel with either the X or Y axis of the mentioned coordinate system. Alpine treeline (ATE) was defined as a join of uppermost ATL positions within the slopes of a given exposition (for discussion about the suitability of using treeline or timberline approach see Körner 1999).

Evolution of the ATL position was assessed by means of comparison of aerial images from different time periods. Images from 1936, 1963, 2001 years were used in the case of the Krkonoše Mts. and images from 1951, 1973, 2001 years in the case of the Hrubý Jeseník Mts. Old grey scale aerial images (all except 2001 year) were ortorectified (eliminating bias resulting from lens curvature and relief topography) using PCI Geomatica software. Consequently, the timberline was determined by thresholding rectified images and resultant lines were compared. If there were differences among positions of timberlines lower than 20 m the tendency of a given ATL section was marked as „stable“ (the value of 20 m was estimated as the maximal error of ortorectification and error caused by shadows of tree crowns). If there were changes of ATL positions recorded in both directions (upwards and downwards), the tendency of the ATL section was called „oscillation“. Overall „increase“ (ATL has ascended and during no period has descended) or „decrease“ (ATL has descended and during no period has ascended) were the other two categories of the ATL tendency.

The sections of ATL obviously lowered either by direct anthropogenic impact or by avalanches, debris flows or presence of block fields were not included in the following analysis.

Analysis of the possible influences of the shape and inclination of slopes on the alpine treeline position

Current alpine treeline position was assesed taking several slope characteristics into account. The reason for assessing the alpine treeline (and not the alpine timberline) was to describe correctly the ecotone position. No local anomalies caused by small disturbances (windthrows, small avalanches) are included in such a line and thus the alpine treeline better represents the mesoscale ecological conditions compared to the alpine timberline. The given line was divided into 100m long sections (using „divide“ tool in ESRI ArcInfo, Esri 2003). Those sections were subsequently analysed with regard to such characteristics as elevation, concavity and convexity, slope inclination. Average, maximal and minimal values were counted for every section of the treeline. All variables were derived from a digital terrain model with a 20m grid. This model was created from contours with a 5m elevation interval using TOPOGRID function (Esri 2003). Concavity and convexity were evaluated both in downslope and contour direction together (Curvature) and in downslope direction alone

(Profile Curvature) (Esri 2003). The former curvature characteristics enables the identification of valleys and valley bottoms, and consequently the influence of valleys on the treeline position. The higher the values of curvature detected, the more convex relief occurs at a given place. Curvature of straight slopes equals zero. The latter characteristic (Profile Curvature) is suitable for determination of distinct convex or concave shapes of slopes. The lower values of profile curvature mean higher convexity of terrain. Convex parts of the relief are understood as deflation areas and concave parts as accumulation areas, concerning snow distribution. All variables were quantitative with normal distribution. Their linear relation to elevation was analysed using Pearson correlation. It was assumed that if the value of a given variable is „favourable“, it would increase the elevation of the analysed section of treeline.

Valley phenomenon was assessed by means of comparison of the average treeline elevations on the valley bottom and adjacent slopes. First the sections of the treeline intersecting the valley floors were identified, then the adjacent sections with the same length were delimited on slopes. Comparison between elavations of „valley“ and „slope“ sections was made using t-test.

Influence of slope shape and inclination on recent dynamics of the alpine timberline

An assessment of the influence of several variables on ATL shifts was performed. A buffer (with either 50 or 100m width) was created around centroids of 100 m long current ATL sections. Variables such as elevation, slope, curvature and profile curvature were analysed within every buffer. The whole buffer area was used for analysis if the ATL tendency of the given section was „stable“ or „oscillation“. If the ATL tendency was „decrease“, only that part of the buffer located above the ATL was used for analysis. Parts located below the ATL of buffers were assessed within ascending ATL sections (with tendency „increase“). The width of the buffer was 25m in the case of oscillation values lower than 50m in a given section, 50m wide buffers were created if the rate of ATL shift was higher. Then the acquired data were carefully checked to find if there were any significant differences in distribution of variables within each category of ATL tendency. Analysis of variance was used for this evaluation. Besides the assessment of the test power (F-statistic), the percentage of variability explained by given factor was also counted according to the following formula (Meloun, Militký 2002):

$$\omega^2 = \frac{S_A - (m-1) MS_e}{S_T + MS_e}$$

S_A … variability explained by categories

S_T … total variability

MS_e … unexplained variability

m-1 … degrees of freedom

Mutual relations between the alpine timberline position and the occurrence of debris flows and shallow landslides

Several approaches were used to assess interactions between the ATL position and the occurrence of such disturbance events as debris flows and shallow landslides. Shallow landslides usually originate in a breaking away of the thin soil/weathering mantle layer (0,5-1m thick) over a moderate area (about 50 m^2 on average). The resulting landform does not have a differentiated transport and accumulation zone (sediments are usually washed away). By contrast, debris flow tracks reveal a distinctly differentiated release zone, a transport zone with lateral ramparts and an accumulation zone (see Pilous 1973). At first, dynamics of the ATL and occurrence of debris flows and shallow landslides was compared using GIS. Assessment was not accomplished for the western part of the Krkonoše Mts. because of missing data. We searched for any relation between position and clustering of releasing zones of the mentioned slope processes and recorded ATL dynamics. The data set describing the occurrence of debris flows was taken from Pilous (1973, 1975, 1977, east Krkonoše Mts.) and Gába (1992, Hrubý Jeseník Mts.). Those data were complemented by results of our own field work (especially the position of recent debris flows). Releasing zones of shallow landslides were identified from aerial images and during the field work. The assessed state of debris flow and shallow landslide occurrences corresponds to the year 2001.

A dendrochronological approach was chosen to explain the reaction of the timberline ecotone to debris flow events. The age structure of trees was investigated at sites with clustered occurrences of debris flows intersecting the alpine timberline (Dlouhý důl valley, Důl Bílého Labe valley in the Krkonoše Mts.). Trees were analysed in groups, which differed according to location: release zone, lateral ramparts, transport zone and control square outside of the debris flow track. The age of the trees was determined by counting the tree rings on cores taken from trees using an increment borer. Standard procedures (sanding, counting of the tree rings on measuring table) were applied to the cores. Cross-dating for identifying the missing tree rings was not accomplished with respect to the relatively robust data set and the purpose of the study. Cores were sampled at 50 cm height. The derived ages of the trees were raised by 10 years, which is the average observed period, which the Norway spruce needs to reach a height of 50 cm. Trees were subsequently divided into age classes. The number of seedlings and saplings was counted within the given part of debris flow track (and control square) as well. Investigated debris flows in the Dlouhý důl valley were probably triggered during the extreme rainfalls in 1882 (Pilous 1975).

We also tended to check the possible influence of the ATL position on occurrence of shallow landslides. The relation between the total area of shallow landslides and their distance from ATL was investigated. The area of shallow landslides within zones bounded by ATL was assessed. The width of every zone along ATL was 50 m. In total, three zones below and ten zones above ATL were created and thus an area covering 150 m below and 500 m above ATL was analysed. The lower number of assessed zones below ATL than above is caused by the significantly less frequent occurrence of shallow landslides there. Both the area of shallow landslides and the width of zones were measured in surface units, that is why the resultant values of width and area better represent the real situation as compared to values derived from orthogonal projection of the given phenomena (for detailed explanation of this method see Treml 2003). In addition, the average slope values for every zone were inferred from the digital terrain model to distinguish the influence of inclination from the possible influence of distance from ATL.

Results

Influence of convex and concave landforms on the alpine treeline position

Based on analysis of terrain curvature, it can be stated that ATE reaches lower elevations on concave landforms than on convex landforms (Fig. 2). Nevertheless, if the overall trend of this relation is expressed as a polynomial fit, it can be seen that there is moreover a weak trend of lowering of ATE position on most convex parts of the relief. Correlations between elevation and characteristics of curvature are not very strong but they are statistically significant (Tab. 1). Better correlations were noticed in the Krkonoše Mts. than in the Hrubý Jeseník Mts.

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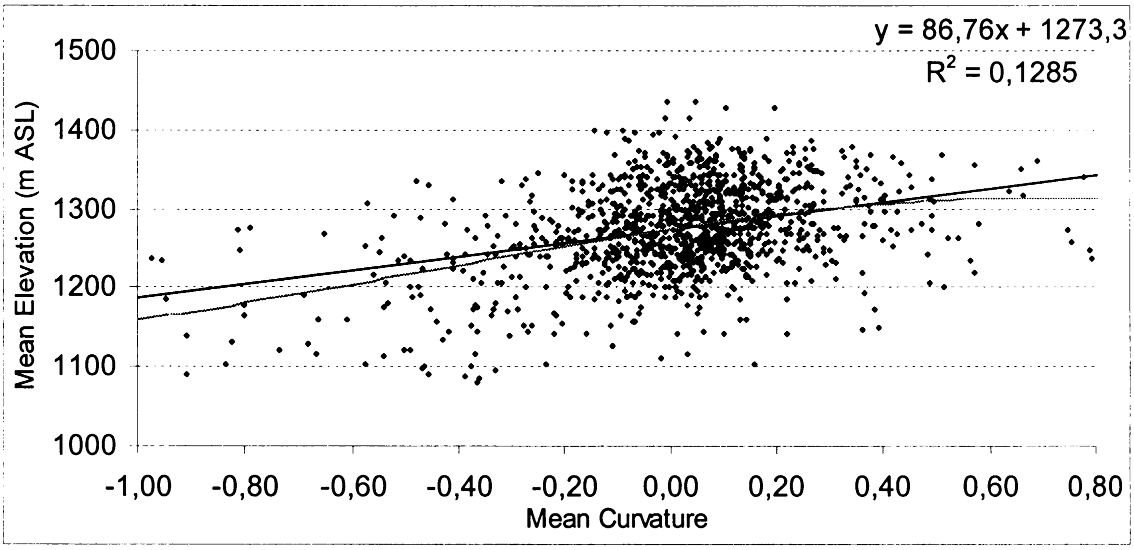
Fig. 2: Relation between mean elevation and curvature; linear trend is symbolised with full line, dashed line symbolizes polynomial fit.



Tab. 1: Correlation coefficient – elevation vs. curvature, all correlations were significant at 0,05 level.

	Mean elevation vs. mean curvature	Mean elevation vs. minimal curvature	Mean elevation vs. maximal curvature
Krkonoše Mts.	0,37	0,41	0,25
Hrubý Jeseník Mts.	0,28	0,29	0,21
High Sudetes in total	0,36	0,41	0,23

Regarding the possible influence of valley bottoms on the treeline course, we found a slight difference in treeline positions (Fig. 3). The treeline is a little bit depressed in valley bottoms compared to adjacent slopes. However, T-test of variability caused by different ATE location (on valley bottoms vs. on slopes) was not significant at 0,05 significance level (p = 0,28, t = -1,07).

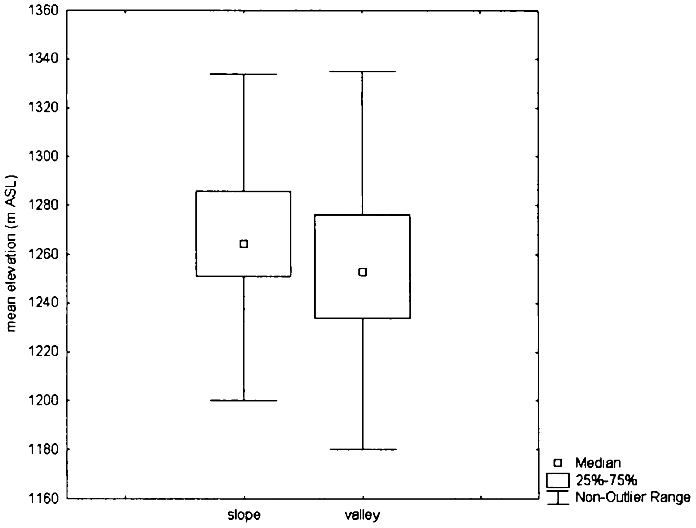
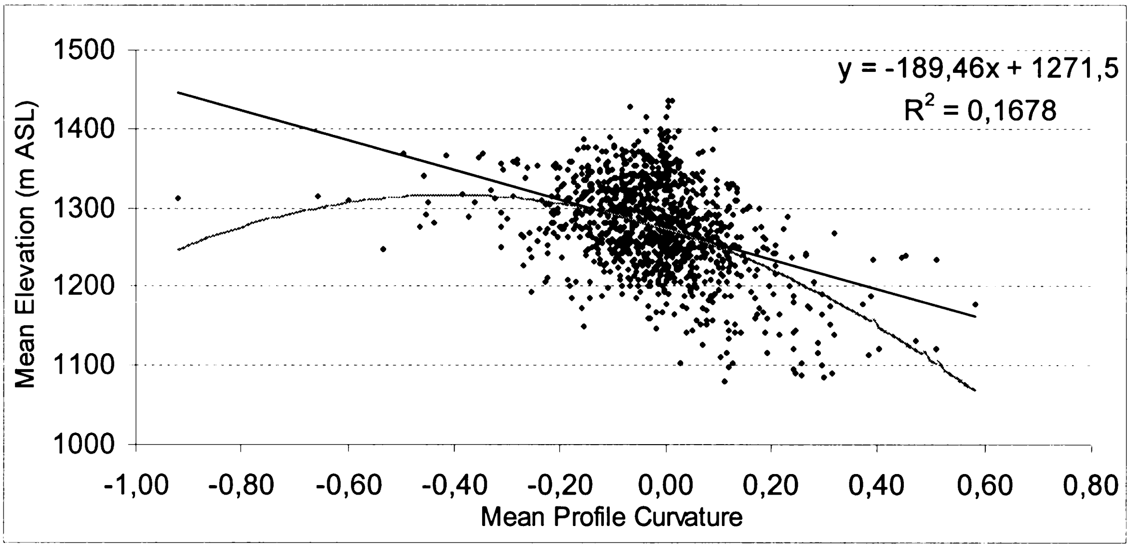


Fig. 3: Distribution of alpine treeline elevations on valleys and adjacent slopes.

When only slope shape (profile curvature) was stressed then we observed that the ATE elevation increases with decreasing values of profile curvature (Fig. 4). However, the highest outposts of the forest are situated on slopes with weak convexity or concavity. It can also be observed that ATE is depressed in the most convex parts of slopes. Remarkable differences were found between the two studied mountain ranges (Tab. 2). Those differences probably result from the position of the treeline, which runs close to the margins of elevated planated surfaces in the Hrubý Jeseník Mts., thus on more convex slopes compared to the Krkonoše Mts.

Fig. 4: Relation between mean elevation and profile curvature; linear trend is symbolized with full line, light grey dashed line symbolizes polynomial fit.



Tab. 2: Correlation coefficient – elevation vs. curvature, all correlations were significant at 0,05 level.

	Mean elevation vs. mean profile curvature	Mean elevation vs. minimal profile curvature	Mean elevation vs. maximal profile curvature
Krkonoše Mts.	-0,45	-0,32	-0,48
Hrubý Jeseník Mts.	-0,18	-0,12	-0,24
High Sudetes in total	-0,41	-0,27	-0,47

Influence of shape and inclination of slopes on dynamics of the alpine timberline

The influence of shape and inclination of slopes on ATL dynamics was significant for most of the characteristics used (average, maximal and minimal values of elevation, curvature, profile curvature and slope inclination). Nevertheless, the percentage of variability explained by factor „tendency“ was usually low (Fig. 5). We observed partially different trends on slopes with similar profile curvatures in the Hrubý Jeseník and Krkonoše Mts. (Fig. 6, 7). A common trend of a higher probability of ATL descent on more convex slopes was found. The stable position of the ATL occurred preferentially on weakly convex to straight slopes. The other two tendencies of relief characteristics were opposite. An ascent of ATL manifested preferably in the most convex parts of slopes in the Krkonoše Mts., whereas in the Hrubý Jeseník Mts. an opposite trend was observed. Differences on slopes with oscillations of ATL were not so distinct – an oscillating trend of ATL was typical for less convex parts of slopes in the Krkonoše Mts. compared to the Hrubý Jeseník Mts.

Fig. 5: Percentage of explained variability with the factor „tendency“ of alpine timberline shifts; results of ANOVA statistics, nonsignificant probability values (level 0,05) are marked by asterisks.

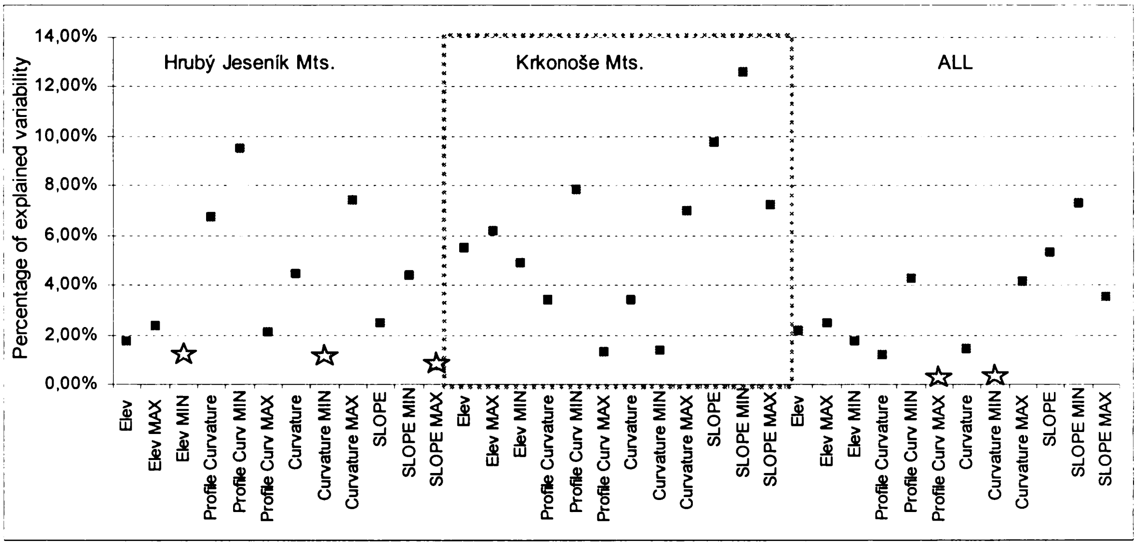
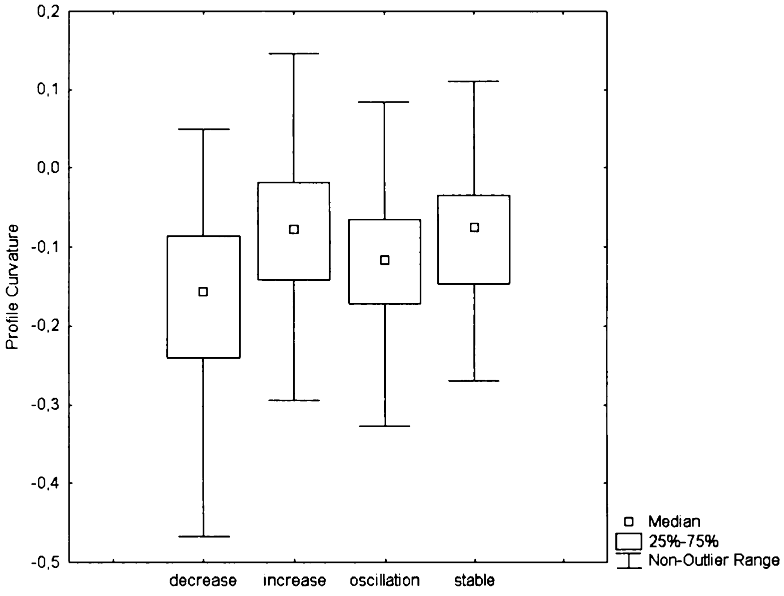


Fig. 6: Distribution of profile curvature minimal values at sections of ATL with different tendencies of altitudinal shifts, Hrubý Jeseník Mts.



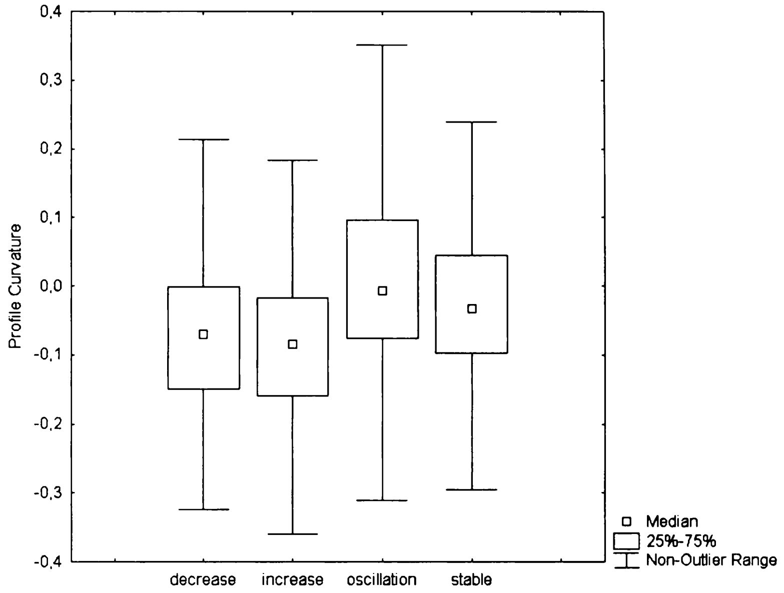
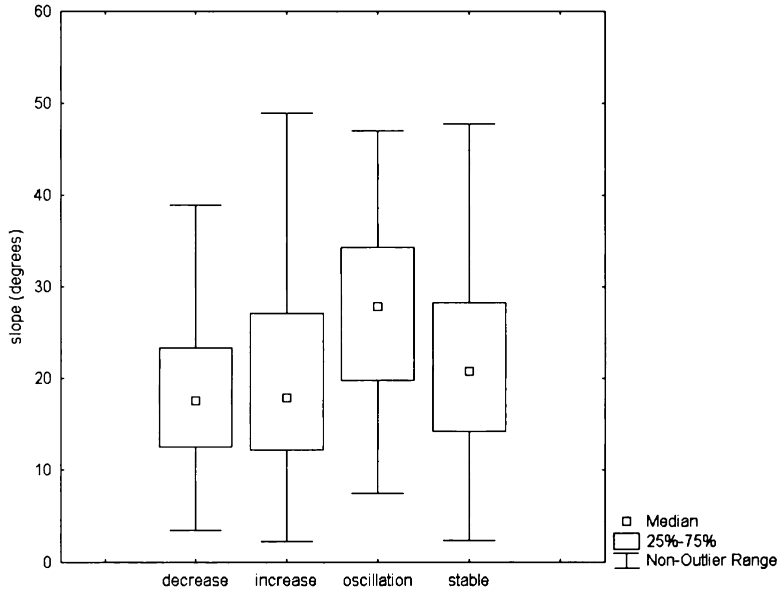


Fig. 7: Distribution of profile curvature minimal values at sections of ATL with different tendencies of altitudinal shifts, Krkonoše Mts.

A relatively strong trend is displayed in the distribution of slope inclination values in the Krkonoše Mts. (Fig. 8). Oscillations of ATL were recorded on the steepest slopes, but to the contrary, overall sustainable upwards or downwards shifts were detected more often on gentle slopes.

Generally, no unambiguous increasing tendency of ATL was found. Upward shifts of ATL have occurred preferentially in middle elevations (median 1250 m ASL), whereas a decrease of ATL was recorded at higher elevations (median 1270 m ASL).

Fig. 8: Distribution of slope values at sections of ATL with different tendencies of altitudinal shifts, Krkonoše Mts.



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Interactions between alpine timberline position and occurrence of debris flows and shallow landslides

While there is apparently no relation between ATL dynamics and position and occurrence of debris flows and shallow landslides in the Hrubý Jeseník Mts. (Fig. 9), there is in several localities in the Krkonoše Mts. (Dlouhý důl valley, Důl Bílého Labe valley), where significant clustering of the mentioned slope processes has led to distinct oscillations or an increase of ATL (Fig. 10). The Timberline in those localities is often lobate with a range of upslope and downslope projections.

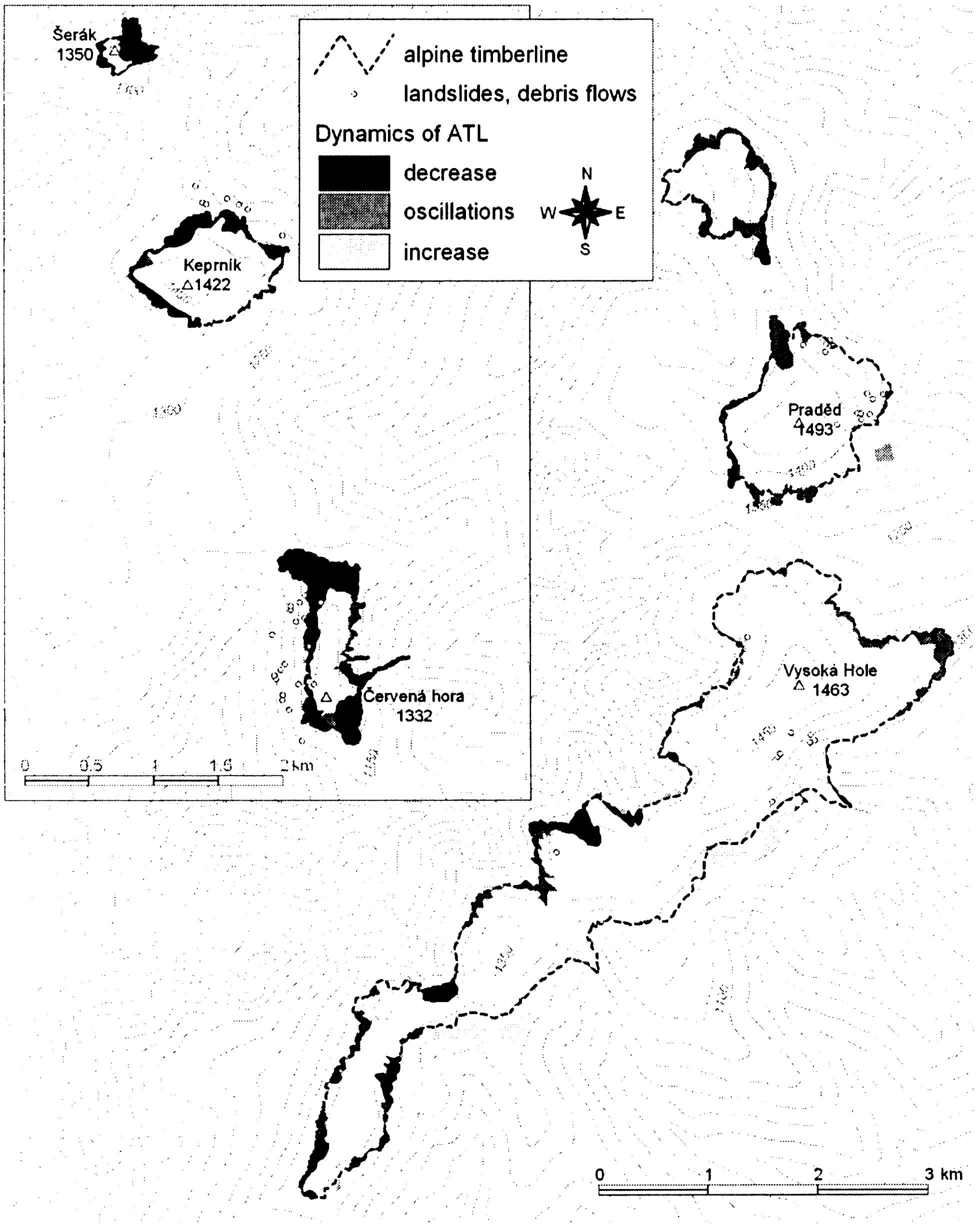
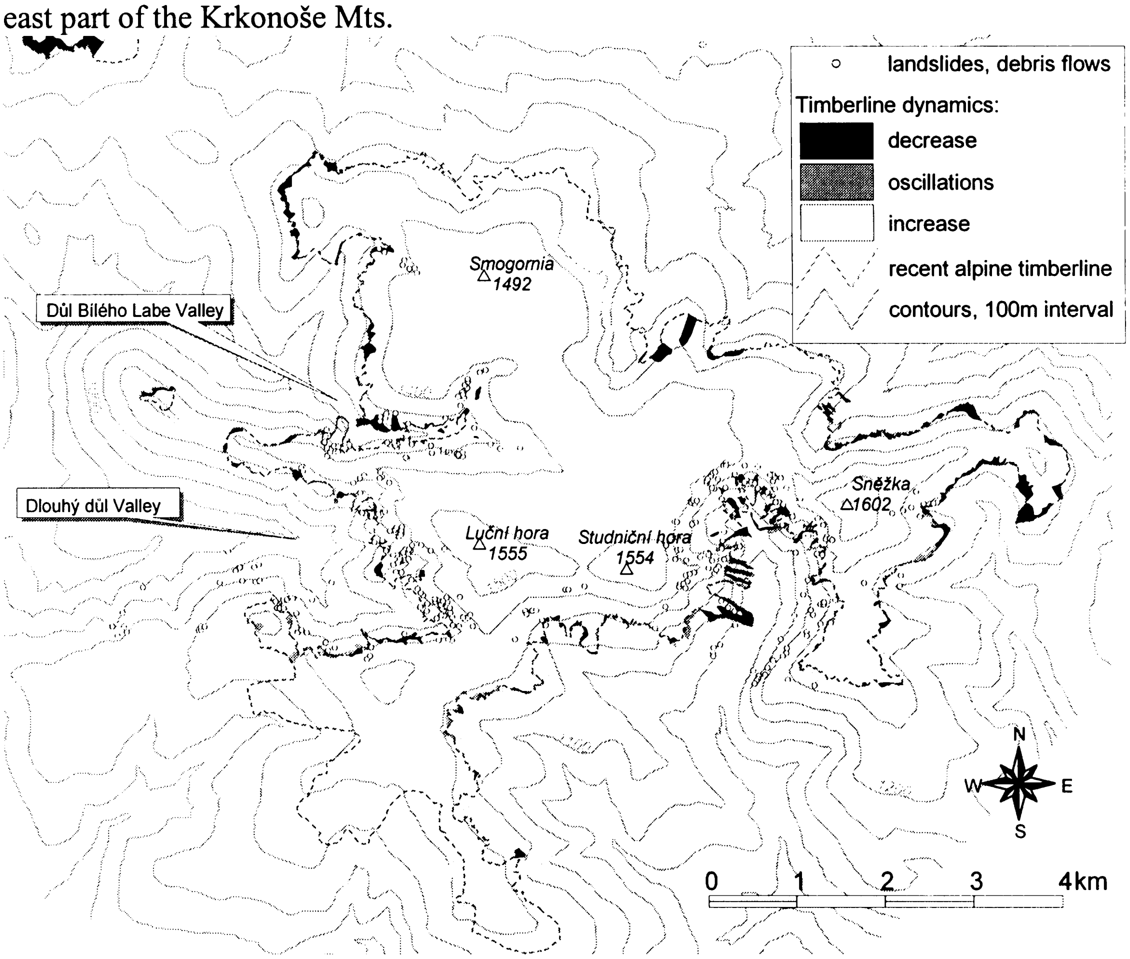


Fig. 9: Tendency of ATL altitudinal shifts and occurence of landslides and debris flows, Hrubý Jeseník Mts.

Fig. 10: Tendency of ATL altitudinal shifts and occurence of landslides and debris flows, east part of the Krkonoše Mts.



This phenomenon could be explained by the way how trees colonise debris flow tracks. Belts of trees ascending into the alpine grasslands can be seen at mentioned sites in the Krkonoše Mts. Those belts are situated on old debris flow tracks. In the case of the Dlouhý důl site, in lower parts of the debris flow tracks we found trees which were established on lateral ramparts during several successive vegetation seasons after the debris flow triggering (1882 sensu Pilous 1975) (Tab. 3). Trees of variable ages occur either within the debris flow track alone, or within higher parts of the transport section (section without lateral ramparts). However, those trees established preferably only on the debris flow track. In contrast, there is very sparse tree canopy in the surroundings of this part of the debris flow tracks. Relatively young trees, including many seedlings and saplings grow, in the highest parts of debris flow tracks (in the releasing zone). Thus, spruces growing in the releasing zone together with trees established on the transport part of debris flow tracks and dwarf pine communities build very prominent belts ascending into the alpine grasslands. Generally, the age structure of trees growing on debris flows is much more variable compared to the ages of trees growing on the control square in the vicinity of ATL. Pilous's (1975) estimation of the period of the debris flows triggering can be confirmed, based on the maximal age of trees established on the lateral ramparts.

Trees established on the lateral ramparts of debris flow tracks prevail also as ascending belts of forest in the Důl Bílého Labe site. The age structure of trees growing in the releasing zone and lateral ramparts could not be compared because of an absence of upright stemmed spruces in the releasing zone. Due to strong pressure of snow sliding, there are only several young krummholz spruces. Trees growing on the lateral ramparts are comprised of spruces of variable age structure (Tab. 3). All analysed spruces were significantly younger than the age of the debris flow track estimated by Pilous (second half of 19. century, Pilous 1975).

Tab. 3: Age classes of trees growing on debris flow tracks in the Dlouhý důl and Bílé Labe sites.

	Number of trees				
	Dlouhý důl valley				Bílé Labe valley
Age class	Control square	Release zone	Transport zone*	Lateral rampart	Lateral rampart
Seedlings and Saplings	1	53	4	12	7
21-30	1	2	0	0	0
31-40	0	8	2	2	7
41-50	0	9	3	2	11
51-60	1	7	2	1	12
61-70	2	7	1	2	3
71-80	1	1	1	0	2
81-90	1	0	0	1	2
91-100	2	0	0	1	1
101-110	0	1	0	0	0
111-120	1	0	0	13	2
121-130	0	0	0	2	0
131-140	3	0	0	0	0
140 and more	7	0	0	0	0
In total**	19	35	9	24	41

* … inner and upper part of transport zone except lateral ramparts
** … without seedlings and saplings

When we focused on the opposite possible relation between recent occurrences of shallow landslides and the ATL position, we found, that a large number of landslides originated in the zone immediately above ATL (Fig. 11). The shallow landslide sample consists of 176 patches covering a total area of 7,8 ha in all aspects and elevation intervals. The distribution curve of shallow landslides extent steeply rises above ATL. The first peak of the curve is reached in the 50-100m interval, then the curve reaches a secondary peak in the 150-200 m distance from

ATL. The majority of the disturbed areas are situated on slopes with 30-40° inclination (67% of all patches; 20-30°- 16% patches, 40-50°- 14% patches). Total areas of disturbed patches broadly correspond to average slope inclination within the given zone. The highest number and the highest total areas of shallow landslides are found in the zones with the steepest slopes. Nevertheless a certain moderating influence of the ATL position can be observed. The area and the number of disturbed patches just above the ATL (where the tree number is still relatively high) is lower than could be expected in terms of highest slope inclination within all the assessed distance zones (Fig. 11).

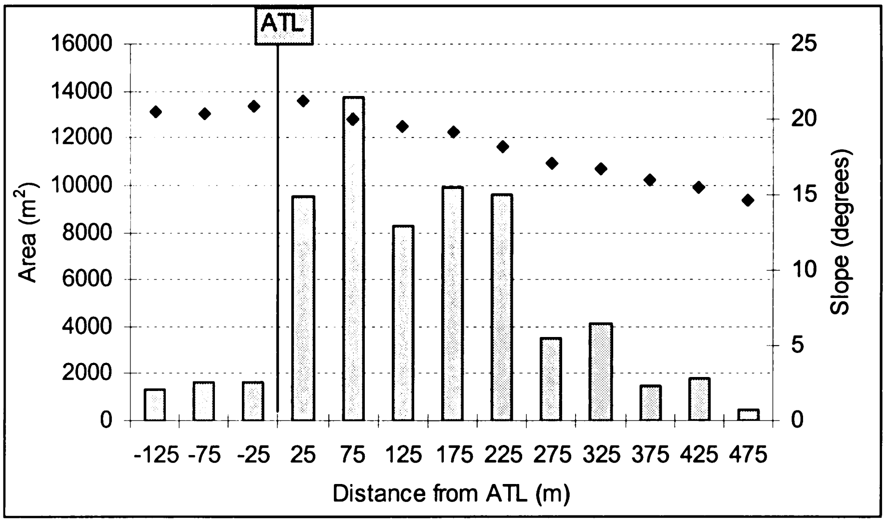


Fig. 11: Total areas of shallow landslides in the zones on either side of ATL, the east Krkonoše Mts. Columns represent total area of shallow landslides, points mark average values of slope within the given zone.

Discussion

Influence of relief characteristics on position and dynamics of the alpine timberline ecotone

The possible influence of concave landforms, particularly valley bottoms, was analysed. It was concluded that the alpine treeline (and thus the alpine timberline as well) tends to have lower positions at valley bottoms than on adjacent slopes. This phenomenon, well known from alpine mountain ranges, is consequently valid even in old hercynian mountain ranges with relatively less deepened valleys. However, elevation differences between valleys and slopes are not and even could not be so distinct as in the case of alpine mountains (Plesník 1971, Holtmeier 2003). The explanation of this so called „valley phenomenon“ could be traditional also in the High Sudetes – the accumulation of cold air at valley bottoms, long lasting snow cover in shaded valley positions and lower values of direct radiation. In addition, avalanches and debris flows often fall down through erosion rills at the bottom of valleys or valley heads. Even though sites directly influenced by the mentioned processes were excluded from analysed sections of the treeline, there is a certain possibility that given impacts of fast slope processes could have affected the treeline in the past. A similar explanation could also be given for the frequent occurrence of treeline minimal elevations on the most concave parts of slopes. Maximal elevations of treeline were detected on straight, uncurved slopes. At such sites there is a high probability that trees could profit from surface heating by direct radiation and, simultaneously, the heating effect would not be lowered by the above mentioned factors acting in valley bottoms. Central parts of slopes, which are characterised by straight profile (neither convex nor concave) also belong to the so called „warm“ zone of slopes (Aulitzky 1967). The depressed course of the treeline is noticeable on most convex parts of slopes. It proves the outcomes of a previous study (Treml 2004), which suggest a more abrupt diminishing of the forest on convex parts of the relief. The above mentioned findings contribute to the explanation of „mass elevation effect“, which could be among others related to a more frequent occurrence of uncurved slopes on more elevated mountain massifs. This effect has usually been referred to the larger surface of high elevated mountains, which reflects more long wave radiation and thus increases temperature during the warm period of the day (De Quervian 1904, Holtmeier 2003).

The partially different influences of convexity/concavity on the alpine treeline position were detected in the Hrubý Jeseník and Krkonoše Mts. Those differences are ascribed to the closer position of the treeline to summit planated surfaces in the Hrubý Jeseník Mts. and consequently to its location on more convex parts of slopes. It could be illustrated with an overall average value of profile curvature at treeline, which equals 0,047 in the Hrubý Jeseník and 0,007 in the Krkonoše Mts.

Certain relations between ATL dynamics and relief properties were recorded. In the High Sudetes, more probable downward shifts occurred generally on the most convex parts of slopes on the highest elevations. Such sites are considered to be the most extreme, which is displayed by the bad growing vitality of the spruce (both the stem and terminal increments are low, Treml 2004). Winter desiccation usually acts strongly in those locations as well (Cairns 2001). It can be deduced that such stressed ATL positions could be more susceptible to other stress factors. A decrease of the alpine timberline mostly happened during the second part of the studied period (1964–2001 in the Krkonoše Mts., 1973-2003 in the Hrubý Jeseník Mts). For this reason it is suggested that high immissions inputs during 70's and 80‘s, which caused local diminishing of the forest at lower elevations, were the driving factor of the recorded decrease of the ATL on most convex slopes in High Sudetes.

A higher probability of stable ATL tendency was found at less stressed positions, which means on straight or slightly convex slopes. A contrasting trend of upward shifts of the ATL was detected in the studied mountain ranges. While in the Krkonoše Mts. this tendency was peculiar for convex parts of the slopes below the lower level of planated surfaces, in the Hrubý Jeseník Mts. the ATL ascended on relatively less convex to straight slopes. However the absolute values of the profile curvature differ between the studied mountains by only a little (median -0,9 in Krkonoše, -0,7 in Hrubý Jeseník). Both in the Krkonoše and Hrubý Jeseník Mts. given sections of the ATL ascended roughly to the level of recent average ATL elevation (cca 1250m ASL in the Krkonoše Mts., 1300 m ASL in the Hrubý Jeseník Mts.). The upward shift in the Hrubý Jeseník Mts. was typical for hillsides of the highest peaks (Vysoká Hole Mt., Praděd Mt., Jelení hřbet Mt.), where the position of the ATL was lower than average in the past. Consequently, this ascent came to pass on the lower and thus less convex parts of the slopes. In the Krkonoše Mts. the sites with the ATL upward shift, which preferably happened bellow margins of lower level of planated surfaces (localities as Luboch Mt. , Stoh Mt. , Růžová hora Mt.), were characterised by low values of slope inclination. Such an increasing trend of ATL on gentle slopes corresponds to a globally suggested pattern of ATL sensitivity to the recent temperature increase (Holtmeier, Broll 2005). A decreasing tendency of ATL was recorded preferably on slopes with lower inclination in the Krkonoše Mts. as well. They were high elevated sites on the margins of the upper level of planated surfaces with the uppermost outposts of forest (Svorová hora Mt., Malý Šišák Mt., Dívčí kameny Mt.). Oscillation of the ATL occurred particularly on very steep slopes. It was probably driven by such disturbances as snow sliding and sporadic small scale avalanches or debris flows.

Interactions between the alpine timberline and the occurrence of debris flows and shallow landslides

It was already mentioned in the previous chapter that besides its position in the relief, the dynamics of the ATL could be influenced also by the occurrence of fast slope processes. This assumption could not be confirmed in the case of the Hrubý Jeseník Mts. In this mountain range the releasing zones of debris flows were usually situated below the recent position of ATL. The only exception was Červená hora Mt. site. However, after depressing of ATL by debris flows, trees establish on the disturbed site again without an overall ATL upward or downward shift. Ascent of ATL on the northeast hillside of Praděd Mt. is spatially related to clustered occurrence of shallow landslides, nevertheless no direct relation between establishing of trees and disturbed sites by landslides was observed in the field.

A distinct relation between the accelerated dynamics of the ATL and the occurrence of old debris flow tracks was found in the Krkonoše Mts., especially in Dlouhý důl and Důl Bílého Labe valleys. An approximately 100m shift of the ATL on debris flow tracks was observed during the last 40 years in the Dlouhý důl site. Here, the debris flows were characterised by extensive releasing zones that were subsequently eroded by slope wash, and thus a dense herbal layer has not been established. Those factors result in the easier establishing of trees because of the decrease in the strong competitive pressure of graminoids, which is considered to be a causal factor in the successful survival of seedlings and saplings (Šerá et al. 2000). Consequently, elongated tree groups have established on releasing zones of debris flow tracks. These groups verge downward into parallel belts of trees growing on lateral ramparts. While younger trees prevail in the releasing zone (the age of the oldest specimen is 70 years but most of them are younger than 30 years), old specimens of spruce dominate on lateral ramparts. Those spruces established over several successive years after debris flow emerged (in 1882, Pilous 1975). The different time spans of colonisation of debris flow track depend particularly on the presence of suitable microhabitats with weak competition of graminoids and without prominent erosion processes. Such habitats were present immediately after debris flow fell on lateral ramparts, however the substrate on the releasing zone had to be stabilised at first because it is the most eroded part of the debris flow track. Subsequently after stabilisation, seedlings can establish successfully. The alpine timberline at the Dlouhý důl site had been lowered before the studied period (before 1938) due to pasture and grass mowing on elevations at approximately 1200 m ASL. On debris flow tracks ATL has then ascended to 1280 m ASL. This is the most intensive upward shift of ATL recorded in the High Sudetes. It appears that there is a distinct potential for ascent of montane forest to higher elevations, but it is conditioned by presence of areal disturbances weakening the competitive pressure of graminoids and dwarf pine communities. Thus the function of disturbances seems to be very important for overall ascent of ATL (Slatyer, Noble 1992).

The described upward migration of forest results however from the combination of suitable environmental conditions. Debris flows of similar number and magnitude occurred at Bílé Labe site. The weathering mantle in the releasing zone had been totally removed here. In addition, the given site is typified by steep slopes (30–40°) and frequent small-scale disturbances (snow sliding, small-scale avalanches). Those factors have prevented any distinct upward shift of the ATL. Thus, only parallel belts of trees growing on lateral ramparts could be observed here and only a slight increase or oscillations (related to disturbances) in ATL position was recorded.

So far, we have focused on the influence of slope processes on the ATL ecotone, but the position of the ATL alone could also affect the occurrence of some small scale landslide events. In this study, the interactions between occurrence of shallow landslides and ATL were stressed. In the case of the eastern Krkonoše Mts., the expected steep increase in number and total area of shallow landslides above ATL compared to the zone below the ATL can be confirmed. Closed forest thus supports stabilisation of the soil/weathering mantle by means of its root system. The highest number and total area of shallow landslides is situated in 50-100 m distance above the ATL, and a second peak of curve is reached in distance zone 150-200 m above ATL. Such distribution of shallow landslides could be partially explained by slope inclination. Nevertheless, the certain influence of the ATL position can also be observed. A lower number and total area of shallow landslides is found in the zone situated directly above ATL compared to the more distant zone (50-100m). By contrast, the average inclination of both compared zones has an opposite tendency. It is also hypothesised that, in a certain way, trees could contribute to an increasing number of shallow landslides in 50-100m zone, due to the uprooting of solitary trees on steep slopes caused by wind, snow sliding, avalanches or high water saturation of soil. It leads to disturbance of the soil/weathering mantle and, consequently to an increase in probability of landslide triggering. Shallow landslides often occur at places where montane forest grades abruptly into newly established avalanche tracks and thus a transition zone from forest to treeless area is absent. This is one of the reasons why the largest area and the highest numbers of shallow landslides are situated within the zones near ATL. Anyway, there are other very significant factors influencing the distribution of shallow landslides. Many landslides in zones near ATL, are situated in the bottom part of nivation-remodelled funnel-shaped valley heads. Such localities have large catchment basins and this is hypothesised to be one of the causal factors in the triggering of this kind of process in the Krkonoše Mts. (Pilous 1977). Lithological conditions are also certainly a significant factor (Pilous 1977, Gába 1992). However, it is assumed that they cannot bias landslide distribution within the distance zones from ATL because of the relatively balanced representation of slopes with a given lithology transected by ATL. The secondary peak of the shallow landslides distribution curve is found in 150-200 m distance zone. It is concluded that this peak has no relation to the ATL ecotone and thus it should be ascribed to the above mentioned factors (inclination, catchment basin, lithology).

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Conclusions

The considerable influence of relief and slope processes on the position and dynamics of the alpine timberline was confirmed on the example of the High Sudetes mountain ranges. The heat sum during the vegetation season is the main driving factor of the alpine timberline position (Körner 1999), however this factor is modified by variable microclimatic conditions on distinctly convex or concave parts of the relief. Thus, the highest elevations of the alpine timberline in the High Sudetes are reached on slopes without significant curvature. Regardless of the absence of distinctly deepened valleys in the study area, a slight depression of the treeline on valley axes compared to adjacent slopes was detected. Particularly, the slope profile and inclination also affect the dynamics of the alpine timberline. An overall descending tendency of the alpine timberline was preferably recorded on the most convex parts of slopes. It is related to extreme microclimatic conditions on such stands, and so if another stress factor is included (in this case the inputs of immissions during 70's and 80's), then at a given site the forest gradually declines. It was found that in some localities, the observed timberline ascent is connected to the occurrence of debris flow tracks. However the ascending tendency at such sites depends on the concurrence of several environmental conditions. Particularly important factors are medium slope inclination, which limits the intensity of slope processes (snow sliding, avalanches, frequent landslides), the presence of extensive releasing zones of debris flows with sufficient amount of fine grained matter (that means a substratum for tree establishing) and finally moderate slope wash preventing the establishing of closed graminoid communities, which strongly decrease the success of seedling and sapling survival.

The position of the alpine timberline ecotone is influenced by terrain morphology and by the presence of slope processes, nevertheless the alpine timberline position alone can modify the occurrence of such small scale erosion events such as shallow landslides. Their total area sharply increases above the alpine timberline and the highest rates of disturbed patches are found within the zones close to the timberline, within the „kampfzone". The stabilising function of the roots of numerous trees probably causes a slightly lower occurrence of landslides in the nearest zone above the alpine timberline than could be expected with respect to the highest slope inclination found just in this zone. It is hypothesised that, as well as standard factors such as slope inclination, lithology and extent of catchment basin, the uprooting of solitary growing trees above the timberline could also contribute to the triggering of landslides by disturbing the weathering mantle.

Acknowledgments

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Exposure effect on the alpine forest–tundra ecotone: a case study from the High Sudetes, Czech Republic.

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Abstract

Taking the High Sudetes as an example, we verified whether the alpine treeline position is really related to the heat load of the site and whether the temperature of the air and of the soil changes along the transects that ran across the slopes with differing exposure to solar radiation. The highest positions of the alpine treeline in the investigated area were found in places with the potentially most favourable temperature conditions. Nevertheless, the exposure effect on measured temperature of the soils shaded by tree branches during the growing season was insignificant both in closed forest and in the highest locations of the tree groups. By contrast the temperatures of the air near the terminal shoots on the limit of the closed forest were more favourable at south to southwest-facing slopes. However, this difference became less pronounced in the highest parts of the alpine forest-tundra ecotone where the strong circulation of the air impedes the warming up of the near-the-ground layer of the air. In winter, the highest locations of the timberline ecotone were the most extreme in terms of soil temperature, but the growing season began earlier here. The shift of the beginning of the growing season caused by accumulation of the snow at the limit of the closed forest was more noticeable at the south-facing slope of the investigated transect.

Introduction

Altitudinal situation of the alpine treeline (defined according to Körner 1999) is determined mainly by temperature during the growing season (Tranquillini 1979, Körner 1999). Beside the crucial factor of temperature, other environmental features also affect the alpine treeline position, such as the terrain morphology, various types of slope processes, herbivor browsing or the occurrence of fires (Holtmeier 2003). The influence of temperature is more significant than other environmental factors, especially with regard to the maximum treeline positions (Plesník 1971, Malyshev and Nimis 1997). In temperate mountains, mean soil temperatures in the alpine treeline vary between 7 and 8°C in the growing season (Körner and Paulsen 2004). Here, we must consider that it is long-term temperature effect rather than current temperature that influences the real position of the alpine treeline and that the respective ecotone behaves conservatively i.e. reacts to temperature changes with some delay (Slatyer and Noble 1992, Paulsen et al. 2001).

Physiological processes, whose activity is limited by low temperature and which reduce tree growth intensity at the alpine treeline, have not yet been explicitly described. To explain this phenomenon, Körner and Hoch (2006) suggested a hypothesis of an insufficient level of metabolic activity in root meristems at low temperatures. The question remains, however, to what extent the decrease of tree growth at the forest-tundra ecotone reflects the influence of low air temperatures on the meristems in tree tops (Grace 1989, Paulsen and Körner 2001, Körner and Hoch 2006).

In northern temperate mountains with a sufficient amount of precipitation, the dependence on temperature of the alpine treeline implies that the position of the treeline should be different in warmer ("favourable") and colder ("unfavourable") parts of the relief (Aulitzky 1961, Plesnik 1971, Holtmeier 2003). Slopes with favourable aspect (south, southwest) are characterised by higher direct radiation (Geiger et al. 2003) and their growing season is longer because snow melts earlier there. The assumption of a favourable slope aspect implying a higher position of the treeline was not proved on a large sample of treeline positions in the Swiss Alps (Paulsen and Körner 2001). The same authors suggested that air temperatures at tree tops and shaded soil temperatures at the upper limit of closed forest do not differ among various slope aspects.

In the present study we focused on whether in the High Sudetes (part of the Hercynian mountains of Central Europe, Grabherr et al. 2003) the highest positions of the alpine treeline occured in relatively favourable places in terms of potential heat load (sensu McCune &

Dylan 2002). Further, air and soil temperature in sites with favourable and unfavourable slope aspects were measured and the relevant differences were analyzed. A correlation between the measured temperature and tree growth (tree height, terminal increment), and possible limitation of the growth of monitored trees by temperature of the site have been verified.

The initial hypothesis was that in a closed-canopy forest soil temperatures would not substantially vary among localities with different exposure to solar radiation because of canopy shading (Paulsen and Körner 2001). We further suppose that in Norway spruce clonal groups (or solitary trees) above the limit of closed forest the warming up of the surrounding unshaded surface and the margins of the spruce groups will be apparent. If these assumptions were right, highest positions of the closed-canopy forest limits should not preferably occur on slopes with favourable aspect.

Methods

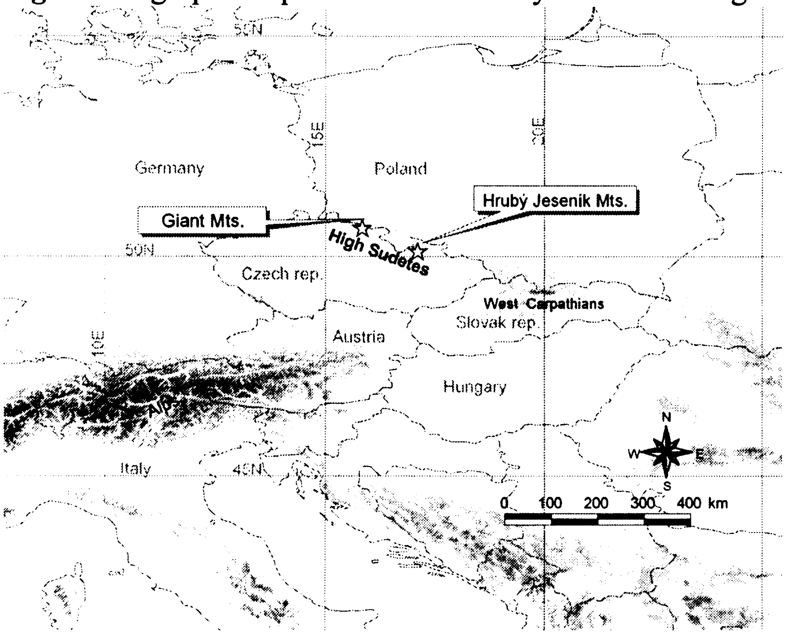
Study area

The highest elevations of the High Sudetes are in fact the only islands of natural alpine forest-free areas between the Scandes on the north and the Alps and West Carpathians on the south (Grabherr et al. 2003, Jeník and Štursa 2003) (Fig. 1). They are old Hercynian mountain ranges, the highest of which are the Giant Mts. (the highest peak Sněžka 1602 m a.s.l.) and the Hrubý Jeseník Mts. (the highest peak Praděd 1492 m a.s.l.). They consist of high-elevated planated surfaces built by granite, gneiss and mica schist.

The study area is characteristic of relatively high precipitation (around 1300 – 1500 mm per year). Average annual temperatures range from 0.1 °C in the highest parts of the Giant Mts. to 1.1 °C in the Hrubý Jeseník Mts. The alpine treeline runs through several tens to several hundreds of meters under the summits. Its position is thus influenced by extreme wind conditions with high precipitation in winter, including frequent rime (Jeník 1961, Migala et al. 2002). The alpine treeline is formed by Norway spruce (*Picea abies* [L.] Karst.). The treeline ecotone grades either into dwarf pine (*Pinus mugo* Turra) growths in the Giant Mts. or into alpine grasslands (Giant Mts. and Hrubý Jeseník Mts.). The actual treeline ecotone is situated approximately at 1230 m a.s.l. on average in the Giant Mts. and at 1310 m a.s.l. in the Hrubý Jeseník Mts. (Treml and Banaš 2000).

The extent of forest-free area has been strongly influenced by man who enlarged it in the past by deforestation, pasture and hay making (Jeník and Lokvenc 1962, Jeník and Hampel 1992). Nevertheless, an extensive part of the alpine forest-tundra ecotone has not been disturbed by man in terms of its current position (but not as regards the structure of the ecotone, Jeník and Hampel 1992, Zientarski 1995, Treml and Banaš 2000 In addition, there has not been any distinctive direct anthropogenic impact on the alpine treeline in the High Sudetes during the last 60 years, since those areas were abandoned after World War II and later strictly protected as nature reserves.

Fig. 1: Geographical position of the study area in the High Sudetes



Analysis of relationships between the alpine treeline position and potential heat load of the respective site

To find out whether the highest positions of the alpine treeline (defined sensu Körner 1999) preferably occur in parts of the relief that are favourable in terms of temperature (favourable slope aspect), a simulated heat load of a site was compared with the altitude of the relevant part of the alpine treeline. At first, the position of closed forest was acquired by supervised classification of contemporary spectrozonal ortorectified aerial images with 0.3 m resolution (Hrubý Jeseník) or panchromatic ortorectified aerial images of the same resolution (the Giant Mts.). To classify an area as a "forest", the minimal tree cover was ≥ 50% in a square of 10 x 10 m. Then the alpine treeline was modelled as a line connecting the highest parts of the forest on slopes sectioned according to their aspect every 5°. The accuracy of the treeline delimitation was verified in the field. Areas where natural factors (avalanches, block fields) or anthropogenic influence (in the surroundings of mountain huts) evidently lowered the treeline were excluded (Fig. 2).

The delimited treeline was divided into 100-meter long sections. Their average altitude and heat load were then determined for each of them. The values were set on the basis of the 20-meter grid terrain model. The grid of potential heat load was calculated as heat load index (McCune and Keon 2002). It means that it is a relative value dependent on the slope orientation, the slope gradient and the mean sun height above the horizon in the growing period (in our case reduced to the May – September period).

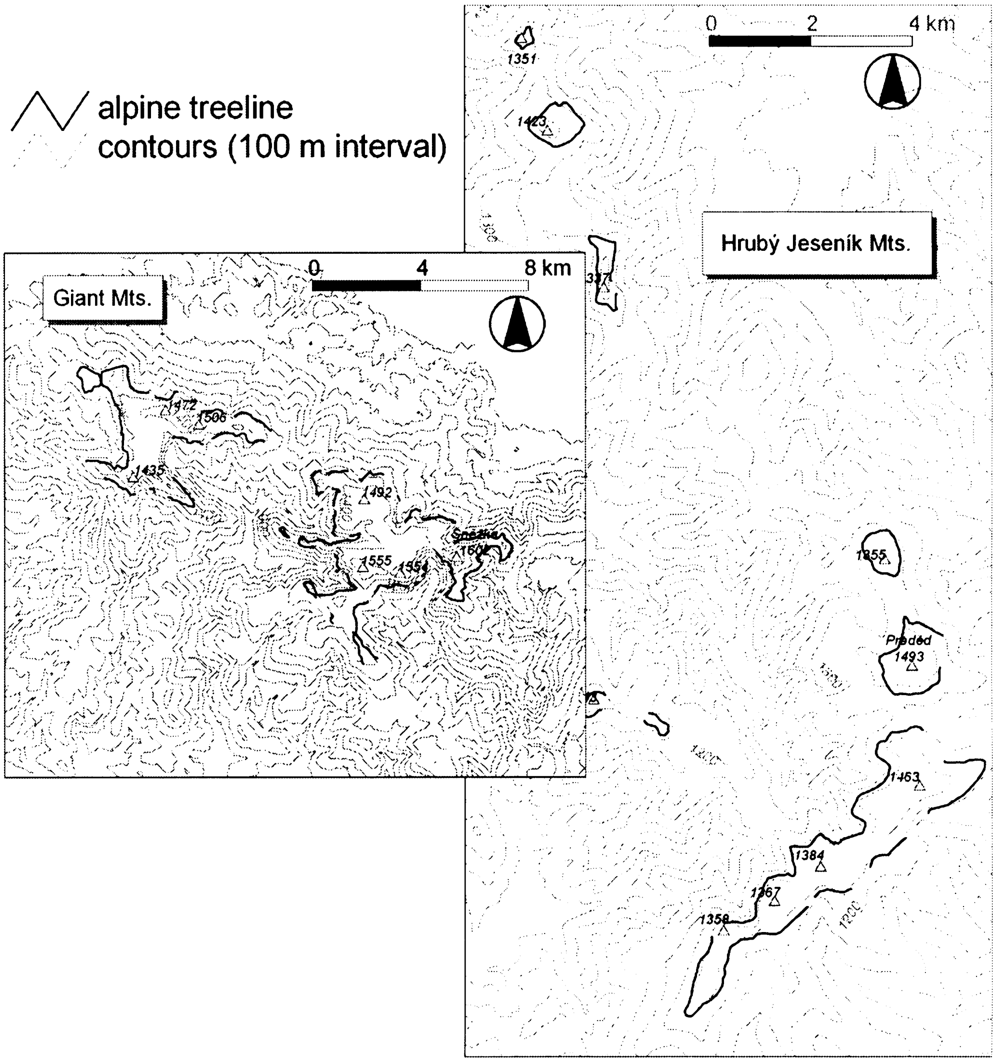


Fig. 2: Analysed part of the alpine treeline. Sections of treeline evidently lowered by anthropogenic or natural factors are excluded.

Temperature characteristics of the alpine forest-tundra ecotone

Two vertical transects across natural alpine forest-tundra ecotone were chosen in the area of Praděd–Vysoká Hole (Hrubý Jeseník Mts.), where the soil temperature and air temperature at tree tops of selected Norway spruces were measured on slopes with favourable (S–SW) and unfavourable (N–NW) orientation. Measurements were carried out in three locations with regard to the alpine forest-tundra ecotone (Fig. 3): (1) on the upper limit of solitary trees/groups occurrence of a minimum height of 2 m, (2) in clonal spruce groups on the upper limit of trees higher than 5 m (i.e. tree limit defined by Jeník and Lokvenc 1962), and (3) on the limit of the closed forest (Tab. 1). To compare temperatures of soil not shaded by trees, *Calmagrostis villosa* dominated stands were chosen, which were situated in an open space of alpine forest-free area close to groups of 5-meter high spruces (positions 0A and 0B, Tab. 1). Measurements were also carried out in seven localities in the eastern part of the Giant Mts. (Fig. 3).

Temperature sensors with accuracy of ±0.2 °C connected to dataloggers EMS MINIKIN (produced by Environmental Measurement Systems, INC.) were used for measuring. Soil temperatures were measured 10 cm deep under the surface, i.e. approximately at the root growth zone (Holtmeier 2003, Körner and Paulsen 2004, Maděra 2004).

Sensors were calibrated by measurement of temperature in water chilled with ice (0°C) to verify the accuracy of measuring. Their accuracy varied within the range of 0 – 0.1 °C. The sensors were placed under an equally thick layer of plant litter and in the same soil horizon (Ah). Localities showed similar moisture conditions. They were situated in sloping, but not concave or convex parts of the surface. The described soil temperature measurement design enabled counting with the same depth-temperature gradient in all monitored areas. Sensors were installed where the surfaces were shaded by branches all the day. In two locations (measurement points J5 and J9, Tab. 1), testing measurements of soil temperatures at two neighbouring spruce groups were carried out. Differences in average temperatures were 0.1 and 0.15 °C. They may have been caused by badly located sensors, or different characteristics of soil.

To measure air temperature hanging sensors EMS MINIKIN with a radiation shield were used. The sensors were always placed on the northern side of a trunk, close under the tree top. Only those spruces were chosen, whose top was not damaged by mechanical breakage. Also stem surface temperature was measured by external sensor placed on the northern side of terminal shoot in measurement points J1 to J8 (Tab. 1).

Temperatures were measured and stored in 1 hour interval. Temperature characteristics for the representative part of the growing season were obtained from the acquired data – average temperatures from the monitored period, average day temperatures ($\Sigma T_{0\text{-}23}/24$) and average minimum temperatures. The length of measured temperature series was different for technical reasons, and therefore only periods measured simultaneously were compared (for the Hrubý Jeseník Mts. June 2 to October 16 of 2006, for the Giant Mts. and the Hrubý Jeseník Mts. together July 24 to October 9 of 2006).

For each measurement point actually measured its potential heat load was analysed (see above) for the surrounding area of 10 m radius. The height of the respective tree and its average terminal increment were measured, the latter according to the number of internodes in the last 10 years.

Tab. 1: Characteristics of the measurement points in the alpine forest-tundra ecotones in the High Sudetes (see also Fig. 3).

Position with regard to treeline	Site code (Fig. 3)	Site characteristics	Elevation (m a.s.l.)	Slope aspect	Slope inclination	Subject of temperature measurement	Period of measurement
1A	J1	highest positioned spruce groups > 2m	1468	SW	10	soil, air, terminal shoot	Sept. 9, 2005–Oct. 10, 2006
2A	J2	tree groups with trees > 5m	1443	SW	11	soil, air, terminal shoot	Sept. 9, 2005–Oct. 10, 2006
0A	J3	treeless area within the zone of tree groups > 5m	1443	SW	11	soil	Sept. 9, 2005–Oct. 10, 2006
3A	J4	trees below the closed-forest limit	1411	SW	12	soil, air, terminal shoot	Sept. 9, 2005–Oct. 10, 2006
1A	J5	highest positioned spruce groups > 2m	1429	NE	13	soil, air, terminal shoot	Sept. 9, 2005–Oct. 10, 2006
2A	J6	tree groups with trees > 5m	1390	NE	14	soil, air, terminal shoot	Sept. 9, 2005–Oct. 10, 2006*
0A	J7	treeless area within the zone of tree groups > 5m	1390	NE	14	soil	Sept. 9, 2005–Oct. 10, 2006
3A	J8	trees below the closed-forest limit	1361	NE	17	soil, air, terminal shoot	Sept. 9, 2005–Oct. 10, 2006
1B	J9	highest positioned spruce groups > 2m	1436	SW	10	soil, air	June 2,.2006–Oct. 10, 2006
2B	J10	tree groups with trees > 5m	1400	SW	15	soil, air	June 2,.2006–Oct. 10, 2006
3B	J11	trees below the closed-forest limit	1348	SW	19	soil, air	June 2,.2006–Oct. 10, 2006
0B	J12	treeless area within the zone of tree groups > 5m	1399	SW	15	soil	June 2,.2006–Oct. 10, 2006
1B	J13	highest positioned spruce groups > 2m	1424	NE	12	soil, air	June 2,.2006–Oct. 10, 2006
2B	J14	tree groups with trees > 5m	1391	NE	12	soil, air	June 2,.2006–Oct. 10, 2006
3B	J15	trees below the closed-forest limit	1355	NE	14	soil, air	June 2,.2006–Oct. 10, 2006
0B	J16	treeless area within the zone of tree groups > 5m	1391	NE	12	soil	June 2,.2006–Oct. 10, 2006
	J17	solitary spruce > 2m	1462	flat	2	soil	June 2,.2006–Oct. 10, 2006
	K1	trees below the closed-forest limit	1341	SE	34	soil	May 18, 2006–Oct. 9, 2006
KA1	K2	trees below the closed-forest limit	1300	N	31	soil, air	May 18, 2006–Oct. 9, 2006
	K3	trees below the closed-forest limit	1304	S	28	soil, air	May 18, 2006 – Oct. 9, 2006
KA2	K4	highest positioned spruce groups > 2m	1491	S	11	soil	July 24,.2006–Oct. 9, 2006
	K5	highest positioned spruce groups > 2m	1477	N	16	soil	July 24,.2006–Oct. 9, 2006
KA3	K6	trees below the closed-forest limit	1218	N	32	soil	June 8, .2006–Oct. 9, 2006
	K7	trees below the closed-forest limit	1229	S	32	soil	June 8, .2006–Oct. 9, 2006

* … soil temperature measurement started on September 1, 2004.

Subsequently, the relationship between measured air and soil temperatures and the potential heat load of the site were assessed. To remove the influence of different elevation, all temperature values were modified to the altitude of 1000 m a.s.l. with the use of vertical temperature lapse of 0.73°C/100 m for average air temperatures in the growing season and 0.36 °C for minimum temperatures in growing season. Lapse values were calculated from the data measured in Velká Kotlina (1175 m a.s.l.) and in Praděd (1493 m a.s.l.) (Lednický et al. 1973), which are very close to the studied transects in the Hrubý Jeseník Mts.

Fig. 3: The location of individual sites with temperature dataloggers; see also Tab.1.

The temperature lapse was applied to soil temperatures, although it was supposed to reach higher values than the air temperature lapse (Green and Harding 1980, Geiger et al. 2003). Unfortunately, the values of local soil temperature lapse were not known.

A linear relationship between the measured temperature characteristics and tree height (or current terminal increment of the shoot) was sought for in order to explain the determining factor influencing the decrease of tree height with rising altitude.

Results

The relationship between the position of the alpine treeline and the heat load

In the monitored sample of the alpine treeline sections, only slight linear relationship can be found obtaining between the height of the treeline and a potential heat load of a site (the Giant Mts: r=0.29, p< 0.01; Hrubý Jeseník, r=0.20, p< 0.01). However, if we consider the distribution of potential heat load values in four statistical quartiles of the treeline altitudes, some regular patterns may be found in the distribution of data in both mountain ranges (Figs. 4 and 5).

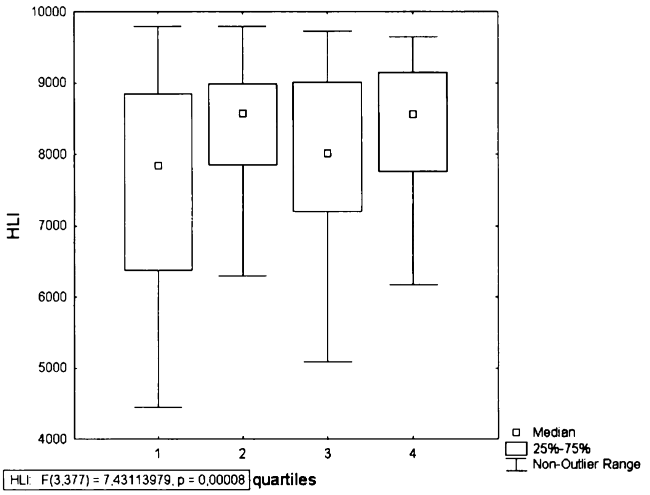


Fig. 4: Distribution of potential heat load values (HLI) in altitudinal quartiles of sections of the alpine treeline (1 – lowest sections … 4 – highest sections) in the Hrubý Jeseník Mts.

The highest sections of the alpine treeline are more likely situated in favourable parts of slopes in terms of temperature. The differences of the potential heat load of treeline sections in individual quartiles (ANOVA statistic) are significant both in case of the Giant Mts. (F=19.8, p<0.05) and the Hrubý Jeseník Mts. (F=9.5, p<0.05).

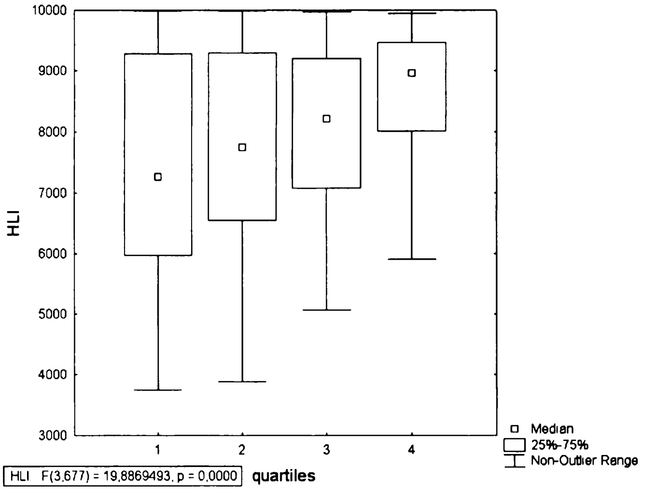


Fig. 5: Distribution of potential heat load values (HLI) in altitudinal quartiles of sections of the alpine treeline (1 – lowest sections … 4 – highest sections) in the Giant Mts.

The relationship of the measured temperature values with the potential heat load and site position in the ecotone

Temperature characteristics measured in the Hrubý Jeseník Mts. show that a generally more rapid soil temperature decrease is apparent in transects leading from forest to the highest outposts of spruce clonal groups, in comparison with the air temperature decrease at tree tops (Fig. 6). As far as soil temperatures in closed forest are concerned, we may detect very similar temperatures both at the favourable and unfavourable slope aspect. Higher in transects, the values of soil temperatures differ more significantly in both slope orientations. However, higher temperature values in given transect position are reached both in the favourable and in the unfavourable slope orientation. It is supposed, that local microclimatic conditions may act here.

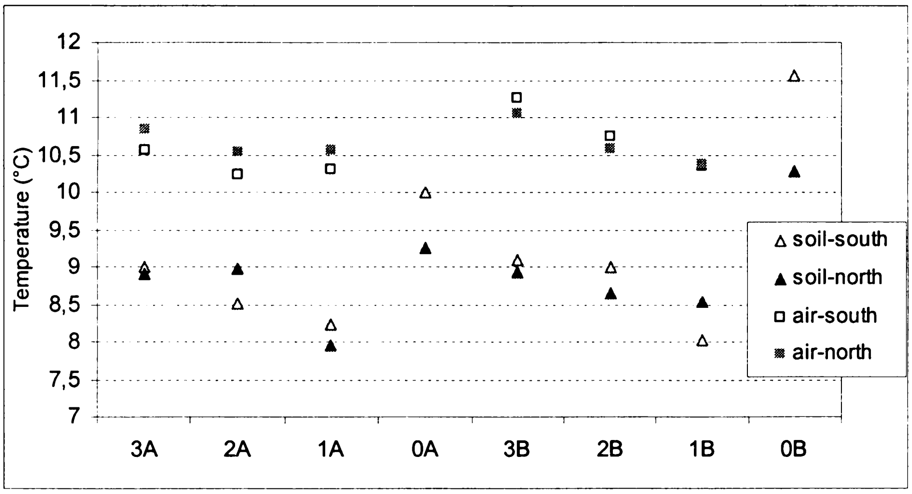


Fig. 6: Average soil and air temperatures in the period of June 2–October 16, 2006, the Hrubý Jeseník Mts.; for abbreviations of transect positions see Tab. 1.

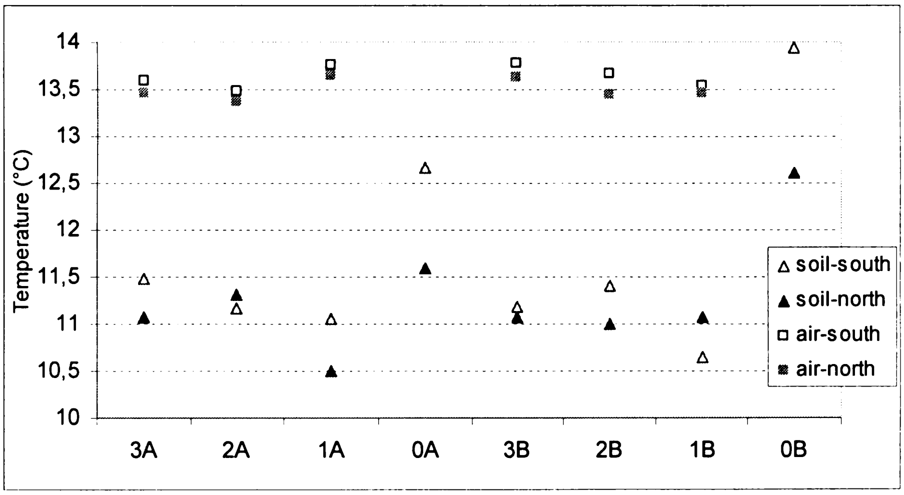


Fig. 7: Average soil and air temperatures in the period of June 2–October 16, 2006, modified to the altitudinal level of 1000 m a.s.l., the Hrubý Jeseník Mts.; for abbreviations of transect positions see Tab. 1.

When eliminating the elevation bias (Fig. 7), air temperatures at tree tops become practically identical in all positions. A slight difference in the "B" transect (in positions 3B and 2B) is caused by markedly steeper southern slope in comparison with the "A" transect (position 3A–1A). Thus, the radiation heating of the surface may be more intensive and heated atmosphere layer may be thicker above the surface. At the highest point of the transect (1B), where stronger air flow may be expected, this difference was not noticed.

Unless the elevation bias is eliminated, soil temperatures display smaller differences on slopes of opposite orientation. As was presupposed, soil temperature conditions are more favourable in free, unshaded areas (positions 0A and 0B, Fig. 6) and these places show also significantly higher differences between favourable and unfavourable slope aspect in comparison with shaded areas.

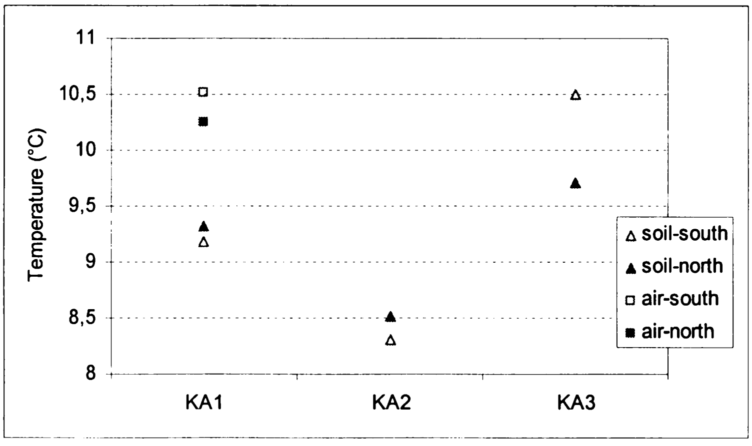


Fig. 8: Mean soil and air temperatures in the period of July 24–October 9, 2006, the Giant Mts.; for abbreviations of transect positions see Tab. 1.

In the KA1 and KA2 localities situated in the Giant Mts. (Fig. 8 and 9), no significant differences in soil temperatures were recorded between favourable and unfavourable slope aspect. In contrast, in the KA3 locality, which represents a closed-forest limit lowered by avalanches and block fields, the southern slope was warmer by about 0.7 °C on average. A substantial difference (higher than potential measurement error) was also recorded in air temperatures at treetops (position KA1). It may relate to a very steeping slope in that locality.

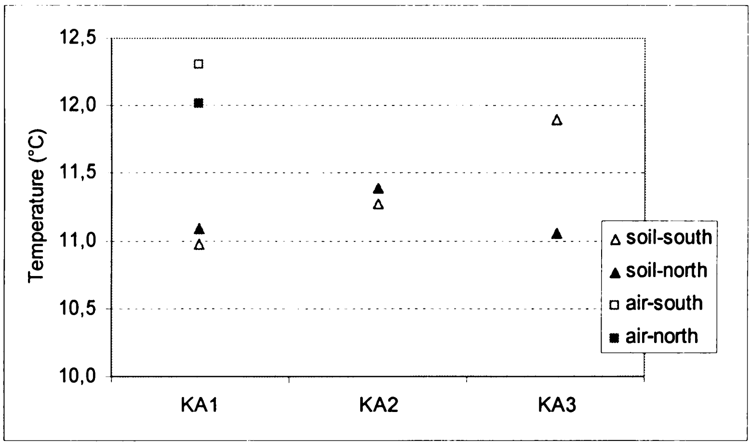
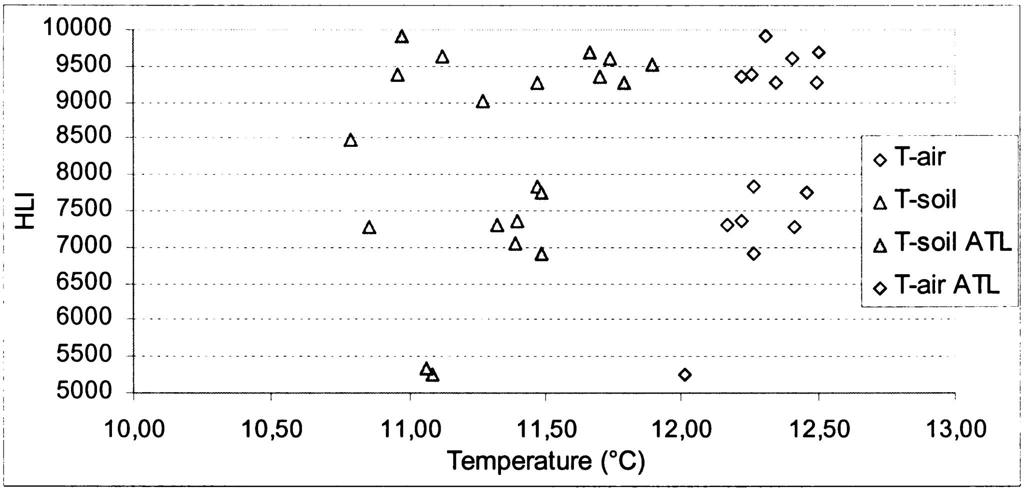


Fig. 9: Mean soil and air temperatures in the period of July 24–October 9, 2006, modified to the altitude of 1000 m a.s.l., the Giant Mts.; for abbreviations of transect positions see Tab. 1.

Comparison of the distribution of soil and air temperatures (after eliminating the elevation bias) with relevant values of a potential heat load shows that air temperature span is markedly narrower in comparison with soil temperatures (Fig. 10). Under similar conditions of the potential surface heating, in fact, temperatures of soil shaded by spruce branches differ more than the air temperatures at tree tops. Differences between favourable and unfavourable slope orientation are minimal within soil temperatures. As regards air temperatures, a moderate correlation with potential heat load of the site may be noticed ($r= 0.59$, $p<0.05$).

Fig. 10: Mean soil and air temperature modified by altitudinal lapse to 1000 m a.s.l. in relationship to the potential heat load (HLI), summarized for the Giant Mts. and Hrubý Jeseník Mts.; values marked ATL refer to the closed forest limit.



The relation of measured temperature and growth characteristics of trees

The height of sample trees used for temperature measurements correlates with both the soil temperature ($r=0.93$, $p<0.01$) and air temperature at tree tops ($r=0.80$, $p<0.01$) (Fig. 11). The length of terminal increments then correlates just with soil temperature ($r=0.49$, $p<0.05$). The correlation with air temperatures was not significant at the 0.05 probability level (Fig. 12).

Fig. 11: The relationship of mean soil and air temperature with tree height.

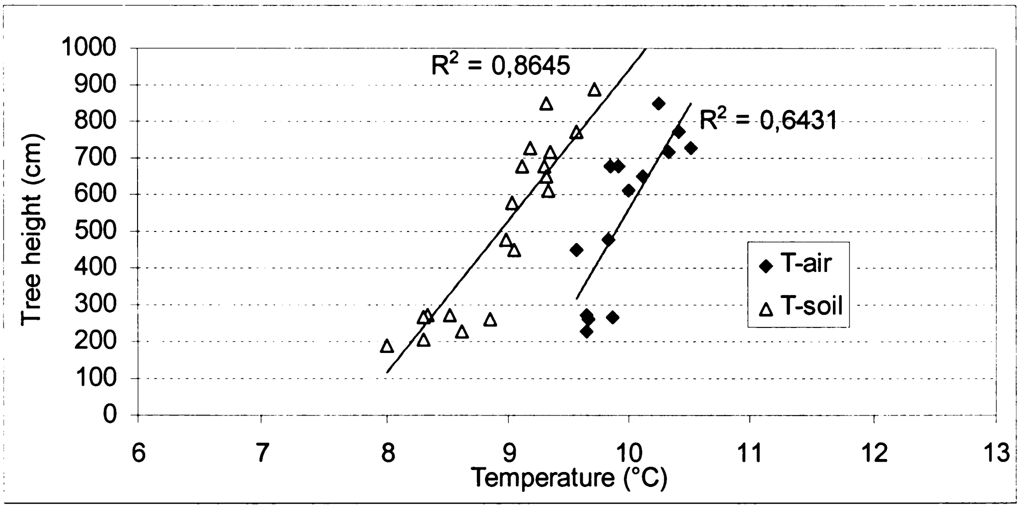
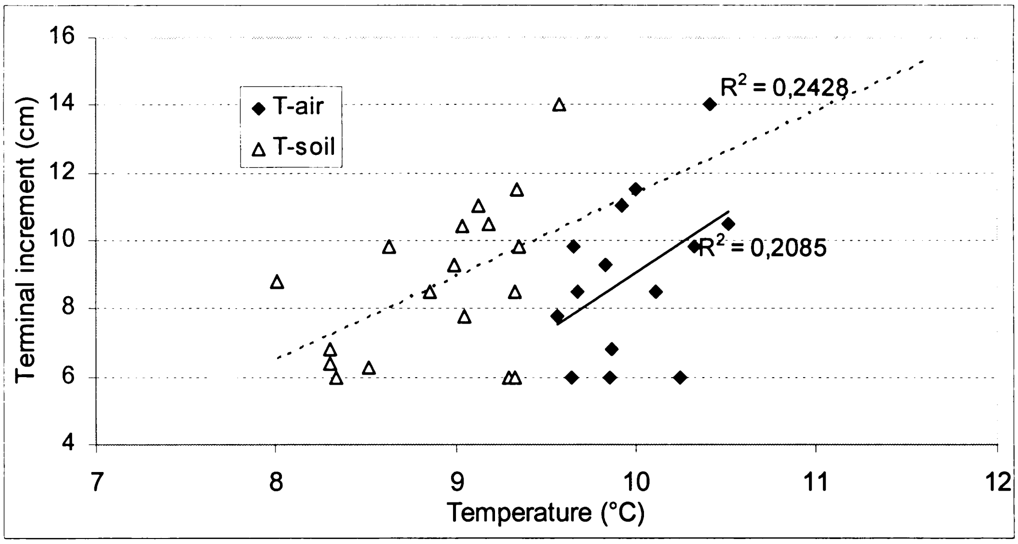


Fig. 12: The relationship of mean soil and air temperatures with the length of terminal internodes (increment).



No difference in the relationship between growth characteristics of a tree and mean minimum or mean diurnal temperatures of air and soil actually was not recorded (Tab. 2). Mean minimum and mean diurnal soil and air temperatures correlated very well, so the result with regard to tree growth cannot be different (soil – r= 0.99, air – r=0.94).

Tab. 2: Values of Pearson correlation coefficient for the relationship of mean diurnal and minimum temperatures with growth characteristics of spruce.

	Tree height	Terminal increment
T soil	0.93** (N=20)	0.49* (N=18)
T air	0.80** (N=14)	0.45 non-significant (N=14)
T soil min	0.93** (N=20)	0.51* (N=18)
T air min	0.79** (N=14)	0.52 non-significant (N=14)

** … significant correlation, probability level p=0.01
* … significant correlation, probability level p=0.05

Temperature during the cold part of the year

Temperature of soils throughout the dormancy period ran differently on slopes with favourable and unfavourable aspect. While on the north-facing slope mean soil temperatures were decreasing with altitude, on the south-western slope they were higher above the timberline than they were bellow the forest limit. The highest positions of the ecotone were the most extreme in terms of a low number of days of the growing season and a high number of days with frozen soil. In this sense, ecotone positions on the closed-forest limit and in tree groups higher than 5m were comparable (Fig. 13). Measured soil temperatures showed that in positions at the closed forest limit, the growing season started later than in the tree groups (Tab. 3). This was caused by long-lasting snow pack, which accumulated here in winter (due to decreased wind speed). Moreover, in closed forest the snow cover was shaded while melting. Differences in the beginning of the growing season between forested and forest-free areas were rather remarkable on the south-western slope.

Throughout the greater part of the winter season in 2005/2006, spruce tree tops were covered with snow and rime, which did not melt until the middle of March. The soil reached temperatures bellow or slightly above zero in the measured depth until the beginning of May. Thus in the period between middle of March and the beginning of May assimilating organs in tree tops may have been susceptible to frost desiccation. The air and stem temperature data showed that there was no clear-cut dependence of the susceptibility to frost desiccation along the increasing altitude. Higher potential for frost desiccation however was found on the southwest-facing slope (Fig. 14).

Tab. 3: Date of the beginning of the 2006 growing season (period with soil temperatures >3.2°C sensu Körner 1999) in individual sites of alpine forest-tundra ecotone (1... the highest, 3 ... the lowest positions in the ecotone) on the north-facing (N) and southwest-facing (S) slope, Hrubý Jeseník Mts.

Position	**1N**	**2N**	**3N**	**1S**	**2S**	**3S**
The beginning of the growing season	13.5.	9.5.	17.5.	16.5.	16.5.	19.5.

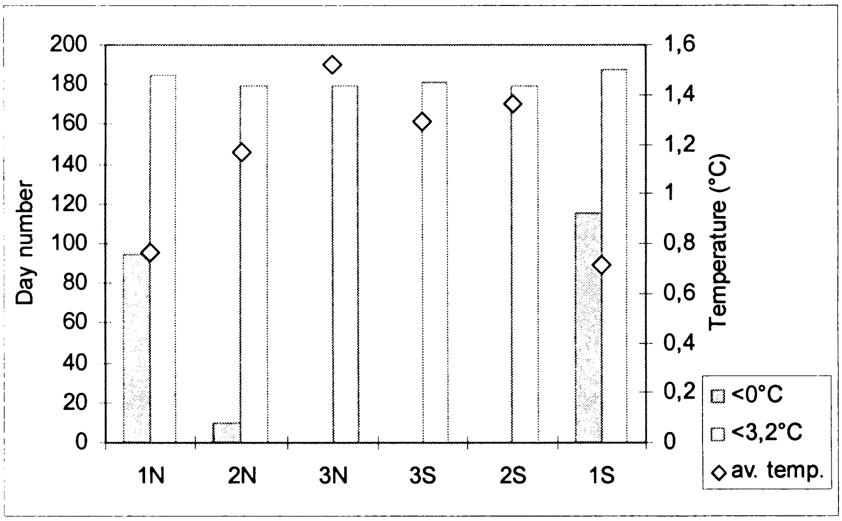
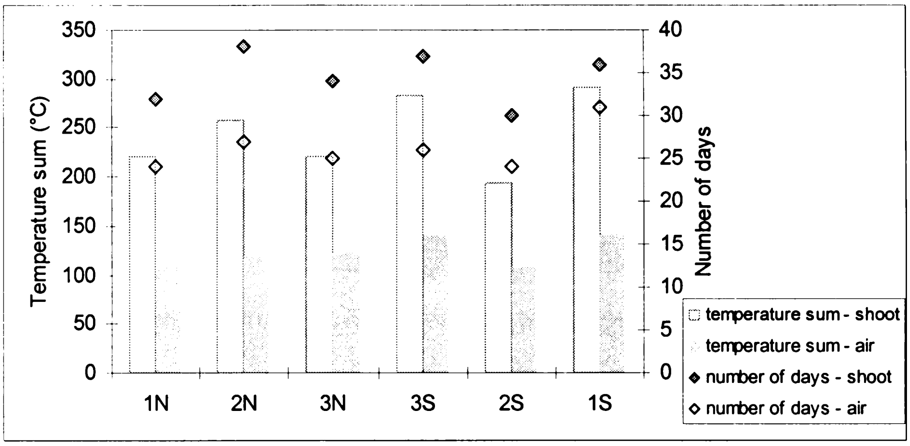


Fig. 13: Number of days with average soil temperature lower than 3.2°C and average temperature in the growing season along the alpine forest-tundra ecotone (1 ... the highest, 3 ... the lowest positions in the ecotone) on the north-facing (N) and southwest-facing (S) slope, Hrubý Jeseník Mts., period from October 13, 2005 to May 11, 2006.

Fig. 14: Number of days with maximum air temperature, or stem temperature at treetops higher than 5°C, and temperature sums of these days along the alpine forest-tundra ecotone (1 … the highest, 3 … the lowest positions in the ecotone) on the north-facing (N) and southwest-facing (S) slope, period March 3 – April 25, 2006.



Discussion

The location of the highest positions of the alpine treeline

Only a slight dependence on the potential heat load was identified for the alpine treeline in the High Sudetes. In other words, higher positions of the alpine treeline do not necessarily have to be situated in sites potentially more heat-favourable than the lower positions of the alpine treeline. This corresponds to the findings obtained in the Central Alps (Paulsen and Körner 2001). The very highest positions of the alpine treeline were however located preferably on southwest-facing slopes in the both ranges studied in the High Sudetes. This finding shows that favourable slope aspect of a locality may shift the forest limit upwards.

The radiation heating of the surface has a positive impact, especially on low-stature vegetation (Körner 1999) including the conifer seedlings, unless it is accompanied by extreme desiccation of the surface or radiation cooling at night (Germino et al. 2002). Because surfaces oriented towards the south quadrant are heated more, easier survival of seedlings in those areas (with enough precipitation preventing drying up of soil) can be assumed. This also implies a faster upward shift of the forest on favourable slope aspects as a consequence of the general temperature increase or due to an increased invasibility of spruce into the alpine grasslands caused by the earlier disturbances (Prach et al. 1996, Dullinger et al. 2003, Treml 2007). Stands originated in this way may then form maximal treeline positions. On the other hand, it is not sure to what extent human long-term influence (lasting at least since the 15-16th century, Lokvenc 1995, Jeník and Hampel 1992) results in the ascertained distribution of the alpine treeline sections within the elevational intervals. Even though during the last 60 years human intervention in the alpine treeline has not been substantial.

In the High Sudetes, the fact that the uppermost positions of the alpine treeline are reached on southwestern slopes of the highest peaks (Sněžka, Praděd, see Treml and Banaš 2000) may also be important. This can correspond to temperature conditions of slopes. On the hill sides of these highest summits, the alpine treeline runs rather in the middle parts of the slopes, which are more favourable in terms of temperature than the upper margins (Aulitzky 1967, Obrebska-Starkel 1984). In the case of maximum treeline position in the Giant Mts., situated on the leeward side of the anemo-orographic system, also mesoclimatic specificity of the locality may play a part (Jeník and Lokvenc 1962).

Measured temperature in the sites with different heat load

The above given fact that no remarkable difference in distribution of the elevation limits of the alpine treeline in favourable and unfavourable slope aspect was found may be explained by similar temperature in a closed forest where insolation induced favourability does not matter. This has been suggested by Paulsen and Körner (2001). Under closed-canopy forest only low soil temperature differences were found in opposite slope aspects. KA3 position was an exception (Důl Bílého Labe valley in the Giant Mts.), where the difference between favourable and unfavourable slope orientation was almost 0.75°C. We attribute this to the timberline character, which consists of narrow protruding belts of trees among avalanche tracks, debris flows and block fields in this locality. Trees often do not branch in the lower part of trunk, so direct solar radiation can penetrate into the stands (the place of measurement however was shaded by branches). This can contribute to a generally warmer microclimate of the inner space of the forest on southern slope.

Higher in tree groups then, local microclimatic differences exerted a more significant influence. The microclimate was not unified by closed-canopy forest stand. Therefore, there was a greater variety in temperatures among sites with favourable and unfavourable slope aspect. This was true of both directions (both higher and lower temperatures in S-SW-facing slopes in contrast with N-NE-facing slopes). Thus, neither here was possible to prove the difference between favourable and unfavourable orientation of slope. This finding is fairly surprising, as it was estimated that closed canopy forest has greater influence on soil cooling than tree groups (Körner 1999), which are heated by the surrounding surface (Holtmeier and Broll 1992). Soil of treeless sites is much warmer on slopes of the south-facing quadrant, which was shown in comparative measurement of unshaded sites (0A and 0B, Figs. 6 and 7).

Lower span of soil temperature values in spruce groups in opposite slope orientations was evident within data unmodified in order to eliminate elevation bias. This may be explained by the fact that temperature sensors were placed in corresponding parts of the transects in terms of tree physiognomy (i.e. approximately the same height) and thus also at places with similar temperature characteristics.

Air temperatures at the Norway spruce tree tops in most cases did not differ in favourable and unfavourable positions, both in closed forest and tree groups above the forest limit. In J2B, J3B and K1 measurement points, however, there was a difference in air temperature in modified data with eliminated elevation bias. Temperatures in favourable slope aspect were higher by 0.1 – 0.3 °C. We assume it was because of steeper slope on the south-facing side in those positions, where radiation heating of surface was greater. In the highest part of the "B" transect (position 1B) in the Hrubý Jeseník Mts. (Figs. 6 and 7), air temperatures are virtually identical. This can be ascribed to an intensive exchange of air masses – the above-mentioned heating of near-surface air layer thus cannot really proceed there.

No relationship was found between directly measured soil temperature in the alpine forest-tundra ecotone and a simulated potential heat load. The relevance of the question as to whether a slope was favourable or unfavourable in terms of direct solar radiation was denied by the soil being shaded by spruce branches. Air temperatures (after elimination of elevation bias) extended on relatively narrow interval compared to soil temperatures. At the same time they correlated with potential heat load of the site. This confirms the suggestion that air temperatures at tree tops are more coupled to free atmosphere temperature (Paulsen and Körner 2001); they are less influenced by local topographic or vegetation irregularities. On favourably exposed, especially steeper slopes, there was a greater heating of active surface (in a meteorological sense, Geiger et al. 2003), which also influenced temperature at spruce tree tops. This influence was completely absent in summit regions with stronger air flow. While heating of middle parts of slopes is a typical phenomenon of deeply cut valleys (see e.g. Aulitzky 1967) and also played an important part with the above-mentioned steeper slopes, the prevailing strong winds (Jeník 1961) and frequent fogs (Blas and Sobik 2000) in the summit areas generally exert their influence in the alpine forest-tundra ecotone in the High Sudetes, limiting the atmosphere heating near the surface layer. This is because the alpine treeline runs relatively close under exposed summit plateaus.

We can arrive at another modification of the relationship of air temperatures at tree tops and the heat load of a site, if we remove data concerning the closed forest. Then we can notice a very even distribution of air temperature values without any relationship to the potential heat load of the site (Fig. 10). It means that above the closed-forest limit, tree tops in tree groups more or less did not profit from higher radiation heating of the surface in favourable slope aspects, which is in accordance with what Körner (1999) suggested. On the closed-forest limit, heating of active surface apparently occured – the air in favourable slope aspects could be heated from the tree tops of closed tree growths (external active surface layer according to Geiger et al. 2003).

That soil temperatures did not correlate with a potential heat load induces the assumption that – in terms of soil temperature – there is virtually no difference whether soil is shaded by just a small group of trees or a forest stand. Soil cooling occurs in closed canopy forest as well as under spruce groups. Forest splitting into tree groups thus may not be explained simply by an "effort" to improve soil temperature conditions, even if a part of root system may extend over the margins of tree groups (Holtmeier 2003, Maděra 2004). A more probable explanation of this phenomenon may be the hypothesis that tree groups above the closed-forest limit are remnants of the former or they may be consequences of current favourable climatic oscillations, which enabled trees to establish themselves above the timberline (Slatyer and Noble 1992).

When interpreting the results, it must be noted that the growing season in 2006 was considerably warmer than long-term average in the the Hrubý Jeseník Mts. In a mountain weather station nearest to the Hrubý Jeseník Mts. (Lysá hora 1321 m a.s.l.), the mean air temperature from May to October 2006 was higher by 1.9 °C than the mean from the period 1961-1990 (May-October 2006 – 10.4°C /Czech Hydrometeorological Institute – oral communication/, May-October standard 1960-1990 – 8.5°C /Coufal et al. 1992/). In the Giant Mts. it was similar. Soil temperatures were higher by about 0.8°C in the growing season 2006 than in 2005, which was a temperature average year (J6 site – 7.5°C in 2005, 8.3°C in 2006). In the monitored period, however, there were both, radiative (most part of July and September) and cloudy weather rich in precipitation (August). Therefore we suppose that the recorded differences among individual sites do not differ from periods with normal meteorological characteristics.

Soil and air temperatures in relation to growth characteristics of spruce

Measured soil and air temperatures correlated well with tree height; however the relationship of soil temperatures and tree height was closer. This supports the above-mentioned assumption that the physiognomy of stands in monitored localities directly corresponded to their temperature characteristics. At the same time, we may take into consideration the more significant effect of temperature in the root zone on tree growth (Scott et al. 1987, Körner and Hoch 2006) in comparison with the influence of air temperature at tree tops (James et al. 1994). Also the recorded relationship of soil temperatures and terminal increment corresponds to this. The variability of terminal increments is high in these conditions though and it is despite the fact that it was always dominant individuals that were being chosen for measuring temperatures. The age of trees varied between 60 to 110 years, i.e. also the influence of age on terminal increment could have caused a certain bias in analysed data.

The above-mentioned relationships are based on the comparison of growth characteristics of trees with temperature means. Their use itself does not have any physiological basis (Hotmeier 2003); however, they are used for practical reasons. The arguments for its use are above all unclearly defined parameter borderlines which do have direct physiological explanation. Such parameters are either based on minimum temperatures or minimum sums of temperatures above certain critical value enabling the growth of meristems in roots or stems (Tranquillini 1979, Grace 1989). Nevertheless, mean temperatures must correlate with these characteristics.

Temperature characteristics of the cold part of the year

Not only temperatures in the growing season but also winter conditions may considerably influence the position and dynamics of the alpine forest-tundra ecotone (Meshinev et al. 2000, Kullman 2007). Concerning the measured temperature data, there were no marked differences between favourable and unfavourable slope aspects in terms of a potential for frost desiccation (i.e. high temperatures of air and/or stem in the period with frozen soil). This contradicts the data presented on a large sample analyzed by Cairns (2001). It may be due to a relatively low inclination of both analyzed slopes, causing smaller differences in insolation of spruce tree tops. A more significant differentiation was found with soil temperatures at the closed-forest limit and in the above-situated tree groups. The growing season began notably later at the closed-forest limit than in higher-positioned tree groups. In contrast, the highest positions of tree groups displayed much more extreme course of winter soil temperatures. They were much lower here than in the middle part of ecotone (tree groups with tree height ≥ 5m) or in the stand at the limit of closed forest. At the same time the period of frozen soil was considerably longer in uppermost Norway spruce groups compared to lower positions. It is mainly connected with snow distribution; snow accumulates right on the closed-forest limit (Štursa et al. 1973, Körner 1999, Holtmeier 2003). In contrast, the margins of summit plateaus are wind swept, and thus deeper freezing of soil is facilitated (Harčarik 2002). Earlier snow melting was rather prominent in tree groups above the closed forest limit on south-facing slopes, which was also reflected in higher soil temperatures in this part of the ecotone.

Conclusions

In the High Sudetes, the highest positions of the alpine treeline lie in slopes with favourable exposure to solar radiation, but in general, the position of the alpine treeline correlates only slightly with the potential heat load of the site. We suppose that the highest outposts of the alpine treeline in the studied area are also influenced by the fact that they run through more heat-favourable middle parts of slopes (Aulitzky 1967). As soon as forest or tree groups are established in such places, differences in soil temperatures in the root zone between favourable and unfavourable slope aspects are negligible. However, as regards air temperatures at tree tops, there was a certain difference between opposite aspects on steep slopes with a great difference of heat load. By contrast, in sites situated in summit locations such difference was not apparent any more. This may be explained by stronger air flow and by consequent attenuation of the heated near-the-ground air layer. Slopes of favourable and unfavourable exposure to solar radiation also displayed a different pattern of the beginning of growing season. The shift of its beginning between the closed forest and above-lying tree groups was more significant on south-facing slopes.

Soil temperatures correlated better with tree height than air temperatures at tree tops did. This finding may be another contribution to the discussion on the decisive influence of temperatures at the tree tops or in root zone on the decrease of tree growth (James et al. 1994, Körner and Hoch 2006). Soil temperatures even correlated with terminal increment. Nevertheless, the variability of monitored increments was high, and therefore this finding cannot be considered fully reliable.

In the studied area soil temperatures and thus the tree growth potential, both under clonal tree groups and at the limit of closed forest, do not differ on slopes with favourable and unfavourable slope aspect. This also applies to air temperatures at tree tops in the uppermost positions of tree groups, where a strong air flow eliminates temperature differences. However, the authors are aware of the fact that their findings result from relatively short-term measurements and specific conditions of old middle-mountains where the alpine treeline runs close to summit planated surfaces on relatively gentle slopes.

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Recent dynamics of the alpine timberline in the High Sudetes, Czech Republic.

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Abstract

The study examines the spatial shifts of alpine forest-tundra ecotone over the last ca. 65 years (the Giant Mts.), resp. 50 years (the Hrubý Jeseník Mts.) by means of a comparison of aerial photographs. Additionally, tree-ring series taken from sample plots at the timberline have been analysed. In both mountain ranges, there was an initial increase in the altitude of the alpine timberline position, which had occurred by the 1960s (the Giant Mts.), resp. 1970s (the Hrubý Jeseník Mts.). In the next period, until 2003, the average altitude of the alpine timberline decreased again to approximately the same level it had had at the beginning of the period under study. The advance and retreat of the alpine timberline coincided with the growth of trees. While in the fifties and sixties there was a period of above-average radial increments, in the seventies and eighties the tree-ring widths decreased. The initial upward shift of the timberline took place mainly from its lower locations. The subsequent decrease, on the other hand, concerned the highest stands of the alpine timberline. The typical feature of the timberline dynamics in the Giant Mts. was the fact that it oscillated in those places with the highest slope gradient. In the Hrubý Jeseník Mts., on the other hand, it ascended in locations with greater dwarf pine cover. An important part in the pattern of the timberline oscillations in the High Sudetes is played by local disturbances of vegetation cover, which facilitated the altitudinal increase of the alpine timberline.

Introduction

The alpine timberline (i.e. upper limit of closed forest according to Körner 1999) is one of the most important vegetation boundaries in mountain relief (Troll 1973, Holtmeier 2003). Its location is mainly driven by temperatures during the growing season (Körner 1999). Its position can be significantly influenced by other factors, too (Plesník 1971, Holtmeier 2003). They include, for example, an intense wind pressure, local irregularities in the distribution of snow cover (Holtmeier 1974, Kajimoto et al. 2002, Mellman-Brown 2005) and even avalanche activity (Jeník and Lokvenc 1962). The relief (block field, steep rock walls) can significantly lower the position of the timberline, too (Plesník 1971, Autio and Colpaert 2005).

Over the last two decades, there has been an increase in the average annual temperature in a major part of the temperate and polar areas of the Northern Hemisphere (Houghton et al. 2001), which typically manifests itself by an increase of temperatures in the vegetation season as well. Thus, it can be assumed that such a trend should be reflected in the position of the alpine timberline and in the growth dynamics of trees along the timberline ecotone, too. Particular current upward shifts of the alpine timberline or tree species line in Europe (for discussion about trees and lines see Körner 1999) have been reported, for example, in the Ural Mts. (Moiseev and Shiyatov 2003), in Scandes (Kulmann 2002), in the north-east of the Iberian Peninsula (Montseney Mts., Penuelas and Boada 2003), and in the Bulgarian mountains (Meshinev et al. 2000). However, the increase in temperature can be also related to certain negative changes in the tree growth, or even a retreat of the alpine timberline to lower locations. This may be connected with increased total precipitation in the winter season (Gamache and Payette 2004, Wilmking et al. 2004) or with paludification (Crawford et al. 2003). The tree physiognomy usually responds better to temperature changes than the timberline position itself (Holtmeier 2003). As a result of climatic warming, changes from krummholz forms to upright stem forms (Holtmeier and Broll 2005) or an increase in radial growth in trees at the timberline (Paulsen et al. 2000) have been observed.

The question is how fast the alpine timberline position responds to climatic changes. While the response of the above-mentioned tree physiognomy is almost immediate (Holtmeier and Broll 2005), the timberline position itself responds with a certain delay (Slatyer and Noble 1992, Malanson 2001), or there does not even have to be any response at all (Daniels and Veblen 2004). The extent and delay of response of the timberline position to positive temperature anomalies is mainly determined by whether the timberline is temperature-limited. If it is limited by topographic or edaphic factors, shifts are less likely to occur. On the other hand, in anthropogenically lowered timberline positions (provided that the anthropogenic pressure has already ceased), the timberline advance is usually fast (Holtmeier and Broll 2005). In temperature-limited highest timberline positions, the response time is influenced by great differences in the extremity of microclimatic conditions between the forest and treeless areas (Moir et al. 1999, Germino et al. 2002), and by the related episodic character of regeneration (Hätenschwiller and Körner 1995). Thus, for the successful establishment of seedlings above the timberline, a relatively long period of favourable climatic conditions is necessary (Körner 1999). Another limit for the generative spread of the timberline conifers is the low invasibility of grassland communities occurring above the timberline (Dullinger et al. 2003).

A relatively open question concerning the dynamics of the alpine timberline position is whether there is a considerable difference in response to negative or positive temperature anomalies. Whereas in some cases, the reaction of the timberline ecotone to negative temperature fluctuations is considered to be rather conservative (Slatyer and Noble 1992), in other cases, authors come to the opposite conclusion, saying that it is negative temperature anomalies that significantly influence the timberline position (Bugmann and Pfister 2000, Hieri et al. 2006), and the alpine timberline thus retreats more easily than it returns to its original level.

In the present study, we focused on an assessment of the spatial dynamics of an alpine timberline, as exemplified by two mountain ranges of the High Sudetes, namely the Giant Mts. and the Hrubý Jeseník Mts. (see Grabherr et al. 2003). On the basis of a series of aerial photographs taken in three periods, shifts of the timberline were compared. The dynamics of the alpine timberline were examined in the period with recorded temperature fluctuations during the growing season between decades ranging up to 1°C (Glowicki 1997). Additionally, the period was marked by a practically complete cessation of the direct anthropogenic impacts on the area at and above the alpine timberline in this territory (Jeník and Lokvenc 1962, Jeník and Hampel 1992). The main purpose was to find out whether there is a certain pattern in shifts in the timberline in relation to relief-based variables (slope gradient, heat load, elevation).

Slope gradient, as a possible explanation variable, was selected because it determines the frequency of catastrophic slope processes that significantly modify the timberline position (Jeník and Lokvenc 1962, Kociánová and Spusta 2000, Holtmeier 2003). The heat load of the given site is vital for the successful survival of seedlings (Körner 1999). The elevation influences timberline dynamics in such a way that timberline sections located lower are more likely to advance because temperature limitation is less significant there. Another criterion was the proportion of dwarf pine in stands above the timberline. This is important because dwarf pine is more competitive in such environments, thus blocking the invasion of Norway spruce (Dullinger et al. 2005), which is the timberline forming species in the studied area. The influence of various grassland communities occurring in the timberline ecotone was not assessed in this study, since the dominant communities (Nardus stricta, Vaccinium sp. and

Calamagrostis villosa-dominated grasslands) show very similar invasibility to spruce seedlings (Šerá et al. 2000).

Furthermore, we tried to focus selectively on tree-growth dynamics at the alpine timberline stands. It was assumed that if periods of worse or improved radial increments in tree stems are recorded, these periods could at the same coincide with the periods of an advance or retreat of the alpine timberline position.

Study area

The High Sudetes belong among the hercynian mountain ranges of Central Europe. The highest mountain ranges within the High Sudetes are the Giant Mountains and the Hrubý Jeseník Mts. (Fig. 1). The summit areas of those mountains represent probably the best-developed alpine islands between the Alps, Western Carpathians and Scandes (Grabherr et al. 2003, Jeník and Štursa 2003). The extent of their primary forest-free areas reaches more than 5500 ha in the Giant Mts. and 1600 ha in the Hrubý Jeseník Mts. (Treml and Banaš 2000). Both the Giant Mts. and Hrubý Jeseník Mts. are characterised by high elevated planated surfaces. Valleys strongly remodelled by glacial activity occur in the Giant Mts. In both mountain ranges the timberline is often limited by extensive block fields and avalanche tracks. In the Hrubý Jeseník the alpine timberline is situated closer to the mountain tops (50–150 m below on average) compared to the Giant Mts., where the forests diminish 200–300 m below the topmost peaks and ridges. The average height of the actual position of the alpine timberline is 1230 m a.s.l. in the Giant Mts. and 1310 m a.s.l. in the Hrubý Jeseník Mts. (Treml and Banaš 2000).

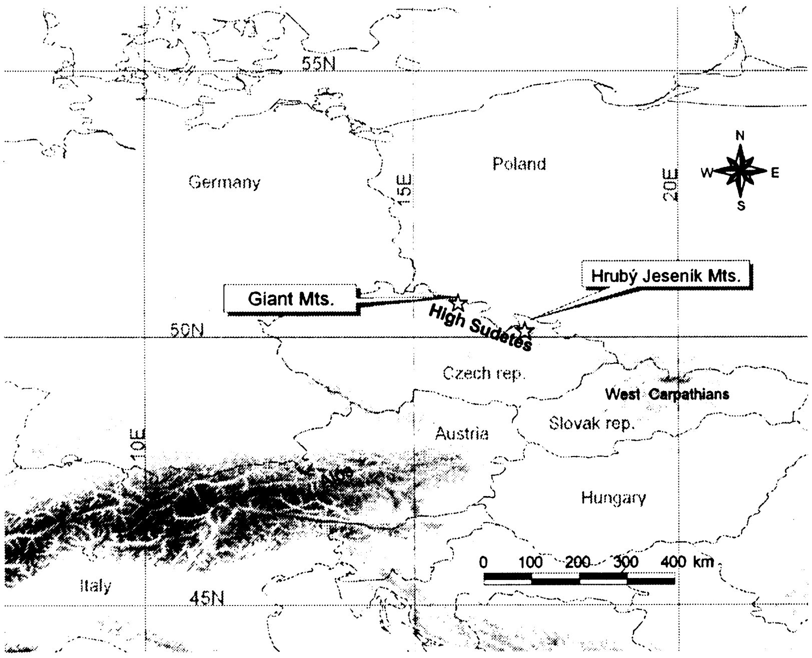


Fig. 1: Geographical position of the High Sudetes.

The mountains described are characterised by relatively high precipitation (approximately 1400-1500 mm per year). The average annual temperatures range from 0.1 °C in the highest parts of the Giant Mts. (Sněžka 1602 m a.s.l.) to 1.1 °C in the Hrubý Jeseník Mts. (Praděd 1491 m a.s.l.). The forests of the upper montane belt and timberline ecotone are composed of Norway spruce (*Picea abies*). Graminoids (*Nardus stricta, Calamagrostis villosa, Calamagrostis arundinacea, Avenella flexuosa*) and dwarf pine (*Pinus mugo*) growths dominate alpine and subalpine communities. The extent of the forest-free area has been strongly influenced by human activity, which increased it in the past by deforestation in both the mountain ranges under study (Jeník and Lokvenc 1962, Jeník and Hampel 1991). Nevertheless, an extensive part of the alpine timberline is not disturbed by man regarding its position (but not as regards the structure of the ecotone - Jeník and Hampel 1991, Treml and Banaš 2000). In addition, there has not been any distinctive direct anthropogenic impact on the alpine timberline in the High Sudetes during the last 60 years, since these areas were either abandoned by their inhabitants or strictly protected as nature reserves.

Methods

Definition of alpine timberline and alpine treeline

The actual alpine timberline position was determined by the means of the supervised classification of ortorectified aerial photographs (acquired in 2003, colour scheme RGB, pixel size 0.3m). Then, a polygon layer of 10 x 10 m squares covering the study area was established and superimposed on a grid of "tree" and "no tree" pixels. The alpine timberline was identified as a line connecting all the uppermost parts of forest/tree groups with tree cover higher than 50% on established 10x10m squares. The squares were defined using the S-JTSK coordinate system and thus this method tends to slightly "lower" the timberline position on slopes parallel with either the X or Y axis of the mentioned coordinate system. The alpine treeline was defined as a line connecting the uppermost alpine timberline positions within the slopes of a given exposition (for discussion about the suitability of using a treeline or timberline approach, see Körner 1999). For this purpose slopes were divided into 5° aspect intervals.

The changes in the alpine timberline position were assessed by means of a comparison of aerial photographs from different time periods. Images from the years 1936, 1964, and 2003 were used in the case of the Giant Mts. and images from 1951, 1973, and 2003 in the case of the Hrubý Jeseník Mts. Old grey-scale aerial photographs (all except 2003) were ortorectified using a 20-m resolution digital terrain model. Consequently, the timberline was determined by supervised classification of the rectified images (the same approach as mentioned above). The position of the alpine treeline in the assessed periods was specified using the same method as for the definition of current position of the alpine treeline. The 1936 and 1964 aerial photographs of part of the Giant Mts. were either missing or were not used because of their poor quality. All analyses were processed using PCI Geomatica (ortorectification, supervised classification, PCI Geomatica 2003) and ArcGIS software (analysis of aspect, slope, elevation, heat load, timberline and treeline definition, ESRI 2005).

Analysis of the alpine forest-tundra ecotone shifts

The average elevation was determined in the individual alpine timberlines/treelines/ from the assessed periods, i.e. as an average value of digital elevation model pixels (20 m cell size) intersecting the timberline or treeline. Average timberline and treeline elevations were compared with one another. For the Giant Mts., where just a relatively shorter part of the timberline with aerial photographs from all three periods was available (Fig. 3), we also compared the average elevations of common timberline sections captured either in photographs from 1936 and 2003, or from 1964 and 2003.

Polygonal layers of "forest" were created for individual assessed periods. These were overlayed, thus forming a new polygonal layer of timberline shifts divided according to the following categories (attributes): overall increase, overall decrease, and oscillation. Oscillation was defined in cases where the timberline in the middle period was higher or lower than in the initial and final periods. The extent of individual parts of the timberline with different tendencies was determined. In cases of an overall altitudinal increase and decrease (i.e. in areas with a general advance or retreat of timberline as regards the initial and final periods), we determined the overall rate of increase or decrease (in meters) and the elevation from which the timberline started to ascend or descend. Further, it was analysed whether there is a linear relation between the overall rate of increase or decrease (as expressed by absolute elevation difference and area size) and the elevation where the increase/decrease started or finished.

Secondary factors affecting the timberline dynamics were assessed as well. For this purpose, the alpine timberline was divided into 100-m-long sections. The overall trend was determined for each of them. If the differences among the positions of the closed-forest limit were lower than 20 m, the tendency of the given alpine timberline section was marked as "stable" (the value of 20 m was estimated as the maximal error of ortorectification and error caused by the shadows of tree crowns). If there were changes in alpine timberline positions recorded in both directions (upwards and downwards), the tendency of the alpine timberline section was called “oscillation”. Overall “increase” (the timberline has ascended and has not descended during any period) or “decrease“” (the timberline has descended and has not ascended during any period) were the other two categories of the alpine timberline tendency. The sections of alpine timberline obviously lowered either by the direct impact of human activity or by the presence of block fields were not included in the analysis.

A buffer (with either 25 or 50 m radius) was created around centroids of 100 m long current timberline sections. The buffer radius was 25 m in the case of timberline shift lower than 50 m in a given section, the buffers with 50 m radius were created if the rate of timberline shift was higher. Variables such as elevation, slope, heat load were analysed within every buffer. The whole buffer area was used for analysis if the timberline tendency of the given section was „stable“ or „oscillation“. If the timberline tendency was „decrease“, only that part of the buffer located above the alpine timberline was used for analysis. Parts located below the alpine timberline of buffers were assessed within ascending timberline sections (with tendency „increase“).

The values of elevation and slope gradient were set on the basis of the 20-meter cell digital elevation model. The grid of potential heat load was calculated as heat load index (McCune and Keon 2002). It means that it is a relative value dependent on the slope orientation, the slope gradient and the mean sun height above the horizon in the growing period (in our case reduced to the May – September period). The dwarf pine proportion was assessed by the means of supervised classification of contemporary aerial photographs within the zone of 100 m above current position of alpine timberline. Analysed zone was divided into individual segments according to 100 m long timberline sections. Consequently, relative proportion of pine in every segment was determined.

By means of a statistic analysis (analysis of variance), it was examined whether there is a considerable difference in the distribution of the values of individual variables (slope gradient, elevation, heat load of site and dwarf pine cover above the timberline) in defined 100-m-long timberline sections divided according to the tendency of shifts (stable, oscillating, ascending, descending – factors in analysis of variance). Besides the assessment of the test power (F-statistic), the percentage of variability explained by any given factor was also counted according to the following formula (Meloun and Militký 2002):

$$\omega^2 = \frac{S_A - (m-1) MS_e}{S_T + MS_e}$$

S_A … variability explained by categories

S_T … total variability; MS_e … unexplained variability; m-1 … degrees of freedom.

By means of a gradient analysis, which direction the size of all analysed variables changed in was examined (redundant discriminant analysis, CANOCO, Ter Braak and Šmilauer 1998). As for the Giant Mts., the statistic evaluation only included those timberline sections with data available for all three monitored periods.

Dynamics of radial growth

For the assessment of the spatial as well as growth dynamics of trees, several plots at the alpine timberline were selected where the radial increment of timberline forming trees was analysed (Fig. 2). In each plot (5 in the Giant Mts., and 2 in the Hrubý Jeseník Mts.), 10-20 trees were selected (dominant ones, not growing in an evidently disturbed site). Using standard procedures (Cook and Kariukstis 1990), one or more samples were taken from each tree approximately at breast height, out of which those without any visible signs of reaction wood formation were selected. A tree-ring series was created and than examined with respect to missing tree-rings, as regards the standard chronology for the given area (T. Kyncl, non-published data). Individual tree-ring width curves were detrended and subsequently, an average tree-ring chronology was established for the Giant Mts. and for the Hrubý Jeseník Mts. Thereafter, the dynamics of radial increments were compared with the observed shifts of the timberline.

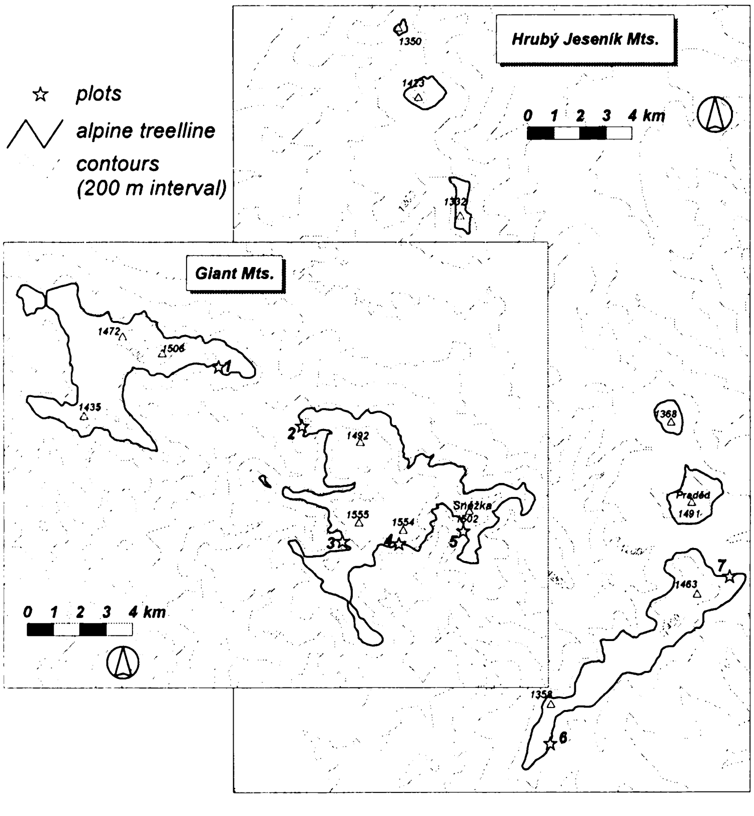


Fig. 2: Position of plots used for radial increment analysis.

Results

Shifts in alpine forest-tundra ecotone

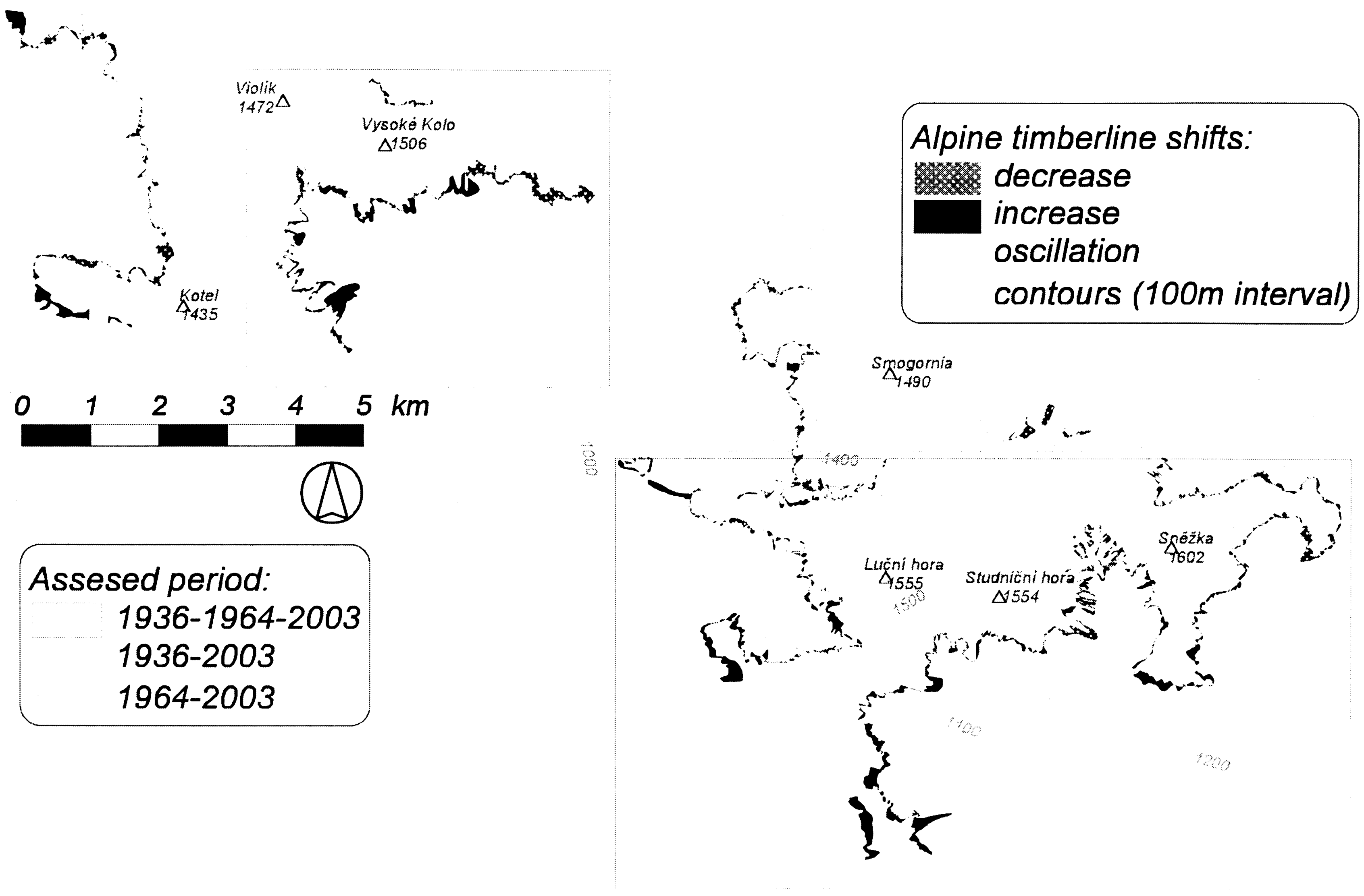
In the Giant Mts., a strong overall advance of the alpine timberline was observed in the period 1936-1964. Apart from avalanche tracks, this typically concerned a coherent forest increase upwards ranging from 20-120 m (up to 50 m in elevation). In the subsequent period (1964-2003), the trend was not that clear any more. A decrease in the overall average elevation of the timberline (and treeline) occurred, which was, however, caused by a local forest retreats than by an overall decrease (Tab. 1). In some places, a significant increase in the altitude of the timberline was observed (Dlouhý Důl valley – south-facing slope up to 120 m, 60 m in elevation). The local advances of the timberline in this period were caused by the uniform ascent of closed forest, the retreat, on the other hand, by the thinning of stands with dead trees. The biggest decrease in the altitude of the timberline occurred on the west-facing slope of Mt. Kotel, on the east-facing slopes of the Labský Důl valley, and on the southern slope of Mt. Svorová Hora (this concerned a forest decline of ca. 250 m, up to 75 m in elevation). Overall advances and retreats of the timberline took place at approximately the same mean elevation, whereas larger areas of oscillating timberline sections were more likely at lower elevations (Figs. 3, 5).

Tab. 1: Average alpine timberline and treeline elevations in individual periods, Giant Mts.

Year	Timberline elevation (m a.s.l.)	Treeline elevation (m a.s.l.)
1936*	1218	1260
1964*	1229	1268
2003*	1216	1264
1936**	1242	1276
2003**	1243	1278
1964***	1235	1272
2003***	1226	1264

* refers to common timberline section 46 km long.
** refers to common timberline section 60 km long.
*** refers to common timberline section 49 km long.

Fig. 3: Alpine timberline shifts in the period 1936-2003, Giant. Mts.



If we focus on the overall altitudinal span of the timberline advances or retreats, it can be said that the biggest shifts upwards occurred in places where the initial altitude of the timberline had been low (r=-0,60, p=0,01). However, these were relatively small advances in terms of areal extent, since the size of such areas did not correlate to the minimum elevation from which the forest ascended. On the contrary, in sections of the alpine timberline with a decreasing tendency, one can see a slight relation between the areal extent of decrease and the altitude from which the decrease occurred, i.e. the higher the altitude, the larger the area of decrease in the timberline was (r=0.27, p=0.01). The biggest absolute decrease occurred in the timberline parts that have a lower elevation today (the bigger decrease thus manifested itself by a considerable decrease in the altitude of the timberline position (r=-0.52, p=0.01).

In the Hrubý Jeseník Mts., a considerable advance of the alpine timberline (as well as the treeline) position occurred between 1953 and 1973 (Tab. 2). Especially in the southern part of the main ridge, in places with a low-positioned timberline, an overall ascent of up to 300 m (70 m in elevation) was observed. The greatest advance of all occurred on the northeast-facing slope of Mt. Praděd, where the timberline moved upwards by 460 m (approx. 120 m in elevation). In the area of Mt. Červená hora the trees invaded in this period in gaps created by debris flows and avalanches, which resulted in an increase in the altitude of the timberline of up to 200 m in elevation. In most case, however, this was not a shift of a coherent forest front upwards, but it was gradual engagement of tree groups that had already been established above the timberline. In the period 1973-2003, the alpine timberline in the Hrubý Jeseník Mts. descended to approximately the same mean elevation as in the initial assessed period (1953). The retreat had a different pattern than the previous advance of the timberline. It was rather a fragmentation of the ecotone formed by 1973. The biggest decrease took place on the slopes of Mt. Červená hora, where the timberline descended by up to ca. 450 m (100 m in elevation).

As regards areal extent, the overall advance of the timberline position generally prevailed during the whole assessed period of 1953-2003 (ca. 50% of the area of all timberline shifts). While the segments of ecotone with an increasing or decreasing tendency were distributed at approximately the same elevations, the biggest area of oscillating parts of the ecotone was located at the highest positions (Figs. 4, 5).

Tab. 2: Average alpine timberline and treeline elevations in individual periods, Hrubý Jeseník Mts.

Year	Timberline elevation (m a.s.l.)	Treeline elevation (m a.s.l.)
1953	1289	1308
1973	1307	1321
2003	1294	1310

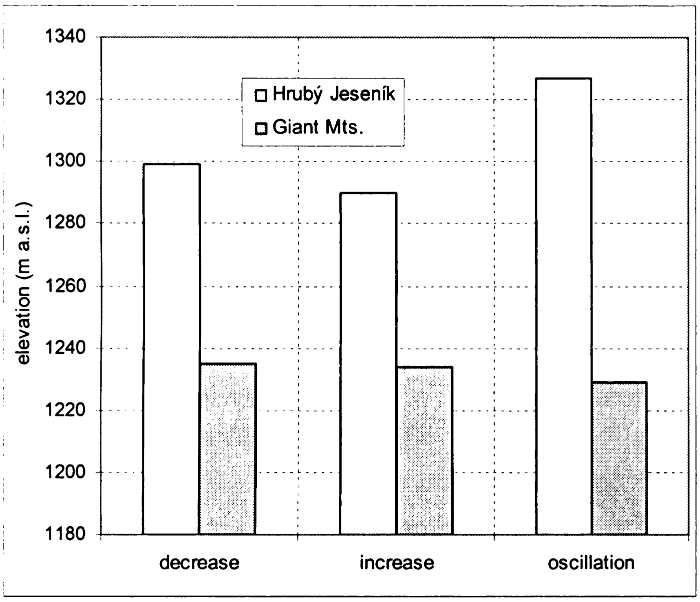
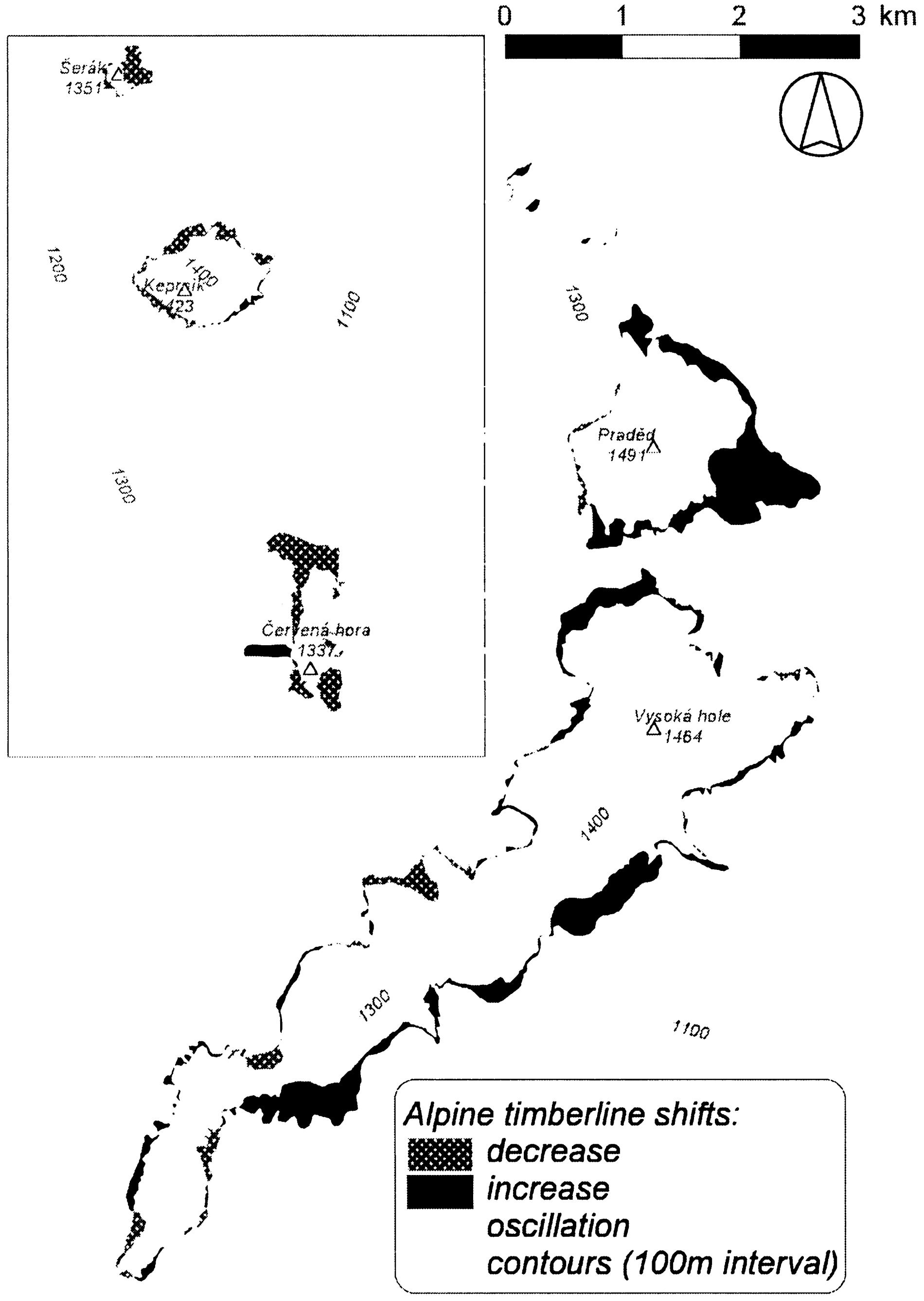


Fig. 5: Average elevation of parts of the timberline ecotone with ascending, descending or oscillating tendency.

Within the whole assessed period, the absolute elevation shift of forest upwards in the Hrubý Jeseník Mts. depended on the elevation from which the forest ascended (negative correlation, r=-0.47, p=0.01). A contrary trend could be seen as regards the areal extent of the sections with an ascending tendency – a greater increase in area was more likely to occur at higher elevations (r=0.23, p=0.05). A greater absolute decrease in the altitude of the timberline occurred in those sections that are located at a low elevation today (r=-0.376, p=0.01). However, the areal extent of the descending parts of the timberline did not show any dependence on the elevation to which they descended or from which they started to descend.

Fig. 4: Alpine timberline shifts in the period 1953-2003, Hrubý Jeseník Mts.



Factors affecting the spatial dynamics of alpine timberline

In the Giant Mts., the altitude of the given alpine timberline section was found to be a variable which changes considerably according to the tendencies of the timberline position (Tab. 3). At the lowest positions of the timberline, oscillations were more likely to occur, while at the highest positions, on the other hand, an overall decrease in the altitude of the timberline was more probable. Significant differences in sections with a different timberline shift tendency were observed on slope gradient variable. It could be seen that oscillations of the timberline were more likely to occur on the steepest slopes, whereas on the gentle slopes, the timberline tended to descend. Significant differences were also seen in the distribution of dwarf pine cover values. In those places with the lowest proportion of dwarf pine growths, oscillations of the timberline were more likely, while in those places with the largest dwarf pine cover, a decrease in the altitude of the timberline was observed more often. In spite of its statistical significance, however, the factor of timberline dynamics could only explain a very low percentage of the variability of dwarf pine cover above the timberline (Tab. 3). On the whole, the dynamics of the timberline were chiefly influenced by the slope gradient, the rising value of which predetermined oscillations of the timberline position (Tab. 3, Fig. 5). The influence of other variables was rather less important (Figs. 5, 6), but the negative linear dependence of timberline oscillations on elevation is worth mentioning. The 1st axis of the ordination plot (Fig. 6) can be interpreted as the gradient from steep dwarf pine-free slopes on avalanche tracks at low elevation to the edges of summit plateaus with a gentler slope and dense dwarf pine growths. The 1st axis explained 93% of data variability and its influence was significant (Monte Carlo permutation test – F = 46.06, p=0.002).

Tab. 3: Results of ANOVA for individual variables depending on the factor of alpine timberline dynamics, Giant Mts.

Variable	F	p	% of explained variability
Mean Elevation	18.6	0.000	5
Slope	34.6	0.000	10
HLI	Not sign.	-	-
Dwarf pine	13.7	0.000	3

Fig. 5: Distribution of values of elevation, slope, and dwarf pine cover proportion within the alpine timberline sections with different dynamics, Giant Mts.

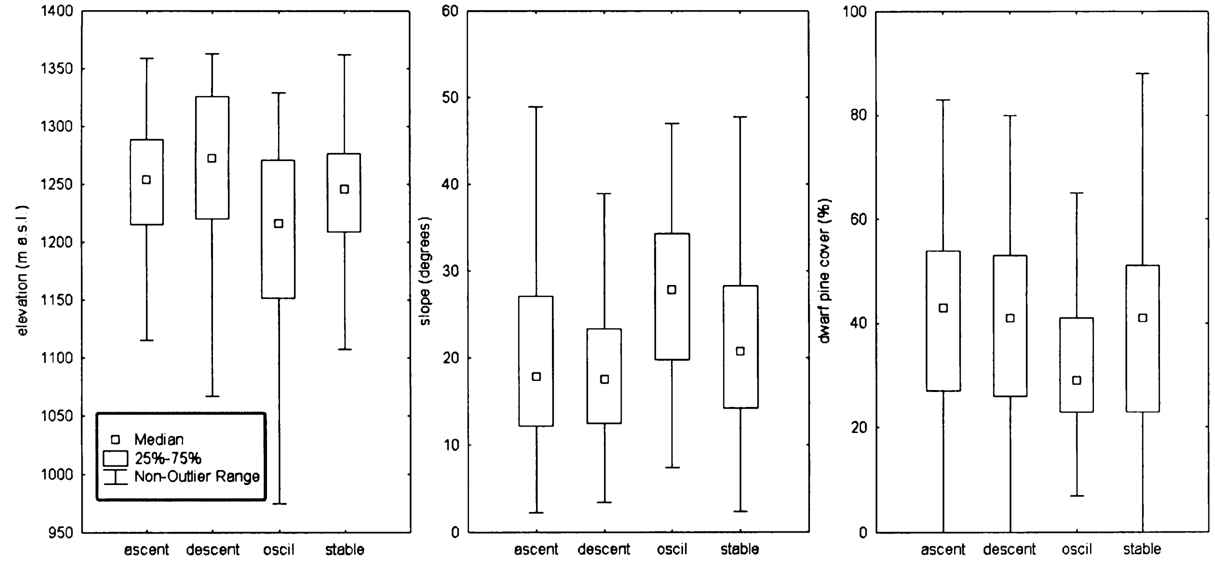
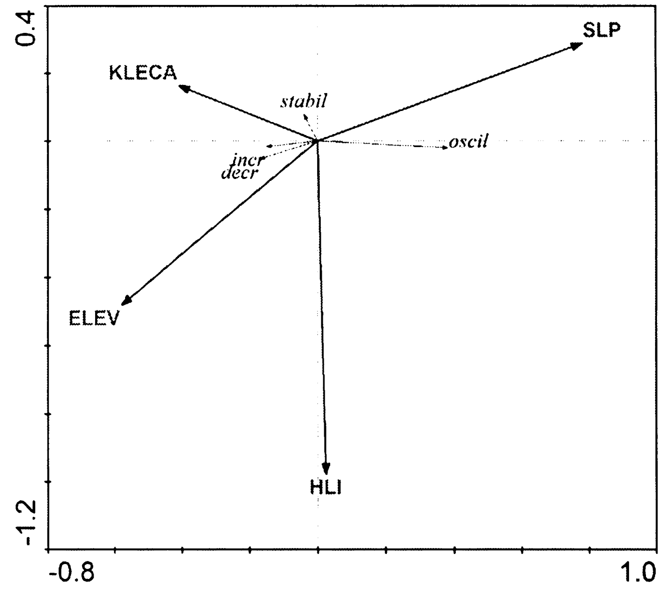


Fig. 6: Factors affecting the tendency of alpine timberline shifts in the Giant Mts. RDA ordination plot. “KLECA” refers to dwarf pine cover, “SLP” to slope, “ELEV” to elevation, “HLI” to heat load index.



In the Hrubý Jeseník Mts., the dynamics of the timberline differed only slightly within the various elevations (Tab. 4, Fig. 7). In more elevated sections of the alpine timberline, oscillations were more likely to occur, while at lower locations the alpine timberline position was either stable or increased. Influence of the timberline dynamics was more significant in the distribution of the slope gradient values. While a decrease in the altitude of the timberline was more likely to occur on gentler slopes, in the case of steeper slopes, on the other hand, an increase was more likely. Similarly to the Giant Mts., the dynamics of the timberline did not differ at all on slopes with a different heat load. The factor of the dynamics of the timberline did not explain a major portion of the variability of the values of dwarf pine cover above the timberline. However, it can be seen that in places with a higher proportion of dwarf pine growths, a more significant increase in the timberline was observed. This trend is evident in the ordination plot (Fig. 8), which shows that the overall ascending tendency could be seen in timberline sections with greater dwarf pine cover. Additionally, it is apparent that stable alpine timberline sections were more likely to occur on steeper slopes.

Tab. 4: Results of ANOVA for variables within the factor of alpine timberline dynamics, Hrubý Jeseník Mts.

Variable	F	P	% of explained variability
Mean Elevation	4.6	0.003	3
Slope	8.1	0.000	4
HLI	not sign.	-	-
Dwarf pine	3.3	0.02	2

Fig. 7: Distribution of values of elevation, slope, and dwarf pine cover within the alpine timberline sections with different dynamics, Hrubý Jeseník Mts.

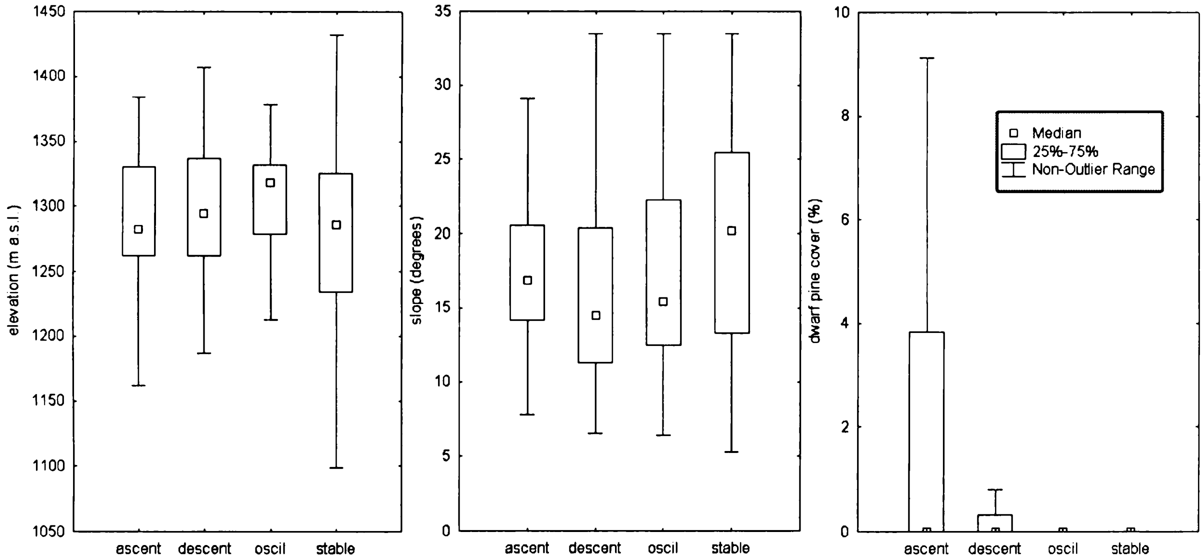
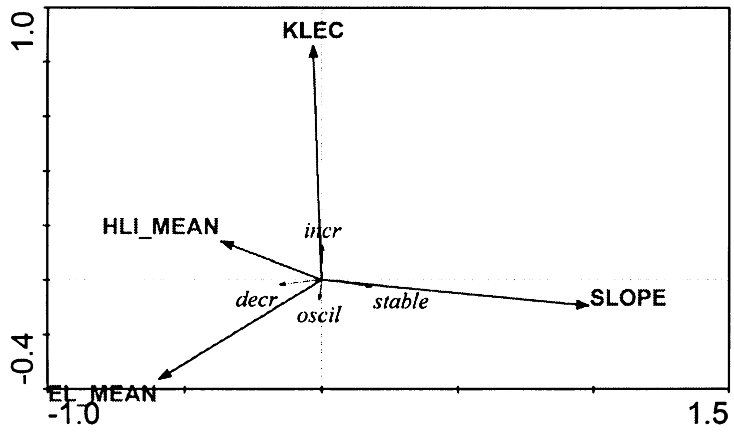


Fig. 8: Factors affecting the tendency of alpine timberline shifts in the Hrubý Jeseník Mts. RDA ordination plot. "KLEC" refers to dwarf pine cover, "EL_MEAN" to elevation, "HLI_MEAN" to heat load index.



Radial growth of Norway spruce at alpine timberline

In the Giant Mts., very similar trends of radial growth were observed in five plots at the alpine timberline. The most important identically observed anomaly in the resultant average chronology of tree-ring widths (Fig. 9) is the period of decreased increments: 1975-1995 (2000). This was preceded by a period of increased ring-widths, approximately between 1950-1975. Before this period, no uniform trend that was identical in all the plots that were analysed can be defined. Negative fluctuations from average tree-ring curves were typically observed in the 1920s and at the turn of the 19th and 20th centuries. The most rapid increase of tree-ring indices can definitely be observed in the late 1990s and at the beginning of the 21st century.

In both plots in the Hrubý Jeseník Mts., we can see a very similar course of the tree-ring curve as in the Giant Mts. (Fig. 10). What is well defined is the period of below-average ring-widths, approximately between 1972-1995, and the period of above-average increments - between 1935-1972. The steepest rise in the curve of tree-ring indices can be seen in the last decade, i.e. after 1995.

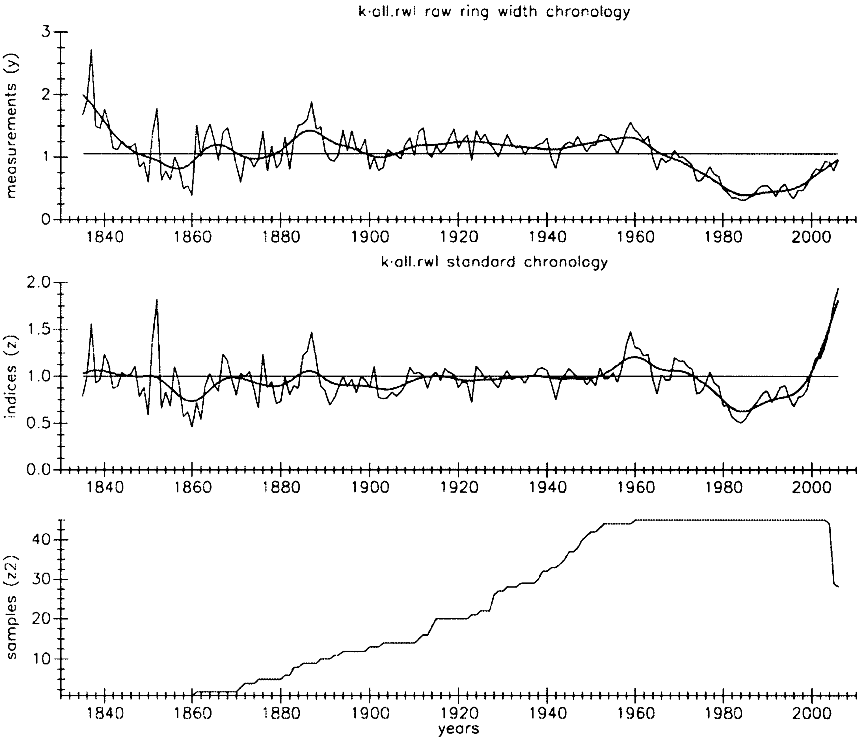


Fig. 9: Tree-ring series of absolute tree-ring widths and tree-ring indices, Giant Mts.

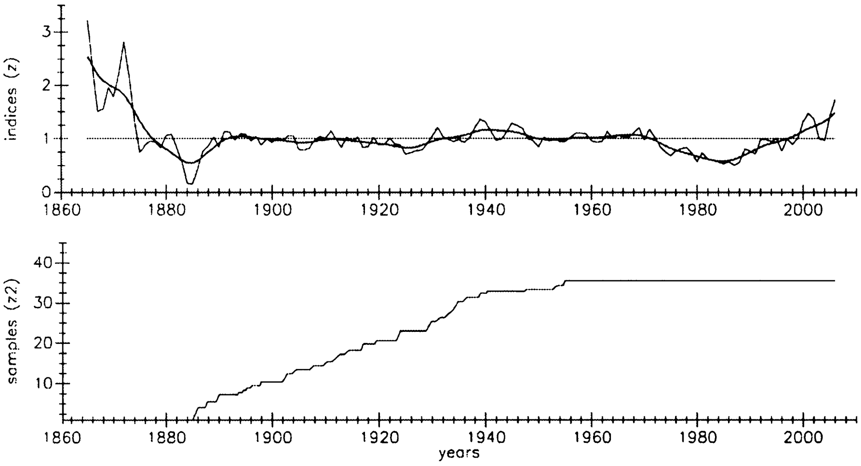


Fig. 10: Tree-ring series of absolute tree-ring widths and tree-ring indices, Hrubý Jeseník Mts.

Discussion

In the High Sudetes, an overall advance of the alpine timberline was observed in the period under study. However, this tendency, similarly to the growth of trees at the timberline, was not uniform within the whole period. In the first part of assessed period (1936-1964 in the Giant Mts. and 1951-1973 in the Hrubý Jeseník Mts.), there was a considerable increase in the altitude of the alpine timberline. At the end of this period, the timberline in both mountain ranges reached practically its maximum position. Furthermore, above-average radial increments of Norway spruce were observed in the analysed plots in the sixties. The overall advance of the alpine timberline in the given period was apparently influenced by several factors. In the '50s and '60s, temperatures in the growing season were higher on average (Dubicka and Glowicki 2000) (Fig. 11), which was also reflected in the tree-ring curve of the trees in the analysed plots. The same phenomenon was also observed in the Labský Důl Valley tree-ring chronology (Giant Mts.) by Brázdil et al. (1997). Improved growth conditions over a relatively longer period enabled the seedlings to survive the critical stage of development (Körner 1999), and the timberline thus ascended. Another important influence was the fact that in this period, the area found itself in a stage just after the cessation of human use of the territory above the timberline (Jeník and Lokvenc 1962, Jeník and Hampel 1992). With respect to a relatively short time after the cessation of local grazing or mowing of alpine grasslands, it can be expected that the thickness of litter layer in this period was considerably less than today. This made possible the better generative regeneration of Norway spruce, which is nowadays prevented by a very thick layer of litter (Prach et al. 1996). In the Hrubý Jeseník Mts., the ascent of the alpine timberline in the first assessed period was even more pronounced than in the Giant Mts. This can be explained by a greater proportion of segments of the timberline whose position was not limited by disturbances (avalanches, debris flows) or by edaphic conditions (block fields) (Treml and Banaš 2000).

In the subsequent assessed period (1964-2003 in the Giant Mts. and 1973-2003 in the Hrubý Jeseník Mts.), the alpine timberline in both areas left its achieved positions and locally descended to lower positions. We suppose that this trend was determined by a synergic influence of several factors. Perhaps the most important one was the impact of acid rains on the territory; this is considered to be the main cause of the retreat of the alpine timberline on the Polish side of the Giant Mts. (Zientarski 1995). In this period, radial growth of Norway spruce decreased considerably in the Giant Mts (Sander et al. 1995), which was also proven in the studied plots at the timberline in both mountain ranges in the High Sudetes.

Furthermore, during most of this period (the '70s and first half of the '80s), the temperatures in the growing season were lower than the long-term average (Glowicki 1997, Fig. 11). In this period, it can be expected that the invasiveness of alpine grasslands was also considerably lower as a result of the already-mentioned thickness of the litter layer. The opening of several new avalanche tracks in the Giant Mts. also contributed to the descent of the timberline (Kociánová and Spusta 2000).

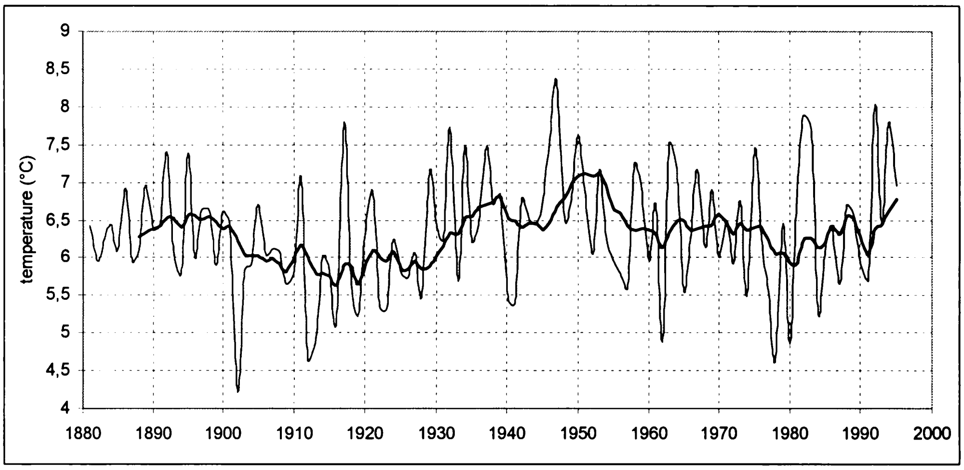


Fig. 11: Mean air temperatures in the growing season (May-September), Mt. Sněžka, 1602 m a.s.l., plotted after data published by Glowicki (1997); bold line indices 8-year moving average.

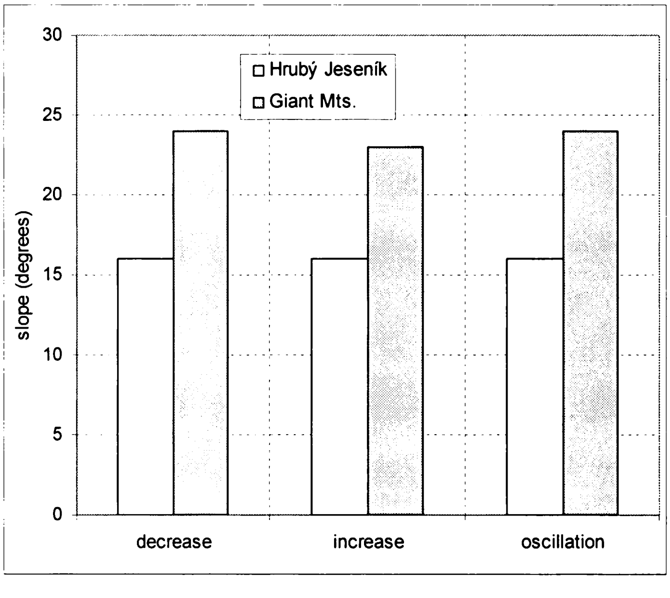


Fig. 12: Average slope gradient of areas where the alpine timberline ascended, descended, or oscillated.

Locally, utterly different trends can be observed in this period as well. This concerned especially the establishing of tree stands on the largest avalanche track in the Giant Mts. (Labský Důl valley) or an ascent of the timberline in altitude of nearly 100 m on the southern slope of Mt. Luční Hora on large debris flow tracks (Treml 2007). This demonstrates the very significant influence of disturbances, because the increase in the altitude of the timberline in these localities was caused by substantial generative regeneration of Norway spruce. The biggest retreat of the timberline was observed in the highest locations in both mountain ranges; this is related to the great sensitivity of such timberline positions to other stress factors.

The character and rate of influence of individual factors that affect the tendency of the movement of individual timberline sections differed in both the mountain ranges under study. In the Giant Mts., the influence of the slope gradient was relatively strong; it mostly determined the timberline oscillations. This is due to the fact that a considerable section of the timberline crosses the avalanche and debris flow tracks (Treml and Banaš 2000), which also occur in places with steep slopes. On the other hand, in the Hrubý Jeseník Mts., alpine timberline sections with a stable tendency were more likely to occur in areas with steeper slopes. We suppose that this phenomenon can be influenced by the fact that the timberline on steep slopes is, in the Hrubý Jeseník Mts., situated nearer the convex edges of summit planated surfaces, where stress factors have a greater influence (blowing out of snow and deep freezing of soils on windward slopes and high accumulation of snow in leeward sites), which makes the possibility of the germination of spruce harder in these locations. If we compared the slope gradients in whole areas with an ascending, descending, or oscillating tendency (i.e. not in partial 100-m sections of timberline), we can see that their average inclination in the Hrubý Jeseník Mts. does not differ. Furthermore, the alpine timberline there, as compared to the Giant Mts., runs nearer the convex edges of summit planated surfaces, and thus also on generally gentler slopes (Fig. 12). Higher dynamics were observed in the Hrubý Jeseník Mts. in timberline sections situated on gentler slopes that were also typically located at higher elevations. Of course, these timberline sections are more sensitive to stress factors (temperature fluctuations, soil acidification), since there is also greater limitation of the timberline by temperatures. In the case of the High Sudetes, this can also be seen in the fact that an overall ascent or descent of the timberline was more likely to occur in the highest timberline positions. The possibly greater sensitivity of the timberline on gentler slopes to positive temperature fluctuations, as assumed by Holtmeier and Broll (2005), might also contribute to this. Temperature gradients at the given distance are lower on gentle slopes than on steep slopes, and as a consequence of temperature fluctuations, the advance or retreat of the timberline can thus be theoretically greater on gentle slopes.

Contradictory trends could be seen in both mountain ranges as regards the dynamics of the timberline position in places with different dwarf pine cover. The assumption was that in sites with closed dwarf pine stands situated above the timberline, the alpine timberline would not advance, since dwarf pine would be competitively stronger than the Norway spruce seedlings (Dullinger et al. 2005). According to our observations, the dwarf pine even suppresses the growth of clonal groups of Norway spruce by preventing layering of the marginal spruce branches. This assumption was more or less confirmed in the Giant Mts., where in places with a dense dwarf pine cover, the timberline did not show a clear tendency (preferably, there was an overall decrease, or the position was stable), whereas timberline oscillations occurred in places that were least covered by dwarf pines. In the Hrubý Jeseník Mts., on the other hand, an increase in the altitude of the timberline was observed in localities with significant dwarf pine cover. However, the character of local dwarf pine stands differs from that in the Giant Mts. Dwarf pines were planted here at the turn of the 19th and 20th centuries (Hošek 1973), and in most places, the stands were, even in the '70s, more open than the old autochtonous dwarf pine stands in the Giant Mts. This made possible the germination of Norway spruce, as well as the continuing growth of clonal spruce groups. That is why an ascent of the alpine timberline could occur even in such areas.

According to the data achieved, the potential heat load of the site did not manifest itself in different timberline dynamics at all. It could be presumed that the positions with higher heat load could be more favourable for the the alpine timberline ascent, since the minimum heat requirements of seedlings that enable them to survive the critical part of their life stage are more likely to be reached here (Körner 1999, Holtmeier 2003). Such a phenomenon is directly observed on gentle southern and western slopes in Lapland (Autio and Colpaert 2005). The fact that this dependency was not found in the High Sudetes cannot be explained by higher stress caused by the lack of humidity in places with a high heat load, because the amount of precipitation in the summer season is sufficient (ca. 700 mm from May to September in the period of 1974-2004, station Labská Bouda, 1335 m a.s.l., Czech Hydrometeorological Institute). Furthermore, the number of clonal spruce groups, in whose proximity the seedlings are more likely to survive, as a result of their protective effect (Germino et al. 2002), is similar both in the "favourable" and the "unfavourable" slope aspects above the timberline in the High Sudetes. Plesník (1972) suggested a more intense fall of spruce seeds above the timberline on west-facing slopes or valleys because of the prevalent west winds. This can in a certain way disturb the possible preferential advance of the alpine timberline in places with a higher heat load (south, south-west slopes). The most significant constraint that prevents an accelerated ascent of the timberline on warmer slopes is probably the prominent influence of grass-cover disturbances on the generative regeneration of Norway spruce. Considerable advances of the timberline took place in those very places that had disturbed vegetation cover (Treml 2007).

Generally, it can be said that a surprisingly good concordance was observed between the growth trends of Norway spruce at the alpine timberline and its shifts. Even relatively short periods of favourable or unfavourable growth reflected themselves in an advance or retreat of the alpine forest-tundra ecotone, as documented by the average elevation of the alpine timberline or treeline. A similar phenomenon was observed by Kullman (1987). However, no response to radial growth amelioration was observed at the timberline in the central Alps

(Paulsen et al. 2001) or in the central Tianshan Mountains (Wang et al. 2006). A descent or ascent of the timberline in the High Sudetes mostly took place through the gradual closing or thinning of tree growths in the transition zone between forest and alpine tundra, i.e. in places that are at least locally favourable as to microclimate, and which can be reached by a sufficient amount of seeds (Holtmeier 2003) that have a good viability even in such extreme conditions (Maděra 2004).

The strongest increase of radial increments of Norway spruce can be observed in the recent period (approximately from the second half of the '90s). It coincides with an increase in temperatures in the growing season. However, other factors seem to play a significant role in Central European mountain ranges as well, such as a gradual reduction in acidification and consequent increase in nutrient availability (Kopáček and Veselý 2005, Oulehle et al. 2006). An important phenomenon that inhibits and reduces the response of the alpine timberline to current positive temperature anomalies is the very low ability of Norway spruce to germinate in closed grasslands above the timberline. It is supposed that, together with a considerably more extreme microclimate (Holtmeier and Broll 2005), this is also the reason why the man-created parts of the forest-free areas in the High Sudetes that are located in low elevations have not been colonised by trees so far.

Conclusions

In both the mountain ranges of the High Sudetes under study, in the Giant Mts. and in the Hrubý Jeseník Mts., a similar development of the position of the alpine forest-tundra ecotone was observed in the monitored period of the second half of the 20th century. In the first part of the assessed period, a general advance of the alpine timberline occurred. It was most significant in positions where the alpine timberline was lower. Mostly, it took place through the gradual closing of tree groups and the colonisation of gaps among them by newly established individuals. Additionally, this period (the 1950s and 1960s) showed above-average vitality of Norway spruce, which was reflected in an increase in radial growth. From the second half of the 1960s (Giant Mts.), resp. from the second half of the 1970s (Hrubý Jesseník Mts.) until 2003, the alpine timberline descended again to the average elevation where it used to be at the beginning of the studied period (1936 in the Giant Mts. and 1954 in the Hrubý Jeseník Mts). The most important cause of this phenomenon was the stress resulting from air-pollution deposition. Moreover, there were other synergic factors that were included, namely lower temperatures during the growing season in the second half of the '70s and in the first half of the '80s, and a very thick layer of litter in alpine grasslands, which hindered the germination of spruce. The stress caused by acid rains and low temperatures in the given period also manifested itself in the considerably diminished radial growth of spruce. The retreat of the alpine timberline took place mostly in its highest positions, i.e. in places that are nearest to the limiting conditions for the growth of spruce. In this period, a local yet significant advances of the timberline position were also observed. However, this was mostly limited to localities with disturbed vegetation cover on former avalanche or debris flow tracks. Apart from the potential heat load, all the assessed variables (elevation, slope, dwarf pine cover above the timberline) had a certain influence on timberline dynamics. In the Giant Mts., the alpine timberline tended to oscillate in lower positions and in places with the highest slope gradients. In the Hrubý Jeseník Mts., the most important trend was the increase in the altitude of the timberline in places with denser dwarf pine cover. In this respect, no universal pattern of alpine timberline dynamics was found, which is related to the fact that in the Hrubý Jeseník Mts., as opposed to the Giant Mts., (1) the alpine timberline is situated closer under the summit planated surfaces, (2) it is not limited by catastrophic slope processes occurring on steep slopes, and (3) in the '50s and '60s, i.e. in the period when the alpine timberline had an ascending tendency, the proportion of dwarf pine stands was relatively low.

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