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Abstract

The easternmost parts of the Hercynian mid-mountains of Central Europe, namely Hrubý Jeseník and Králický Sněžník, are characterised by extensive alpine areas at altitudes above approximately 1300 m a.s.l. In order to determine the contribution of human activities to the extent of these summit grasslands we analysed charcoal assemblages and pollen profiles taken from high elevation sites. The first burn was dated to the Iron Age (about the first to second centuries BC), with successive fire events recorded in the early Mediaeval epoch from about AD 670. Significant human influence as recorded in pollen diagrams was detected as late as during the High Middle Ages (about the twelfth to thirteenth centuries AD). Charcoal assemblages reveal similar trends in species composition. The oldest and/or deepest samples are represented by charcoal fragments of *Picea abies* and various broadleaf trees and shrubs such as *Betula* sp., *Sorbus* sp., *Juniperus* sp. and *Salix* sp. Towards the surface, *Picea abies* gradually becomes dominant and then *Vaccinium* charcoal particles dominate the charcoal pool. Radiocarbon data of individual charcoal fragments did not, however, confirm a stratification of charcoal in the soil. According to anthracomass, pollen and macrofossils, the pattern of forest-free areas was originally determined by terrain morphology. While forest-free patches occurred on exposed summits and the convex edges of summit plateaus, open canopy tree growths dominated high elevation summit flats, and closed canopy forests occurred on adjacent slopes.

Keywords

charcoal analysis, East Sudetes Mts, forest-free area, human impact, pollen analysis, vegetation changes

Introduction

The extent of alpine forest-free areas in Central Europe is probably influenced by both climate and human activities (e.g. Jeník and Lokvenc, 1962; Obidowicz, 1993; Plesník, 1971; Speranza *et al*., 2000a). Since the treeline ecotone, which forms the lower boundary of an alpine area, is generally temperature driven, the development of alpine forest-free areas during the Holocene has also followed climatic changes (e.g. Haas *et al*., 1998; Körner, 1999; Kullman and Kjällgren, 2000). Nevertheless, human impacts of various intensity and duration, such as pasturing or fire setting, began playing a distinct role in the formation of alpine treeless areas during the middle and late Holocene in Central Europe (e.g. Burga, 1988; Schwartz *et al*., 2005). In the Alps, the beginning of anthropogenic transformations of the treeline ecotone has been dated to the Iron Age or even earlier periods (Burga, 1988; Gobet *et al*., 2005; Tinner and Theurillat, 2003).

Treeline oscillations are well known in the Alps (e.g. Tinner *et al*., 1996; Wick and Tinner, 1997). Literature referring to the intermediate-elevation mountains (hereafter mid-mountains) of Central Europe is significantly more scarce, however, although some of these mountains (the Vosges, Schwarzwald, Harz, High Sudetes) are characterised by prominent treeless patches in summit areas. The (sub)alpine belt of these mountains, with frequent heliophilous species and complex grassland plant communities, has been traditionally regarded as a naturally forest-free space with only local human alterations to sections of the treeline ecotone (e.g. Carbiener, 1963; Jeník, 1961). However, strong anthropogenic influences on the formation of 'alpine' areas have been suggested by some recent studies (Beug *et al*., 1999; Rybníček and Rybníčková, 2004: Schwartz *et al*., 2005). Currently, forest-free mid-mountains of Central Europe can be divided into three groups according to their development during the Holocene (Treml *et al*., 2006). In the Schwarzwald Mts temperature-limited alpine areas had already disappeared at the beginning of the Holocene (Lang, 2006), in the Vosges, Harz and Hrubý Jeseník Mts the extent of forest-free patches has fluctuated (sometimes disappearing) on limited summit areas throughout the Holocene (Beug *et al*., 1999; De Valk, 1981; Edelman, 1985; Rybníček and Rybníčková, 2004), whereas in the Krkonoše Mts large and permanent alpine areas have persisted (Treml *et al*., 2008). The evolution of these Central European mid-mountain summit areas has been generally studied by means of pollen analysis. This approach alone, however, may

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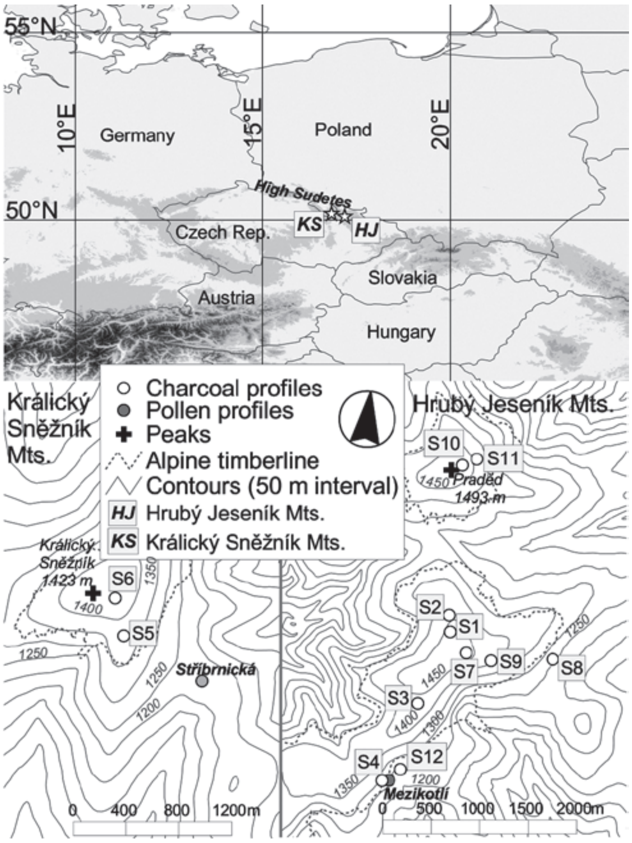

Figure 1. Location of the study area

not allow a spatially explicit reconstruction of the extent of forest-free areas because of regional pollen influxes (Hicks, 2001; Jackson and Kearsley, 1998; Tinner *et al*., 1996). The use of methods covering both regional (e.g. pollen analysis) and local scales (e.g. macrofossils, charcoal particles) (Gobet *et al*., 2005; Kultti *et al*., 2006) would likely be more precise.

This study is focused on the alpine areas of the East Sudetes Mts, which are the easternmost part of the Hercynian Mountains of Central Europe, adjoining the Carpathians. Evidence of forest-free patches on the uppermost summits during the Sub-Boreal/Sub-Atlantic transition has been given by pollen spectra and dated periglacial landforms (Rybníček and Rybníčková, 2004; Treml *et al*., 2008). As a result of large-scale human impacts, the treeline was substantially lowered approximately 500 years ago (Rybníček and Rybníčková, 2004). Nevertheless, questions remain regarding (a) the dimension of this human impact and its contribution to the formation of forest-free areas; (b) the timing of the human impact, and whether there had been any prior human influence, similarly as in the Alps. In order to answer these questions, we used pedoanthracological methods combined with pollen and macrofossil analyses.

Study area

The study area is in the easternmost part of the High Sudetes mountain range, including the Králický Sněžník and Hrubý Jeseník Mts (Figure 1). The highest summits of these mountain ranges surpass altitudes of 1400 m (e.g. Praděd 1493 m a.s.l., Vysoká Hole 1464 m a.s.l.), and elevated planated surfaces at altitudes of 1300–1400 m prevail along the mountain ridges (Czudek, 1997).

At the highest elevations, the mean annual temperature is 1.1°C and annual precipitation varies around 1400 mm. The snow pack usually reaches depths of 1–3 m and typically lasts until May. The lower boundary of the treeline ecotone (e.g. the alpine timberline *sensu* Körner, 1999) is situated at 1310 m a.s.l. on average (Treml and Banaš, 2003). The Alpine treeline position is influenced by strong westerly winds, which induce a lowering of the treeline driven by wind-exposure, which is in turn related to small-scale topography (Jeník, 1961). Montane forests and the treeline ecotone are dominated by Norway spruce (*Picea abies* (L.) Karst), with admixtures of European beech (*Fagus sylvatica*) in lower elevations (below 1250 m a.s.l.). Sites with deep and long-lasting snow cover are occupied by broadleaf shrubs (e.g. *Betula carpatica*, *Salix silesiaca*). Alpine areas are dominated by graminoids (e.g. *Festuca supina*, *Nardus stricta*, *Calamagrostis villosa*, *Calamagrostis arundinacea*, *Avenella flexuosa*) and Vaccinium shrubs (*Vaccinium myrtillus*, *V. vitis-idaea*). Scattered shrubs of juniper (*Juniperus communis* ssp. *alpina*) also occur in the summit grasslands. Non-indigenous dwarf pine (*Pinus mugo*) was planted during the nineteenth and twentieth centuries.

The presence of human impacts in the foothills of the Hrubý Jeseník Mts since the Bronze Age has been documented (Brachtl, 1985; Goš, 1969). Nevertheless, direct evidence of human-induced changes to mountain valleys or summit areas during this period are missing. There is, however, no doubt about strong human influences at the highest elevations during the Middle Ages. Deforestation, hay production and pasturing are considered to be the main forces that caused the enlargement of alpine forest-free areas in this period (Hošek, 1973; Jeník and Hampel, 1991).

Methods

Sampling sites

Charcoal fragments were sampled from soil profiles excavated in 2006 and 2007, from both the summit and slope parts of the study area (Figure 1, Table 1). Sites were situated in the vicinity of the Praděd and Vysoká Hole peaks (Hrubý Jeseník Mts) and on the east-facing slope of the Králický Sněžník peak. Profiles were dug on flat or gently sloping surfaces situated both above or below current timberline position. For the main soil profiles (S1–S6), soils were sampled in 5 cm thick layers covering 1 m^2, extracting 5 l of fine-grained soil from every layer. Excavated soil profiles were haplic or entic Podzols (according to Food and Agriculture Organization (FAO) classification system, FAO, 1998) with a high content of skeleton (20–40%), and with the horizons Ah, E, Bs/Bhs, and B/C present. Maximum sampling depth was limited by a high amount of skeleton in deeper parts of soil horizons. In addition, samples of 10 l of fine-grained soil dug from the upper 20 cm (mostly horizons Ah, E, Bhs and Bs) were acquired for supplemental soil profiles (S7–S12, Table 1).

Two pollen profiles were sampled. The first site, Stříbrnická, is situated on a ridge east of the summit of Králický Sněžník. An oval, approximately 3000 m^2 large, ombrotrophic mire is surrounded by a closed montane forest dominated by Norway spruce, at an elevation of 1230 m a.s.l. (50°12′7″N, 16°51′36″E, Figure 1), located approximately 80 m below the upper timberline. A 180 cm deep profile core formed of peat and decomposed sedges was taken using a Russian peat sampler of 7 cm diameter.

The second pollen profile was excavated at the Mezikotlí site (1250 m a.s.l., 50°02′46″N, 17°13′31″E), which is at the bottom of

Table 1. Description of studied sites

Site	Position, altitude (m)	Soil horizons	Sample – sampling depth (cm)	^{14}C sample code	Age ^{14}C uncal. BP	Calibrated year BC/AD	Specific anthracomass (mg/kg)	Number of fragments	Dated species
S1	summit plateau, 1458	Ah, E, Bhs	0–5	Poz-22137	695±30	AD 1270	239.05	159	*Picea abies*
			5–10	Poz-22139	650±30	AD 1300	106.37	107	*Picea abies*
			10–15				149.03	111	
			15–20	Poz-22140	645±30	AD 1305	276.73	315	*Picea abies*
S2	plateau below slope, 1435	Ah, E, Bhs	0–5	Poz-22141	1315±30	AD 670	1982.82	884	*Picea abies*
			5–10	Poz-22142	620±30	AD 1320	20 283.66	4462	*Picea abies*
			10–15	Poz-22143	540±30	AD 1430	14 727.98	1453	*Picea abies*
			15–20	Poz-22166	1245±30	AD 730	235.73	146	*Picea abies*
S3	summit plateau, 1432	Ah, E, Bs	0–5	Poz-22149	380±30	AD 1475	3.32	7	*Picea abies*
			5–10				9.41	10	
			10–15	Poz-22150	470±30	AD 1430	332.13	62	*Picea abies*
			15–20	Poz-22151	480±30	AD 1440	6.09	6	*Picea abies*
S4	plateau below slope, 1285	Ah, Bs, B/C	0–5				317.72	147	
			5–10	Poz-22144	250±30	AD 1650	1244.87	472	*Picea abies*
			10–15	Poz-22145	185±30	AD 1770	201.11	80	*Picea abies*
			15–20				110.24	84	
			20–25	Poz-22146	175±30	AD 1775	8.58	12	*Picea abies*
			25–30	Poz-22147	115±30	AD 1850	6.92	13	*Picea abies*
S5	gentle slope on a ridge, 1382	Ah, E	0–5				6.64	13	
			5–10				32.68	65	
			10–15	Poz-22152	960±30	AD 1110	3.04	4	*Picea abies*
S6	summit plateau, 1418	Ah, E, Bs	0–5	Poz-22153	1190±30	AD 833	2.21	4	*Picea abies*
			5–10				1.66	3	*Picea abies*
			10–15				15.78	13	*Picea abies*
S7	summit plateau, 1460	Ah, E	0–20	Erl-10192	402±36	AD 1460		215	*Picea abies*
S8	gentle slope, 1250	Ah, Bs	0–20					0	
S9	gentle slope, 1330	Ah, E, Bs	0–20	Erl-10187	447 ±35	AD 1440		165	*Picea abies*
S10	summit plateau, 1480		0–20	Erl-10188	2099±38	120 BC		32	*Picea abies*
S11	gentle slope, 1440	Ah, E, Bhs	0–20	Erl-10189	399±36	AD 1450		63	*Picea abies*
				Erl-10190	531±35	AD 1420		18	*Picea abies*
S12	gentle slope, 1230	Ah, E	0–20					0	
Mezikotlí	bottom of a nivation hollow, 1250		127	Erl-10185	1520±39	AD 550			sedge seed
			63	Poz-22134	785±30	AD 1250			sedge seed
			46	CRL-6221	528±71	AD 1420			*Picea* twig
Stříbrnická	saddle, 1230		175	Poz-22135	2635±30	810 BC			*Sphagnum* leaves
			73	Poz-22136	1030±50	AD 1010			*Sphagnum* leaves

S1–S12: Soil profiles; Mezikotlí and Stříbrnická: radiocarbon dating from pollen profiles. Calibration of radiocarbon data to calendar years was computed using the OxCal program (Bronk Ramsey, 2001). Calibrated years correspond to centres of 99.7% probability range.

a nivation hollow. A small peat bog (area of 820 m^2) with lagoons is situated directly at the alpine timberline, which is lower at this location because of anthropogenic impacts and avalanches. The peat bog is formed in front of a ridge built by debris flow deposits. A 125 cm deep profile was taken. Profile consists of sedge-peat with frequent fine clasts (sediments of a slope wash) at the base.

Anthracological analysis

Extraction of charcoal from the soil material followed the standard flotation and wet sieving procedure (Jacomet and Kreuz, 1999), using staggered sieves with mesh size of 1 mm. Charcoal analysis was performed only on fragments from the largest fraction (>2 mm). Identification of charcoal fragments, carried out using an episcopic microscope, was done with an interactive identification key (Heiss, 2000 onwards) in addition to the standard literature (Schweingruber, 1990).

Individual taxa were weighed with accuracy to 0.001 g, and soil anthracomass (mg charcoal per kg of soil, Talon *et al*., 1998) was determined from charcoals bigger than 2 mm. Charcoal samples for AMS ^{14}C dating were taken from those soil layers considered prominent from the point of view of charcoal taxonomy and stratigraphy (Table 1). One charcoal of *Picea abies* per layer was dated. In total, the age of 21 charcoal fragments was determined. Exclusively *Picea* charcoals were selected, because *Picea abies* had been the dominant treeline-forming species since at least the end of Sub-Boreal period (Rybníček and Rybníčková, 2004) and thus provide information about the presence of upper-montane forest or forest-free area.

Overall charcoal spectra of individual profiles were compared by multivariate methods in CANOCO version 4 (ter Braak and Šmilauer, 1998), and a Canonical Correspondence Analysis (CCA) was performed.

Pollen and macrofossil analysis

Pollen samples were processed using the standard acetolysis method, and at least 500 pollen grains were counted from every sample. A pollen diagram was created using POLPAL software (Walanus and Nalepka, 1999). Local pollen zones were established based on principal component analysis and constrained single link of samples (Walanus and Nalepka, 1999). A list of radiocarbon data is presented in Table 1. Simple depth–age models were constructed from this radiocarbon data, including the zero surface age, in order to assign pollen zones to approximate time periods.

Macrofossils from the Mezikotlí site were obtained by wet sieving on a 200 μm diameter mesh. Macrofossils were counted and identified using a binocular microscope (×10–50), and then volume percentages of macrofossils standardized to 20 cm^3 were derived. A simplified macrofossil diagram was created covering those species which may indicate forested or deforested landscapes.

Results

Charcoal age

The results indicate ages dating back even to the Iron Age (the summit of Praděd – S10, 120 cal. BC) (Table 1). Records dated to the early Middle Ages were found nearby at the locality S2 (AD 670 and 730). Fires were also recorded at the beginning of the ninth century (AD 830) at the summit of Králický Sněžník (S6) and at the turn of the eleventh century (AD 1110, S5) on the slopes of this same mountain.

Vegetation on summit areas was subsequently influenced by burning from the thirteenth to fourteenth centuries (S1). Evidence of fires was detected in the upper parts of the slopes and on lower-situated plateaus during the fourteenth and fifteenth centuries (S2, S3, S7 and S9). The most recent record of fire comes from the lowest part of the current forest-free area of the Hrubý Jeseník Mts (S4), where charcoal dates from the seventeenth to nineteenth centuries.

In most of the profiles, the presence of fire events at a particular site occurs with intervals of 50 to 100 years. The only exception is from the profile S2, where a fire event was found at the turn of the seventh century and then again at the turn of the fourteenth century.

Charcoal taxa identification

A total of 9112 charcoal fragments were analysed. The samples were dominated by *Picea abies* and *Vaccinium* sp. Small quantities of the light-demanding woody species *Sorbus* sp., *Salix* sp., *Betula* sp. and *Juniperus* sp. also occurred (Figure 2). Towards the surface, the presence of spruce charcoal within the profile gradually decreased, while the frequency of *Vaccinium* sp. (probably *Vaccinium myrtillus*) charcoal increased. Other woody species, which were more frequent at the bottom of the profiles, disappear completely in the middle sections and then reappear in the upper layers. The presence of *Juniperus* sp., *Sorbus* sp. and *Betula* sp. are most correlated to both the oldest dates and to the most elevated parts of the study area (Figure 3).

Profiles situated between 1432 m and 1458 m a.s.l. (S1, S2 and S3) show generally similar trends. Abundant charcoal fragments of spruce (*Picea abies*) at the bottom profile layers are replaced by *Vaccinium* charcoal towards the soil surface.

A similar species composition was found at both locations on Kralický Sněžník (S5, S6), which are situated at approximately the same elevation as the above-mentioned sites. The base layers are dominated by *Picea abies* and the frequency of *Vaccinium* sp. is very low, while the situation is reversed in the upper sections. The entire charcoal assemblage consists of just three species. The discovery of *Betula* sp. at the bottom of profile S6 is particularly interesting.

The lowermost situated profile S4 (which lies at the current timberline of 1285 m a.s.l.) shows the poorest species composition, which indicates the presence of a closed-canopy, tree species-poor forest dominated by *Picea abies*. The dating of charcoal from this profile implies deforestation at the turn of the eighteenth century.

The profiles S8 and S12, situated within the currently closed spruce forest (about 100 m below the timberline), do not contain any charcoal particles. It is thus likely that these sites were not affected by frequent fires.

The analysed samples significantly differ from each other in both species composition and mass (Figure 2). The overall mass of each individual taxa is comparable with the frequency with which it occurs, with the exception of spruce charcoal fragments which had a higher mass than numbers. This was caused by the fact that spruce charcoal fragments occurred in bigger fragments. The largest spruce charcoals were found in profile S4, whereas the highest proportion of small spruce twigs and charcoal was detected in profile S1. Profiles could be divided according to calculated anthracomass into three groups, characterised by either high (S2, S4), low (S5, S6), or variable (S1, S3) values (Table 1). Significant mass differences among individual charcoal samples were found (Figure 2B, Table 1). Both the weight of charcoal samples and anthracomass of profile S2 considerably exceed the respective values from the remaining profiles.

Pollen and macrofossil analysis

The Mezikotlí profile can be divided into three local palynological zones (LPZ) (Figure 4A). The first (M1, 128–85 cm, approximately AD 532–950) contains 70% arboreal pollen, with *Fagus sylvatica*, *Abies alba* and *Picea abies* most common (about 15% of pollen spectra). *Pinus* sp., *Betula* sp., *Alnus* sp., *Corylus avellana*, *Carpinus betulus* and *Quercus* sp. are also well represented, though less common. Pollen of *Tilia* sp. and *Ulmus* sp. is rare. The NAP spectra consist mainly of sedges and grasses (about 10%). *Artemisia* sp. and *Rumex acetosella*-type are also considerably represented. *Sphagnum* spores reveal closed curve. M1 is significant also by frequent macrofossils of *Juniperus* sp., and the presence of *Potentilla* sp. macroremains is distinct compared with other parts of the profile. The next LPZ, M2 (85–35 cm, approximately AD 950–1500), is characterised by a variable AP/NAP ratio ranging from 60 to 90%. *Picea abies* pollen dominates (40%) and the proportion of *Pinus* sp. increases (20%). In contrast, the pollen of *Fagus sylvatica* and *Abies alba* rapidly declines. The presence of other tree species is rather constant. The proportion of sedges and grasses in the NAP spectra are variable, with the most frequent pollen belonging to *Artemisia* taxa. In addition, cereal pollen and *Plantago lanceolata* appear during M2. The relative number of *Sphagnum* spores is constant. The M2 zone is also characterised by a decline in *Juniperus* sp. macrofossils and an abrupt increase in spruce needles and seeds. The LPZ M3 (35–0 cm, AD 1500–recent) is distinct because of considerable changes in the pollen spectra. The AP/NAP ratio ranges between 50 and 80%. *Picea abies* pollen is dominant (30%), though *Pinus* sp. pollen is common also (20%). The pollen of broadleaf trees occurs more or less sporadically. Grasses increase up to 20% in the NAP spectra, and the proportion of sedges is also significant. The M3 zone is characterised by a large proportion of anthropogenic pollen indicators such as *Plantago lanceolata*, Chenopodiaceae and cereals. *Calluna* and *Vaccinium* pollen reach relatively high numbers compared with the older pollen zones. In contrast, the number of *Sphagnum* spores decreases. Similarly as with pollen, *Picea abies* macrofossils gradually recede, whereas macroremains of *Juncus* sp., indicating local development, rapidly increase in number.

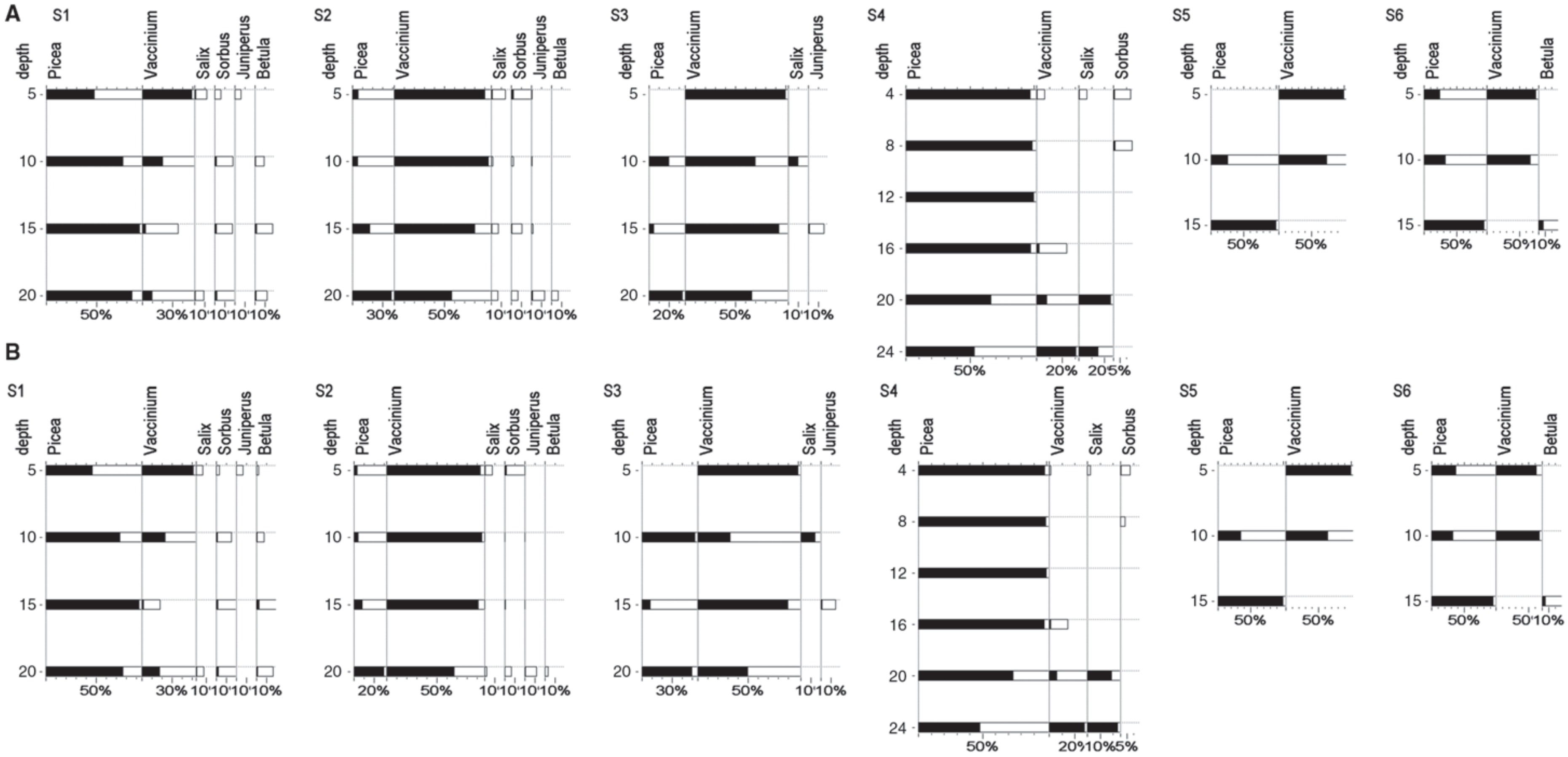

Figure 2. The relative proportion of individual taxa, (A) according to number of charcoal fragments exceeding 2 mm in size, and (B) according to their weight

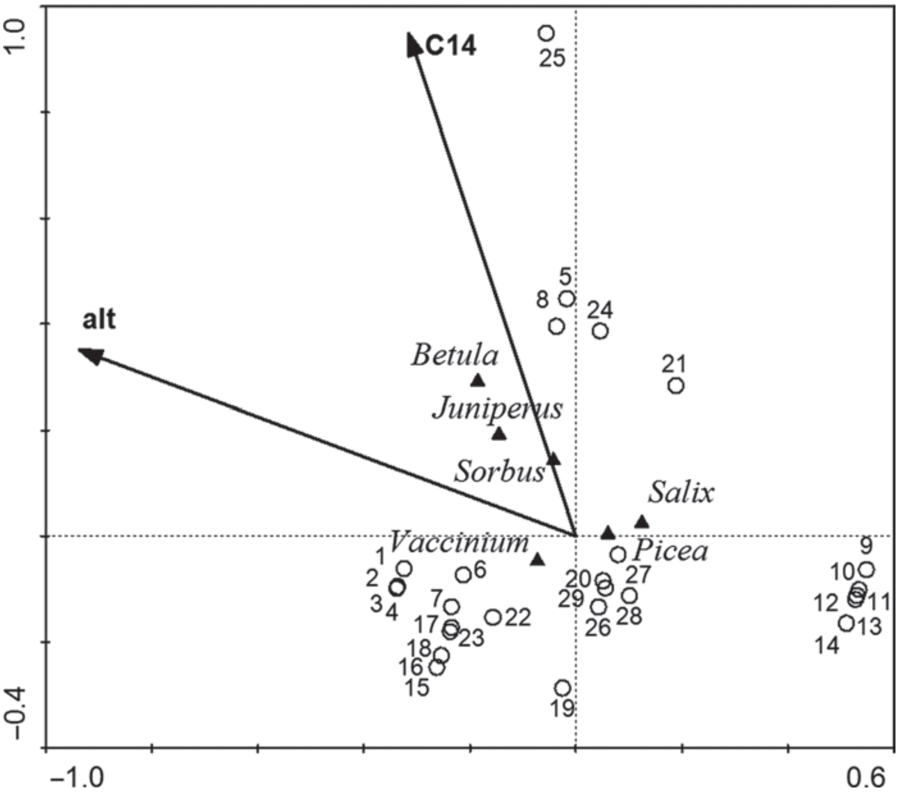

Figure 3. CCA ordination plot ($p < 0.001$, $F = 12.515$) of samples, charcoal species, charcoal ages (C14) and site altitude (Alt)

The pollen profile taken from the Stříbrnická site (Figure 4B) can be divided into four zones. Arboreal pollen composes up to 90% in the first LPZ (K1, 175–145 cm, 790–250 BC). Trees are represented mainly by spruce (20 to 40% of pollen spectra); *Fagus sylvatica*, *Abies alba* and *Pinus* sp. are less abundant (10–20%). *Corylus* sp. and *Tilia* sp. gradually decline in numbers. The NAP spectra consist mainly of grasses and sedges (about 5% of the pollen spectra), while *Calluna* sp., *Artemisia* sp. and *Vaccinium* sp. are rare. A large number of *Sphagnum* spores were recorded. No changes in the AP ratio (90%) occur in the following LPZ K2 (145–95 cm, 250–700 BC). Nevertheless, significant differences are found in the proportion of *Abies alba* (35%), *Fagus sylvatica* and *Picea abies* (20%). *Pinus* sp., *Quercus* sp., *Carpinus betulus*, *Betula* sp. and *Alnus* sp. reveal closed curves. Broadleaf trees such as *Tilia* sp., *Ulmus* sp., *Corylus avellana* and *Fraxinus* sp. occur just sporadically. The NAP spectra are similar to the K1 zone, except for a decline in *Sphagnum* spores. The proportion of AP spectra decreases to 70% in LPZ K3 (95– 5 cm, AD 700–1400). While the pollen of *Picea abies* still dominates the arboreal pollen (30%), *Abies alba* declines gradually, and *Fagus sylvatica* sharply, to 10–5% at the end of the zone. On the contrary, *Pinus* sp. pollen increases to almost 30% of the pollen spectra. The pollen of *Quercus* sp., *Carpinus* sp., *Betula* sp. and *Alnus* sp.are relatively rare. Anthropogenic indicators such as cereals, *Centaurea cyanus*, *Plantago lanceolata*-type, *Urtica* sp. and Chenopodiaceae become significant. The final LPZ K4 (45–0 cm, AD 1400–recent) has quite a complicated development. The AP spectrum declines to 55%. *Pinus* sp. and *Betula* sp. dominate the arboreal pollen spectra. *Alnus* sp., *Fagus sylvatica*, *Quercus* sp., *Carpinus betulus* and *Fraxinus* sp. are less common. The NAP spectrum contains mainly grasses (10%) and less frequent sedges. Anthropogenic indicators are significantly represented by cereal pollen, *Plantago lanceolata*, *Artemisia* sp., Chenopodiaceae and *Rumex acetosella*. However, *Centaurea cyanus* and *Fagopyrum* are rare compared with the previous pollen zone. The amount of *Vaccinium* sp. pollen is remarkable at the 10 cm depth, and the proportion of *Sphagnum* spores increases up to 5%.

Discussion

Composition of burnt plant communities

In the area above the current timberline, six species of trees and dwarf shrubs were identified by means of charcoal analysis. Charcoal assemblages were dominated by *Picea abies*; nevertheless, charcoal fragments of heliophilous broadleaf species such as *Sorbus* sp., *Salix* sp., *Juniperus* sp. and *Betula* sp. were also found. In addition, charcoal particles of *Vaccinium* sp. were common in analysed soil samples. Charcoal from heliophilous species were usually observed together with the oldest *Picea abies* charcoal and/or at the bottom layers of soil profiles. It is difficult to distinguish small charcoal fragments of *Picea abies* from *Larix decidua* (Talon, 1997), but neither larch macrofossils nor pollen have been found within any late-Holocene profile in the East Sudetes (Jankovská, 2007). Therefore these charcoal fragments are considered as being *Picea abies.*

The position of broadleaf tree species suggests that they were part of the earliest burnt plant communities. The presence of such charcoal in deeper parts of the soil profile may be explained by soil stratification being only partially preserved (Berli *et al*., 1994) or by a sufficient time period for the distribution of charcoals through the profile due to pedoturbation.

Anthracomass (milligrams of charcoal per kilogram of soil) is related to the total biomass of wood stored in ecosystem during the past fire events (Carcaillet and Talon, 2001). The amount of charcoal

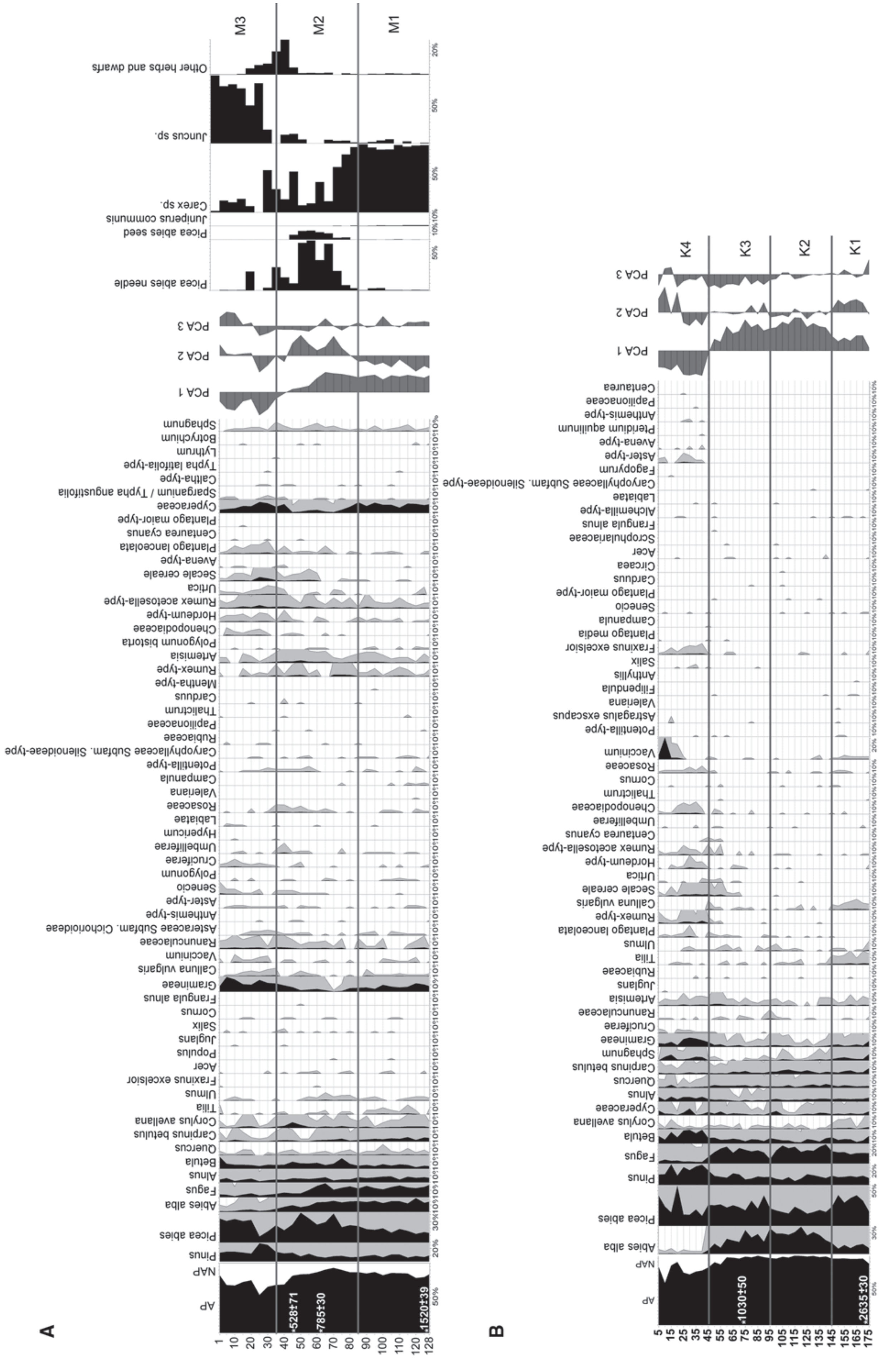

Figure 4. Simplified pollen diagrams and macrofossils from the Mezikotlí site (A) and from the Stříbrnická site (B)

therefore enables to estimate the character of burnt tree growths/forest (Carnelli *et al*., 2004). The anthracomass values measured at our sites suggest that tree growth must have been established even at the highest altitudes in the past. Anthracomass values of several milligrams to hundreds of mg/kg were found at sites S1 and S3 situated on less exposed summit plateaus. Such values correspond with those of Carcaillet and Talon (2001) from the upper range of a subalpine conifer forest, as well as to values of Schwartz *et al*. (2005) from montane forests in the Vosges. However, charcoals smaller than 2 mm, which were not included in our total charcoal mass analysis, form a prominent part of the soil anthracomass in those studies (Carcaillet and Talon, 2001).

Hundreds to thousands of mg/kg were found at sites S2 to S4. Those sites are situated on small ledges below slopes, which allowed the deposition of charcoal from a broader area; thus these profiles contain more spatially extensive information about species composition.

Anthracomass values ranging between 1 and 32 mg/kg were found at sites S5 and S6. Compared with alpine regions (Carcaillet and Talon, 2001; Carnelli *et al*., 2004; Talon *et al*., 1998) this indicates open canopy tree growths at (probably) treeline ecotone. The presence of charcoal from heliophilous species further supports this hypothesis. In addition, large amount of twigs in soil samples probably results from the burning of dense fully branched spruces which are typical for open stands. These sites are characterised by strong deflation (exposed summit and ridges) which effectively suppresses the establishment of dense tree growth.

The occurrence of forest-free patches is also indicated by the many native species of plants or insects strictly limited to forest-free areas (e.g. *Poa riphaea*, *Campanula gelida*, *Erebia epiphron* ssp. *silesiana*, Kubát *et al*., 2002; Kuras and Helová, 2002). In addition, patterned ground with pronounced relief is typical for the exposed summits and the margins of summit plateaus at our sites (Křížek *et al*., 2007). It has been supposed that pronounced patterned ground morphology would be destroyed under a closed forest canopy (Treml and Křížek, 2006).

No charcoal fragments were found at two sampled sites situated in the closed forest (S12, S13). Those sites were probably influenced by timber harvesting rather than by burning, which is more typical for open, small-sized growths (e.g. Sitko and Troll, 2008).

Dating of abrupt vegetation changes

It should be noted that the age of environmental changes indicated by the radiocarbon age of charcoal is often older than the event that we wish to date (Gavin, 2001). Trees 150 to 200 years old are presently common at the treeline ecotone in the Hrubý Jeseník Mts, so underestimations of the age of fire events may be as much as 100 years. We have attempted to take this into account when interpreting the events documented here.

The oldest radiocarbon age of charcoal suggests a fire event already during the Roman Age (around the first century BC). Other direct evidence of human-induced impact in the highest altitudes is missing, however. Trade routes passed through these mountain valleys even in the Bronze Age, when a number of settlements were present in the southern foothills of the Hrubý Jeseník Mts (Brachtl, 1985; Goš, 1969). The distance from these trade routes to the summit areas ranges between 8 and 15 km.

Similar mountain areas in the Vosges have evidence of anthropogenic impacts in summit regions dating to about 200–100 cal. yr BC (Schwartz *et al*., 2005). Several periods of human impact on the treeline ecotone since the Neolithic period have been found in the Alps (e.g. Küster, 1996; Oeggl, 2009; Tinner and Theurillat, 2003). So it is quite surprising that no direct evidence of human impact of such age has yet been found in the East Sudetes. In addition to the single dated charcoal from this study, other possible indications of the presence of humans at the highest altitudes do exist, however. For example, the formation of many ombrotrophic mires started in the period 1800–2200 ^{14}C uncal. BP (Rybníček and Rybníčková, 2004), which may be ascribed to (human-induced) paludification. Similarly, the formation of earth hummocks on the summit of Keprník Mt started about 2100 ^{14}C uncal. BP (Treml *et al*., 2008). In the Hrubý Jeseník Mts, such patterned ground is related to high-organic cryptopodzols (entic podzols), which is a common soil type on previously burnt sites. All the above-mentioned features might be also explained by natural fires and/or increase in humidity or cooling. The majority of temperature and humidity reconstructions in Central Europe, however, indicate a wetter and cooler period earlier than our data would suggest, approximately between 800 and 400 cal. yr BC (Davis *et al*., 2003; Haas *et al*., 1998; Heiri *et al*., 2003; Speranza *et al*., 2000b).

Another significant alteration of the vegetation pattern may be seen at the bottom of the Mezikotlí profile (1250 m a.s.l.), currently situated at the timberline. The frequent macrofossils of *Juniperus* sp. indicate an open forest or forest-free area in the vicinity of this profile between about AD 530 and 900. This may be linked to either pasturing or to avalanches and snow creep, which are common at the Mezikotlí site in more recent times (Cudlín, 1973). In addition, higher values of δ^{14}C were reported for the period around AD 500 (Stuiver and Braziunas, 1991), and glacier expansion plus a decrease in pollen indicating human activity has been recorded in the Alps (Holzhauser *et al*., 2005; Tinner *et al*., 2003). A negative temperature anomaly has also been reported to be expressed in diatom assemblages (Heiri *et al*., 2003) and in pollen diagrams across Central Europe (Davis *et al*., 2003). The forest-free area could thus also be linked to negative temperature anomalies and related high snow pack and an increase in avalanche frequency. All these factors might result in a retreat of the treeline ecotone. However, the human impact indicated by charcoal fragments at sites S2 and S6 could have played a role at the end of this period. Subsequently, after about AD 900, a closed forest dominated by Norway spruce once again expanded in the vicinity of the Mezikotlí site, as is shown by both macrofossils (increases in spruce stomata and needles) and by the high proportion of arboreal pollen.

Expansion of forest at the Mezikotlí site after AD 900 is, however, in contrast with the human impact at site S2 evidenced by charcoal fragments since the eighth century AD. This site was probably affected by fires considerably earlier and more frequently, as shown by the high anthracomass and the wide timespan in radiocarbon data. It has been suggested that the area around the prominent isolated rock near S2 (Petrovy kameny) was seen as a cult site where fires had been made since the Mediaeval epoch and probably even before (Waldhauser, 1972). If true, such disturbances were probably restricted to a limited area, because other proxy data (pollen, archaeological finds) do not indicate human impacts.

Good agreement was found between dated charcoal taken from the slopes of Králický Sněžník (site S5, about eleventh to twelfth century AD) and vegetation changes recorded in the corresponding pollen profile (the Stříbrnická site). Deforestation and expansion (or even the formation) of summit grasslands could thus be attributed to the end of the early Mediaeval period. Extensive human impact has also been detected during the same period in high elevation areas of the Krkonoše Mts (West Sudetes, Speranza *et al*., 2000a). The summit of the regionally dominant Králický Sněžník mountain itself was probably under moderate human influence earlier (site S6, charcoal dated to ninth century AD), similarly to the area of the Petrovy kameny rocks mentioned above (site S2).

The most extensive human-induced expansion of the forest-free area in the East Sudetes summit region occurred at the turn of the thirteenth century, as shown by the highest number of charcoal fragments and the pollen profile from the Mezikotlí site (zone M2), with the abrupt decrease of spruce macrofossils associated with the increase of non-arboreal pollen and pollen of anthropogenic indicators. Such an abrupt change in vegetation composition has been found in almost all analysed pollen profiles from summit areas of the Hrubý Jeseník Mts (Rybníček and Rybníčková, 2004). The colonisation of high elevations of the Hrubý Jeseník Mts during the fourteenth century is also documented in written sources describing iron mining in adjacent valleys (Jeník and Hampel, 1991). Frequent charcoal particles dated to the fifteenth and sixteenth centuries AD are in agreement with the development of summer farming (hay making, pasturing) in summit areas (Hošek, 1973). Nevertheless, the site S4 situated at the current alpine timberline reveals deforestation dated to as late as the eighteenth or nineteenth centuries, when human impact in the area was probably the most significant (Jeník and Hampel, 1991).

Charcoal distribution in soil profiles

From a pedoanthracological point of view, it is still challenging to interpret possible charcoal stratification in soil profiles (Berli *et al*., 1994; Carcaillet, 2001). However, stratification was not detected in four analysed profiles that had a sufficient number of both charcoal particles and radiocarbon data. We found just either one (site S1, S3, S4) or two (site S2) fire events/periods. It has been suggested that after fire events, charcoal particles are distributed through the soil profile through bioturbation, up-rooting or colluviation (Carcaillet, 2001). It seems that the longer the period elapsed after a fire, the more regular is the distribution of related charcoal throughout the soil profile. Pedoturbation led to the regular distribution of charcoal in the S4 soil profile even within a range of 100–200 years. Nevertheless, our dating strategy may be another reason that a good depth–age relation for charcoal was not found. Radiocarbon dating was applied to single charcoal particles and not to pooled charcoal fragments (Carcaillet, 2001). A rough stratification of charcoal fragments is indicated from the species composition, however (Figure 2). The proportion of heliophilous trees decreases towards the soil surface, whereas *Vaccinium* charcoals showed the opposite distribution trend. The radiocarbon data obtained are also influenced by the exclusive selection of *Picea* charcoal fragments, irrespective of their sometimes marginal proportion in the charcoal pool.

Site effects and interpretation of palaeoecological data

The development of forest-free summit areas of the East Sudetes outlined here has many features similar to other mid-mountains of Central Europe. Generally, there is a discrepancy in the dating of human impacts determined from charcoal or macroremains and that from pollen diagrams. While charcoal fragments indicate human impacts in high elevation areas already during the early Mediaeval period (East Sudetes) or even during the Iron Age (Vosges, Schwartz *et al*., 2005), pollen data mostly indicate late Mediaeval deforestation in these areas (Edelman, 1985 – Vosges; Rybníček and Rybníčková, 2004 – Hrubý Jeseník). Pollen profiles taken at exposed summit locations contain regional information, including adjacent lowlands and foothills, whereas profiles situated in valleys are more representative of local vegetation development (e.g. the Mezikotlí site). The delay in indicating human impacts from pollen compared with charcoal could be due to higher pollen production in open canopy forests and possibly also to the greater age of burnt trees, which should be subtracted from calibrated radiocarbon data in order to obtain the exact date of the fire event.

Aeolian transport of charcoal particles from lower elevations (Benedict, 2002) might also be considered in cases of extremely windy summit areas such as in the High Sudetes (Jeník, 1961). Nevertheless, we discount the significance of this factor at our sites, considering the high anthracomass detected (sites S1, S2, S4) and the good agreement of charcoal radiocarbon data with pollen profiles (sites S3, S5, S6).

Conclusions

The current extent of forest-free areas in the East Sudetes has largely resulted from past human activities. Before human-induced alterations, naturally forest-free patches were probably restricted to exposed summits, the convex margins of summit plateaus and to avalanche tracks. At the same time, summit plateaus were overgrown by open canopy tree growths dominated by *Picea abies* with frequent heliophilous tree species, diffuse into *Picea* forests on adjacent slopes.

The first possible human impacts at the highest altitudes of the East Sudetes are likely indicated by charcoal and perhaps also by the formation of ombrotrophic mires at the end of the Iron Age (about 100 BC–AD 0). Subsequent forest retreat is documented at one site at the beginning of the early Mediaeval period (about AD 500). Nevertheless, conclusive evidence of human-induced changes is still lacking. The one charcoal fragment found, the formation of mires dated to the first century BC, as well as the presence of a forest-free area after AD 500 at a site situated below a steep slope, could all be ascribed to natural processes as well, such as fires, climatic oscillations or avalanches. However, there are no doubts about the human-induced burning of tree growths on summit plateaus during the second half of the early Middle Ages (AD 800–1000). Nevertheless, the effects of those fires were probably rather local. Extensive deforestation of high elevation sites began after approximately AD 1300.

A similar tree species distribution pattern indicated by charcoal particles was identified in analysed soils. The deepest soil samples were characterised by the presence of heliophilous tree species (*Sorbus* sp., *Juniperus* sp., *Salix* sp., *Betula* sp.) with dominant charcoal particles of *Picea* sp. Broadleaf tree species decline towards the soil surface, and the *Picea abies* dominance simultaneously decreases because of the increase in *Vaccinium* charcoal mass. The specific pattern of species composition indicated by charcoal in most of the soil profiles suggests possible charcoal stratification. However, this is not at all supported by the radiocarbon data.

In general, in contrast to what has been assumed up to now, our data suggest that humans influenced the summit areas of the East Sudetes significantly earlier than in the late Mediaeval period.

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