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EFFECTS OF SKIING AND SLOPE GRADIENT ON TOPSOIL PROPERTIES IN AN ALPINE ENVIRONMENT

ABSTRACT: Topsoil properties were studied in a ski slope at Petrovy kameny, Hrubý Jeseník Mts. Effect of skiing was combined with a complex slope gradient, which comprised effects of vegetation type and soil horizons. Soil sorption complex and humification properties were expected to reflect both factors. Cation exchange capacity and to some degree saturation of adsorption complex were systematically lowered due to ski slope, and they were influenced also by vegetation type. C:N reflected vegetation type, but it reflected skiing only indirectly. The slope gradient significantly affected the soil sorption complex, yet contrary to our expectations. Several possible interpretations include species traits (litter decomposability, nutrient uptake) and patterns of topsoil horizon types, which can be associated to the history of the upper treeline.

KEY WORDS: alpine zone, humification, skiing, soil sorption complex, vegetation

1. INTRODUCTION

Skiing and related activities have created increasing anthropogenic impact to the mountainous and alpine environments in the 20th century, and has been expanding since then (Weiss *et al.* 1998). The effects of skiing have been studied since the 1970s and 1980s (*e.g.* Baiderin 1982, Bayfield 1974, Mosimann 1985). Skiing-related activities have a twofold direct effect on ecosystems of the affected mountain slopes. First, it causes disturbances due to machine grading and snow preparation during the skiing season; second, snow cover properties are substantially changed on ski slopes (Fahey and Wardle 1998, Roux-Fouillet *et al.* 2011).

Snow cover, as the major natural factor in alpine environments, affects amount and quality of light penetrating beneath soil surface, alters concentration of gases and influences water availability in vegetation season (Körner 2003). On the ski slopes, snow conditions are changed due to artificial snowing and compacting. Artificial snowing increases insulation capacity of snow cover; water from artificial snow can have fertilising effects; and it can mitigate soil disturbance due to ski slopes preparation (Rixen *et al.* 2003). Compacting on ski slopes increases snow density, hardness and heat conductivity (Keller *et al.* 2004). Gas balances are altered following snow compaction and subsequent formation of ice layers; namely O_2 concentrations decrease, while CO_2 increases (Cernusca *et al.* 1990, Newesely *et al.* 1994). The increased heat conductivity lowers snow insulation ability, which is reflected by lower soil temperature in ski slopes (Rixen *et al.* 2004). This lowers soil microbial activity (Meyer 1993) and carbohydrate reserves in the belowground biomass (Zeidler *et al.* 2008).

Soils on ski slopes are depleted of organic matter and changed in their microstructure, namely porosity decreases (Delgado *et al.* 2007). Length of vegetation season can be reduced by several weeks due to slower snow melting in ski slopes (Wipf *et al.* 2005). Changed snow conditions and disturbances in ski slopes have a direct effect to the structure and composition of vegetation (Bayfield 1980, Tsuyuzaki 1990, Titus and Tsuyuzaki 1998, Kammer 2002, Banaš *et al.* 2010) and distribution of animal species (Negro *et al.* 2009). Machine treatment of ski slopes significantly changes soil properties including chemistry and humification processes, and vegetation properties including cover, productivity and species richness (Fahey and Wardle 1998, Wipf *et al.* 2005, Roux-Fouillet *et al.* 2011).

The existing studies on effect of skiing comprise a wide scope of research. Some papers focused on the impact of artificial snowing (Mosimann 1987, Cernusca *et al.* 1990, Fissore *et al.* 1990, Rixen *et al.* 2003), other addressed the impact of ski slopes in general, looking often in a great detail at their effects to soil and vegetation parameters (Tsuyuzaki 1990, Keller *et al.* 2004, Delgado *et al.* 2007, Roux-Fouillet *et al.* 2011). Much of the research was conducted in the temperate zone of Europe, mostly in the Alps, but other regions of the world were also studied (Baiderin 1982, Fahey and Wardle 1998, Titus and Tsuyuzaki 1998, Delgado *et al.* 2007).

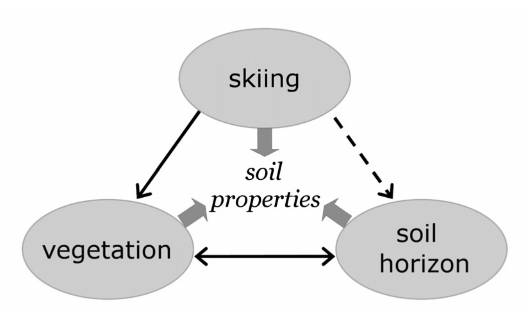

Fig. 1. Model of the studied system showing factors influencing soil properties. Soil properties are influenced by skiing, vegetation and horizon type, and the factors mutually influence each other.

In the present paper, we studied impact of skiing on soil properties in a mid-elevation mountain range in Central Europe. A complex pattern of interactions between environment and soil properties was simplified to a model with two main factors, skiing and slope gradient; the latter underlies a sequence of vegetation types (Fig. 1). Next to it, measurable soil properties correlate with visually recognizable vertical soil structures, the characteristic sequences of soil horizons (Bockheim and Gennadiyev 2000). They are result of long-term interaction of environmental factors including vegetation. The slope gradient was thus treated as a gradient of vegetation types and of horizon types, whereas only effect of the former was statistically examined.

Soil sorption complex and quality of humification were expected to vary under the influence of the both factors. We assumed that skiing would lower sorption capacity of soils, and increase C:N due to worsened organic matter decomposition under the prolonged presence of snow cover. The vegetation gradient was expected to alter the topsoil properties as well; vegetation with readily decomposable litter would result in a better quality of humus hence contributing to higher values of sorption complex and lower C:N, while vegetation with slowly decomposable litter would do the opposite. Combined effect of both factors was also expected.

2. STUDY SITE

With eight ski slopes in elevations from 1235 to 1442 m a.s.l., Praděd skiing resort is the highest elevated skiing resort in the Czech Republic. It is located in the summit area of the Hrubý Jeseník Mts. (Fig. 2). This study was conducted in the uppermost part of the resort, on the NW slope of the rock-topped Petrovy kameny (1448 m a.s.l., 50°04'N, 17°14'E). Parts of the slope prepared for skiing purposes are delimited as five downslope lanes (Bureš *et al.* 2009: supplement C). There is no artificial snowing at the resort. The studied part of the slope comprises an elevation range of 70 m. The highest point is at about 1420 m a.s.l.

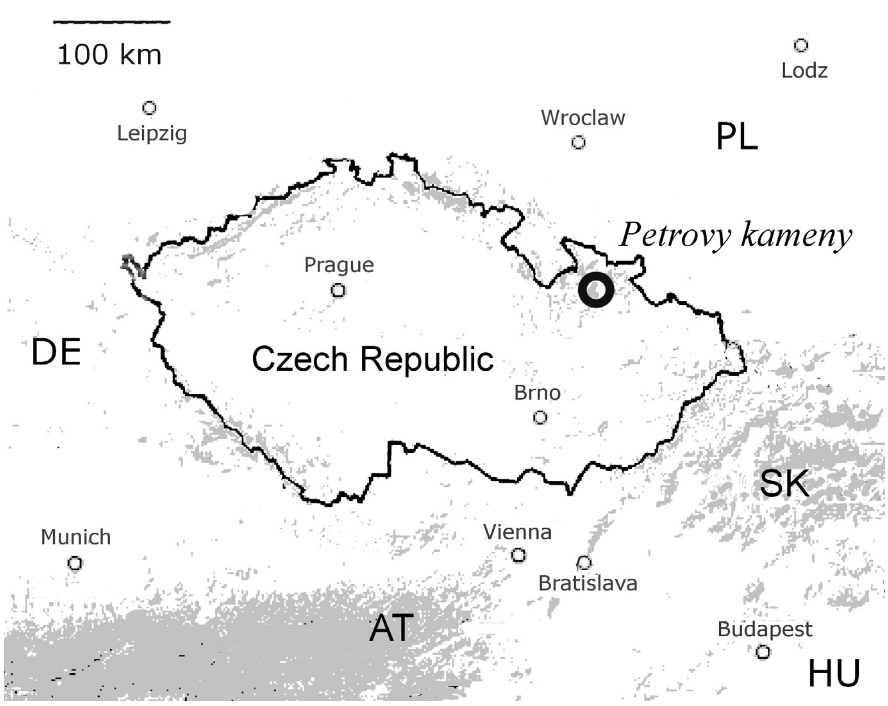

Fig. 2. Location of the study site, Petrovy kameny, in the Czech Republic.

and the lowest point at about 1350 m a. s. l., just above a frequented tourist trail. It is also above the current upper tree line located in average at 1310 m a.s.l. (Treml and Banaš 2008).

Climate is cold, with average yearly temperature of 1.1°C (Lednický *et al.* 1973; data from a nearby climatic station at the Mt. Praděd). Precipitation is 1231 mm/yr, with 200 rainy days/yr in average, and most precipitation in July. Snow cover lasts for 167 days/yr in average, from early October to the mid-May. The average maximum of snow depth is 195 cm (Tejnská and Tejnský 1972). Substrate is built of metamorphic rocks, mainly of phyllites. Soils are skeletic; content of stones larger than 20 cm is about 50% in depths of 20–50 cm, in 50–80 cm the stoniness reaches 80% (R. Hédl and J. Houška, unpublished data). Prevailing soil types are Skeletidystric Cambisols and Skeletic Podzols (FAO-ISRIC-ISSS 1998).

There has been a considerable human impact in the area surrounding the Petrovy kameny (reviewed in Bureš *et al.* 2009). Livestock pasturing can be dated back at least 300 years (Rybníček and Rybníčková 2004). One of the major chalets operated in the vicinity of the studied slope, maintaining some cattle until the 1940s. The area of Praděd has been under the strict legal protection since the 1940s–1950s when several nature reserves were established; at present, it is a National Nature Reserve. A first permitted skiing facility was established in the late 1950s and since then, skiing has heavily expanded in the Petrovy kameny (Bureš *et al.* 2009). Although there is no artificial snowing recently, the snow is intensively machine-prepared during the skiing season.

3. MATERIAL AND METHODS

3.1. Vegetation types

Despite the narrow elevation range, there is a relatively steep gradient of environmental conditions along the studied slope. Several vegetation types are distributed along the slope gradient (Bureš and Burešová 1990, Bureš *et al.* 2009: supplement F). It runs from wind-sheltered fern-dominated stands of the lower slope to a wind-swept edge of summit plateau with short shrubby and grassland vegetation. Except for plantations of non-native mountain pine, *Pinus mugo* Turra, three contrasting vegetation types occur in the area of the ski slope. They are further referred to as the *Vaccinium*, *Calamagrostis* and *Athyrium* types. There are no substantial differences between the skiing-affected and skiing-free parts of the slope, although differences in species composition were observed within the *Athyrium* type (Banaš *et al.* 2010).

1. The *Vaccinium* type comprises a vegetation mosaic of dwarf shrubs, like *Vaccinium vitis-idaea* L., *V. myrtillus* L., *Calluna vulgaris* L (Hull.), and short grasses, mainly *Deschampsia flexuosa* (L.) Trin., *Nardus stricta* L. and *Festuca supina* Schur. Mosses and lichens are common. It occupies the wind-exposed tundra-like upper part of the slope with relatively shallow snow cover (Klimešová 1993). It is an ecophysiological counterpart of the Athyrium type as snow is not a major constraint for dwarf evergreen shrubs, which are able to photosynthesize throughout winter and under the snow cover (Starr and Oberbauer 2003, Saarinen *et al.* 2011).

2. The *Calamagrostis* type is tall grassland with the dominance of the hairy reedgrass *Calamagrostis villosa* (Chaix) J.F. Gmelin. This type occupies the middle part of the slope. The grass develops belowground shoot and root system enabling its fast spreading in areas with favourable conditions. They are often sites where soil acidification and/or deforestation occurred (Fiala *et al.* 1989, 2005). Significant soil acidification over the past sixty years was documented in Hrubý Jeseník Mts. (Hédl *et al.* 2011). The *Calamagrostis*-dominated vegetation may therefore be more common in the studied slope now than it was in the past.

3. The *Athyrium* type covers the lowest quarter of the slope with thick growths of tall forbs. The dominant species is Alpine lady-fern *Athyrium distentifolium* Tausch et Opiz. The biology and ecology of this fern is rather specific. Plants make lush growths reaching over 1 m height, yet leaves are extremely sensitive to frost (Kappen 1964, McHaffie 2005). At the study site, green leaves persist only for three to four months a year. They start to unfold in late May to early June, getting a senescent rusty colour in August to September (Banaš *et al.* 2010, R. Hédl – field observation).

3.2. Soil sampling

Soil was sampled on 1 December 2006, after the end of growing season and before the arrival of the snow cover. We have distinguished for parts of the slope with skiing impact and without it (cf. Bureš *et al.* 2009: supplement C). Six neighbouring compartments were then defined by the combination of skiing impact (with or without) and the three vegetation types forming a slope gradient. In each compartment, three samples were placed in homogeneous growths. The samples representing sampling variants were all in a same compartment. Therefore, they were not statistically independent (Gotelli and Ellison 2004). Distance between samples was 30 to 50 m. Each sample accounted for about 1 kg of fresh soil taken from the upper 10 cm of the soil profile.

Horizon type was noted for each sample, varying between organomineral A and eluvial E horizon (FAO-ISRIC-ISSS 1998). Horizon A was dark, organic matter-rich soil, with no or slight signs of bleaching (uncoated white sand grains). Horizon E was grey, largely leached of humus and sesquioxides. There were transitional cases between the horizon types. They were moderately bleached, humus-rich soil with more than just occasional white sand grains; this was denoted AE horizon.

3.3. Soil laboratory analysis

After transportation from the field, soil samples were air dried and sieved. The resulting <2 mm fraction was analysed. Content of base cations (CBC) and cation exchange capacity (CEC) were measured following Zbíral (2002). Saturation of the adsorption complex (SAC) was computed as CBC×100/CEC. Values taken for statistical analysis were arithmetic averages of two parallel measurements from one sample. For calculation of C:N ratio, total carbon and total nitrogen contents were determined using the analyser LECO TruSpec (MI USA). For calibration the standard by LECO TOBACCO (502-082, Lot No.1008) was used, with the declared contents 2.45% N and 45.81% C. Gases were helium, oxygen 5.0, air medic. Temperatures were 850/950 °C, approximate soil charges were 0.1 g. Resulting values are arithmetic averages of two to three parallel measurements.

3.4. Statistical analysis

Analysis of Variance (ANOVA) was applied to test for effects of ski slope and vegetation type on soil properties (Sokal and Rohlf 1994, Gotelli and Ellison 2004). Statistica, version 10 (StatSoft, Inc. 2011) was used for computations. The effects of the combination of the factors was tested for too, denoting a mutual interaction of the impact of factors. The explanatory factor "ski slope" had two variants: presence (samples from within the ski slope) or absence (outside the ski slope). Factor "vegetation type" had three variants, corresponding to location of the samples in *Vaccinium*, *Calamagrostis* or *Athyrium* types. At the same time, the variants represent slope gradient from the upper to the lower part of the skiing slope. Variances of three soil variables were to be explained; they were two parameters characterizing the soil sorption complex, i.e. the cation exchange capacity (CEC) and the saturation of the adsorption complex (SAC), and the humification quality parameter, i.e. C:N. For an easier interpretation of ANOVA results, we used graphical visualization suggested by Gotelli and Ellison (2004). Means for variants of one factor (vegetation types, at x-axis) were connected with lines, while distinguishing for the other factor (ski slope). Standard deviations were visualized, enabling for visual assessment of variance within the groups by vegetation type-ski slope.

Role of the horizon type was assessed in two ways. The relative proportion of the horizon type (A, AE or E) in the three vegetation types was visualized using bar graphs in order to assess this potential source of variability in soil properties. Effect of horizon type on the three soil properties was tested using Welch's t test (due to unequal variances) and visualized using bar graphs. Because of the low number of cases in A horizon, it was merged with AE horizon.

4. RESULTS

All three soil parameters performed differently regarding the explanatory factors. Cation exchange capacity (CEC) was significantly influenced both by ski slope and vegetation type, however the factors were independent from each other (Table 1, Fig. 3). Saturation of the adsorption complex (SAC) was significantly influenced neither by ski slope nor vegetation type (Table 1, Fig. 4). C:N was independent from ski slope, but was significantly affected by vegetation type, effect of which was both independent from ski slope and significantly interacting with it (Table 1, Fig. 5).

CEC was systematically lower inside the ski slope than outside it. CEC values were significantly linked also to vegetation type, with highest average values in the *Vaccinium* type (82.3 mmol 100 g^{-1}) and the lowest average values in the *Athyrium* type (41.8 mmol 100 g^{-1}). The effect of ski slope on CEC clearly follows the slope gradient of vegetation types. SAC was not systematically affected by vegetation type, but it was apparently influenced by ski slope in a similar way as CEC, yet not statistically significantly. Diverting most in the *Vaccinium* type for samples from outside and inside the ski slope (33.0 and 22.4%. re-

Table 1. Results of ANOVA (F-ratio and *P*-value) showing effects of two factors and their interaction on the three analysed soil parameters: cation exchange capacity (CEC), saturation of the adsorption complex (SAC) and C:N. Statistically significant differences (*P* <0.05) are given in bold.

Factor	D.F.	CEC		SAC		C:N	
		F	*P*	F	*P*	F	*P*
Ski slope	1	**5.45**	**0.038**	0.82	0.383	0.02	0.882
Vegetation type	2	**4.88**	**0.028**	0.52	0.608	**4.88**	**0.028**
Ski s. × Vegetation t.	2	0.28	0.763	0.55	0.591	**6.71**	**0.011**

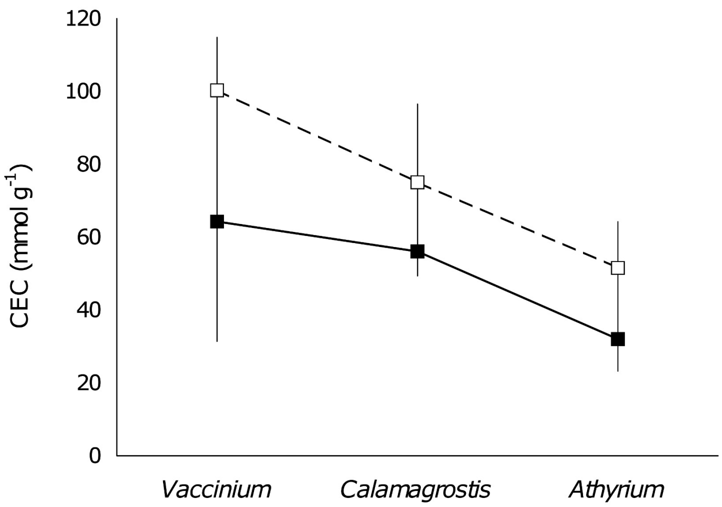

Fig. 3. Effect of skiing and vegetation on the topsoil cation exchange capacity (CEC). Averages and (squares) standard deviations (vertical lines) are shown. Full symbols and solid lines indicate soil inside the ski slope, open symbols and dashed lines stand for soils outside ski slope. Note that horizontal lines were used to highlight the effects of analysed variables, they are not trend lines. Lower CECs systematically occur in all three vegetation types inside the ski slope.

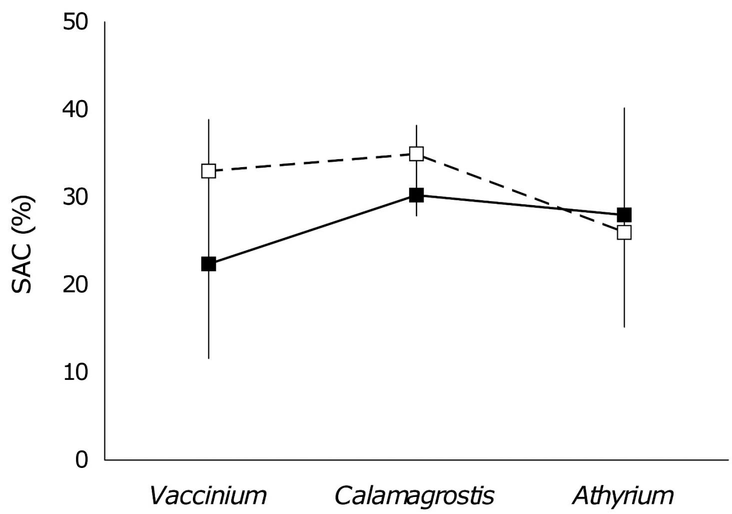

Fig. 4. Effect of skiing and vegetation on the soil adsorption complex (SAC). For explanations see Fig. 3. No clear pattern can be observed neither in the effect of vegetation type nor of the ski slope.

spectively), SAC had almost same average values in the *Athyrium* type (28 and 26%). C:N followed different patterns in all three vegetation types. While in the *Vaccinium* type C:N was in average highest observed and was almost identical outside and inside the ski slope (15.2 and 15.8, respectively), the other two vegetation types showed clearly differing patterns. In the *Calamagrostis* type, samples from inside the ski slope had smaller C:N than samples from outside the ski slope (11.8 and 15.1, respectively). On contrary, the *Athyrium* type samples had lower C:N average outside the ski slope (11.9) than it was inside it (14.5). However, relatively narrow C:N range indicate about the same humification conditions throughout the studied slope.

Soil horizon types were represented unequally among the vegetation types (Fig. 6). Whereas the *Vaccinium* and *Calamagrostis*

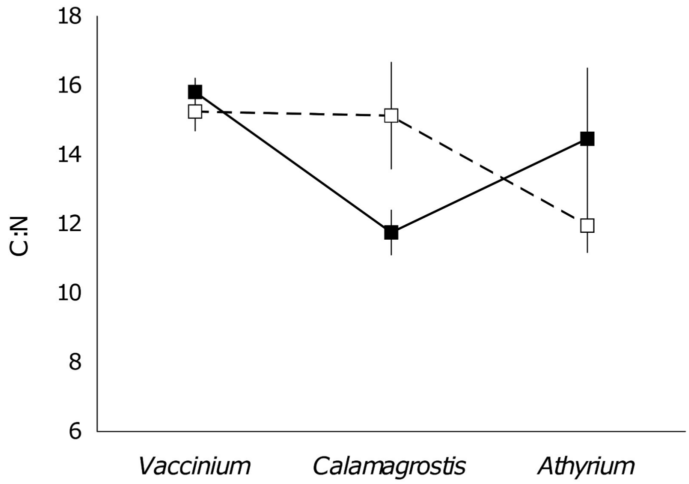

Fig. 5. Effect of skiing and vegetation on C:N. For explanations see Fig. 3. *Athyrium* vegetation type markedly influences C:N regarding the position to ski slope, yet in opposite manner than the *Vaccinium* and *Calamagrostis* vegetation types.

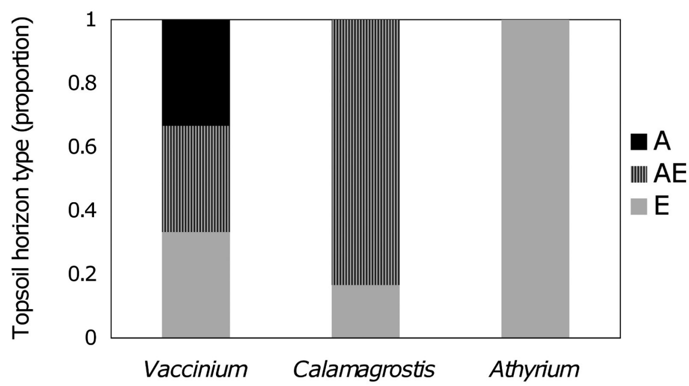

Fig. 6. Occurrence of the topsoil horizon types (A – organomineral, AE – transitional and E– eluvial horizon) varies within the three vegetation types (*Vaccinium*, *Calamagrostis* and *Athyrium*).

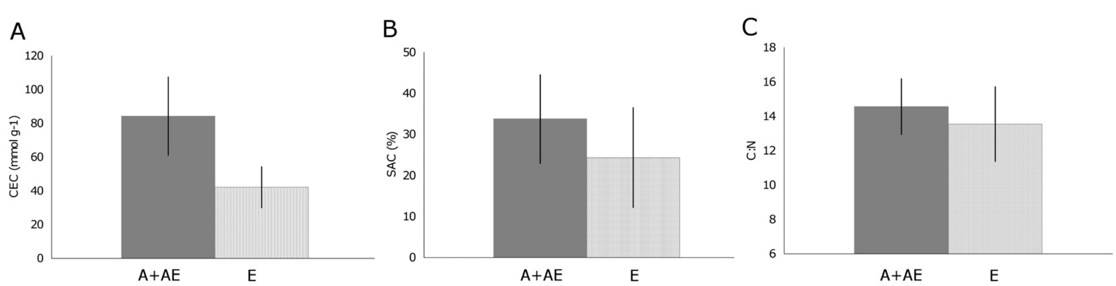

Fig. 7. Effect of horizon type (A+AE and E) on three topsoil properties: cation exchange capacity CEC (Fig. 7A), soil adsorption complex SAC (Fig. 7B) and C:N (Fig. 7C). While difference in CEC and SAC is statistically significant ($P < 0.05$), in C:N it is not. Bars denote averages, vertical lines are standard deviations.

types were linked with the organic matter rich A horizon or the transitional AE horizon, the *Athyrium* type was encountered only on topsoil formed by the humus-depleted E horizon. The effect of vegetation type therefore interfered with the effect of horizon type. The horizon type affected all three soil properties. They had lower values in A+AE horizons compared to E horizon. The difference was significant for CEC (P <0.001, Fig. 7A) and SAC (P = 0.048, Fig. 7B), but not for C:N (P = 0.306, Fig. 7C).

5. DISCUSSION

This study provided further support to research showing significant influence of ski slopes on mountain ecosystems. In our case, the focus on topsoil properties indicated that parameters of soil sorption complex were systematically lower in the skiing-affected part of slope. This confirmed our expectations. The connection was clear regardless the significant effect of the vegetation type, which did not interact with the ski slope. However, no enhancement of soil sorption complex depletion due to joint effect of both factors could be observed, in contrary to what was expected. The only exception from the general pattern was values of the soil adsorption complex in the lower slope with the *Athyrium* vegetation type. We assume that the worsened sorption properties of the topsoil are probably the consequence of five decades of snow compactation in the ski slope (Wipf *et al.* 2005, Roux-Fouillet *et al.* 2011). On the other hand, humification properties as indicated with the C:N, did not systematically worsen in the ski slope, which was contrary to expectations. Humification apparently depends on other factors including vegetation cover.

The vegetation type is clearly a more complex factor than skiing. It comprises not only differential effect of nutrient uptake and litter decomposition. In the study site, it must be linked with the gradual change in horizon types (A to E), which were classified by signs of eluviation, i.e. depletion of humus and other soil elements. This is an important distinction, because organic matter content accounts for a large part of sorption complex in podzolic soils (Schnitzer 1965). Upper parts of slope (the *Vaccinium* type) are covered with soils only partly leached of humus. In contrast, on the lower part of slope (the *Athyrium* type) only humus-depleted topsoil was encountered. The eluviation (humus depletion) gradient runs downslope coinciding with the significant decrease of CEC. Such a pattern in humus distribution may be surprising, considering that the vegetation cover should underlie an opposite gradient in CEC, i.e. its decrease upward the slope. That is, the *Vaccinium* type should produce the relatively worst decomposable litter, the *Camalagrosti*s type stands intermediate, and the *Athyrium* type with soft and easily decomposable fronds should result in soils rich in humus. An explanation should be sought in species traits. McHaffie (2005) states that *Athyrium distentifolium* produces large amounts of slow decaying litter that releases toxic compounds; consequently, an effect to litter-decomposing microorganisms can be considered. On the other hand, high-cellulose litter of *Vaccinium myrtillus* can decompose and release nutrients rather fast (Johansson 1993). Nonetheless, litter decomposition is a complex process onto which not only litter quality but also climate, herbivores and other factors take part (Facelli and Pickett 1991, Aerts 1997, Wardle *et al.* 2002). Content of soil nutrients is associated not only with litter decomposing. Nutrient uptake by dominant plant species can be equally important. Fiala *et al.* (2005) found that *Calamagrostis* prevents base cation losses from acidification-exposed mountainous soils, so may play an ameliorative role. Tůma *et al.* (2006) concluded that *Athyrium distentifolium* lowers content of Ca and Ca to Al ratio; hence its functioning is opposite to that of *Calamagrostis*, which is able to accumulate nitrogen in biomass (Fiala *et al.* 2005), lowering its content in soil and increasing C:N. This is congruent with our results.

An alternative explanation for the 'reversed' pattern in the soil sorption complex gradient is the history of the upper treeline. It can be reconstructed following the soil stratification and various kinds of deposits, such as fossil pollen and charcoal. Based on the evidence of altitudinal distribution of podzolised soils, Earl-Goulet *et al.* (1998) and Carnelli *et al.* (2004) concluded that the upper tree line was historically probably lower than at present, respectively in the mountains of Scandinavia and in the Alps. Podzolisation is associated with long-term of vegetation cover producing acidic litter, namely the coniferous forests. The historical upper tree line is thereby imprinted in soil horizons. In the studied slope, the observed distribution of the organomineral (A) and the eluvial (E) horizons suggests that the historical tree line could have intersected the slope in a higher elevation than it does at present. Subsequent lowering of the tree line should be attributed to the past human activities. There was burning at least since the Iron Age (the 1st to 2nd centuries BC), as documented with charcoal of trees including the Norway spruce, *Picea abies* L. (Karst.), and of low shrub, mainly *Vaccinium* spp. A spruce forest once covered the uppermost slopes and in open formations also the summit plateau of the Hrubý Jeseník Mts. (Novák *et al.* 2010). Mountain pasturing can be detected in pollen record from the 17th century onwards (Rybníček and Rybníčková 2004), which helped to maintain the spruce-dominated treeline in lower altitudes than it would be naturally. The 20th century with its airborne sulphuric deposits did not have a significant acidifying effect on soils in the highest elevations of the Hrubý Jeseník Mts. (Hédl *et al.* 2011). The present pattern in the soil sorption complex in the Petrovy kameny slope can be at least partly attributed to the long-term history of the upper tree line.

This study involves several potential drawbacks which may distort the general validity of our conclusions. We examined only one site and there were a low number of replicates – statistically speaking they were pseudoreplicates (Sokal and Rohlf 1994). In addition seasonal variation in soil sorption parameters (especially in the soil adsorption complex) should be considered. Furthermore, it seems to be appropriate to treat the slope gradient as a continuous variable, avoiding disputable division to vegetation types. Despite its limitations, this study demonstrated effects of skiing on soil in one of the most valuable and vulnerable natural sites of Central Europe.

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