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Snow Depth and Vegetation Pattern in a Late-melting Snowbed Analyzed by GPS and GIS in the Giant Mountains, Czech Republic

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Abstract

A large, late-melting snowbed and famous landmark was analyzed on a south-facing slope in the Giant (Krkonose/Karkonosze) Mountains, the High Sudetes, Czech Republic. So far, only its maximum snow depth, reportedly between 4 and 20 m, had been merely estimated. Wire probes can be reliably used up to snow depths of 3 m only. To get more realistic data, two digital models using kinematic carrier phase–based GPS measurements were developed: (1) a model for snow surface data, applied at the end of five winter seasons from 2000 to 2004, and (2) a model for the underlying snow free ground surface, applied after the snow melt in August 2000. These two models, overlaid in the GIS environment, have identified snow depths for each of the 111 phytosociological relevés in plots 2 m × 2 m in size. The snow depth maxima recorded in the above given winter seasons were 15.7, 6.1, 13.4, 7.6, and 14.2 m, respectively. To determine the effect of the obtained variables on the vegetation pattern, the relevant snowpack thickness together with snow melting rate, position of the relevé, amount of soil skeleton, depth of litter horizon, and depth of the soil profile were used as environmental variables in the Canonical Correspondence Analysis (CCA), which explained 23.1% of the species data variability. The most powerful environmental variables were soil parameters. The vegetation cover significantly decreased as a function of the snow depth. The tiny forb *Gnaphalium supinum* and the grasses *Avenella flexuosa*, *Deschampsia cespitosa*, and *Nardus stricta* appeared to be the most tolerant species surviving under the deep snow layer and possessing a short vegetation season. Comparison with an earlier study suggested a stabilized pattern of the snow-patch vegetation even after about 50 years.

Introduction

Uneven distribution of the snow in mountainous terrain is a well known phenomenon of alpine and arctic regions. This unevenness results in a mosaic of sites with different snowpack depth, melting date, snow-free period, and vegetation pattern. In ecology, a site with a deep snowpack and, subsequently, with a short snow-free period is called a snowbed; Gough et al. (2000) consider snowbeds to be sites where the snow cover remains for at least 4 weeks longer than in their surroundings. In physical geography the term "snowpatch" is used in similar meaning; according to Goudie (1994), a snowpatch is an isolated area of snow which may last throughout the summer and initiate processes associated with nivation. In the present paper we use the terms "snowbed" and "snowpatch" as synonyms.

The plant cover is influenced by the thickness and duration of the snowpack, both during winter, when the snow protects aboveground life from physical wind abrasion and low temperatures, and during summer when a snowbed acts as a water reservoir, prevents oxygen supply, and shortens the vegetation season. Also, snow deposition indirectly affects vegetation structure through nivation, a process of localized hillside erosion by frost action, mass wasting, and the sheet flow of meltwater at the edges of, and beneath, persisting snow (Goudie, 1994).

The snowpack in snowbeds varies from several meters (Wijk, 1986; Stursa et al., 1973) to 20 m or more (Kudo, 1991). Snow depth is reported to be highly correlated with snow melting date on sites with similar inclination and aspect; low correlation was revealed between sites with the same snow depth and different inclination and/or aspect (Klimesova, 1993). According to Kudo (1991) or Sebesta (1978), the snowmelt pattern in various years is very consistent, and the respective dates of snowmelt among microsites are very predictable (Billings and Bliss, 1959; Stanton et al., 1994). Differences in the snow melt date for the same place vary between one week (Stanton et al., 1994) and several months (Jenik, 1958; Vrba, 1964; Hejcman and Dvorak, 2001). The reason for these year-to-year differences in snow disappearance is not only the spring/summer weather conditions, but mainly different snow deposition in winter, which depends on precipitation, relevant wind speed and direction at snowfall, and subsequent wind transport and snow deposition on various lee slopes. In many snowbed studies, however, only the date of snow disappearance was observed (Stanton et al., 1994; Kudo and Ito, 1992). Lacking snow depth measurements are due to difficulty in customary snow depth surveying, which rules out the standard wire probes, and snow avalanches, which threaten the surveyor in the period of high snow accumulation.

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FIGURE 1. Situation of the investigated area in Europe and in the Giant Mountains; two locations are marked: Lucni Bouda chalet, where snowpack depths and duration of snow cover are regularly recorded, and Modry Dul valley, where the detailed study of the Map of the Republic took place.

In the Central European middle mountains, treeless alpine tundra above timberline covers only a few thousand hectares. Exceptionally snow-rich sites are rare, and a large late-melting snowbed on the warm, south-facing flank of the Giant Mountains has necessarily attracted the attention of many visitors and naturalists since the 18th century. In view of its outline resembling the shape of the state frontier of the former Czechoslovakia, a country split into two parts since 1993, some naturalists and visitors nicknamed this snowpatch the Map of the Republic. Jirasek (1915) estimated its maximum snow depth at up at 20 m, while Jenik (1958) expected 4 to 6 m only (measured at right angle to the ground). Unsuccessful attempts to measure the snow depth were performed in the winter seasons of 1961 to 1964 by Messner (Vrba, 1964); his measuring gauge was repeatedly distorted by the shear stress of the creeping snowpack, but he managed to estimate 15 m snow depth according to parallel observations on neighboring less snow-loaded slopes.

If snowpack is deeper than 3–4 m, traditional measurements by wire probes are hardly feasible. In view of this difficulty, we developed a new method based on GPS (Global Positioning System) data collection, and GIS (Geographic Information System) data processing. Without loss of precision this method enables the determination of the depth of even very thick snow accumulations and quantifies the volume of snow over a large area, e.g., for hydrological purposes.

GPS is an all-weather, global, satellite-based, round-the-clock positioning system developed by the U.S. Department of Defense. Despite the U.S. DoD's control of several "levers" constraining the GPS navigation performance available to the general public, the use of appropriate GPS techniques can determine to centimeter level accuracy the position vector between two simultaneously observing GPS carrier phase–tracking receivers. The standard mode of high accuracy differential positioning requires one GPS receiver to be located at a "base station" whose coordinates are known, while the second mobile receiver simultaneously tracks the same satellite signal. When the carrier phase data from the two receivers are combined and processed, the mobile (kinematic) receiver's coordinates are determined in relation to the reference (static) receiver (see Janssen and Rizos, 2003, and citations therein for details). To enable post-processing, data must be collected by a differential GPS (DGPS), not by a handheld tourist GPS unit of low accuracy.

In this case study we tested this new approach (1) in the measurement of snowpack thickness, and (2) in the assessment of mutual relationships between vegetation pattern, snow depth, melting rate, and soil characteristics.

Materials and Methods

STUDY SITE

Our investigation refers to the late-melting snowpatch called the Map of the Republic, situated in the Giant Mountains (Krkonose in Czech, Karkonosze in Polish), the topmost range of the Sudetes, a chain of middle mountains along the border between the Czech Republic and Poland (Fig. 1). In spite of their moderate altitude (the highest peak being Mount Snezka, 1603 m a.s.l.), the Giant Mountains display two regions with a continuous alpine timberline, large arctic-alpine ecosystems, numerous avalanche tracks, and occasional landslides (Jenik, 1961; Soukupova et al., 1995; Stursa, 1998). On the summit plateaus, average annual temperatures range between 1 and 2°C, and average annual precipitation reaches 1450 mm. Continuous snow cover persists from November to the beginning of May, with a maximum snow depth observed in March or at the beginning of April. Mean snowpack thickness reaches values of about 1.8 m (Vrbatova Bouda, meteorological station at 1400 m a.s.l., period 1963–1975).

The studied snowpatch, Map of the Republic, is situated in a nivation niche on a south-facing slope beneath the Modré Saddle (1499 m a.s.l.) between Mount Studnicni (1554 m a.s.l.) and Mount Lucni (1555 m a.s.l.). The prevailing bedrock is mica schist, and quartzite debris at the eastern edge of the area; soils are a mosaic of shallow leptosols and lithosols. The inclination of the slope surface ranges between 20° at the upper level and 37° at the bottom level of the area typically covered by snow in summer. The first written records of this snowbed appeared in the 18th century; occasional observations have been published ever since (Jenik, 1958). In most years the last snow disappears at the end of July or during the first weeks of August. The snowbed is situated mainly in the lee of the northern and northwestern winds affecting the snow deposition (a) during particular snowfall events and (b) during long-term wind loading by snow drifted from the neighboring summit etchplain. Exceptional amounts of snow and their duration on the leeward site of the Map of the Republic were described by several authors (Jenik, 1958, 1961; Vrba, 1964; Spusta et al., 2003a, 2003b).

Regular records of the snow depths and data of disappearance of the continuous snow cover are available due to measurements near Lucni Bouda chalet in the center of the etchplain; these data provide a suitable comparison with observations in the studied snowbed. In the area around the Map of the Republic, snow starts melting out usually at the end of April, and the snow persists up to the end of July or the first week of August; old observations suggest the ultimate melting date to fall in September (Partsch in Jenik, 1958); Vrba (1964) and Hejcman and Dvorak (2001) recorded the snow disappearance at the end of July. The typical area of the Map of the Republic, usually appearing in June, covers an area of about 10 ha. Jenik (1958) described the Map of the Republic as a starting zone of periodic snow avalanches which induces local soil disturbance and creates conspicuous insertion of dwarf pine (*Pinus mugo*) and distinct herbaceous vegetation into surrounding spruce forests. Vrba (1964) recorded considerable snow creeping, which was probably responsible for local landslides and soil surface disturbances in the locality.

SNOW COVER MEASUREMENT

The kinematic carrier phase–based GPS measurements with TRIMBLE Pathfinder ProXR and Pathfinder Power receivers were conducted in periods of the highest snow accumulation, i.e., in April 2000, May and June 2000, May 2001, February and May 2002, March and April 2003, and April 2004. For a greater part of the snowbed with potential high snow accumulation, relevant data were collected by parallel line measurements 2 m apart (collection of line data by walking or slow horizontal skiing or by a rope-driven sledge with a GPS receiver across the snowbed), combined with a "stop and go method" (walking followed by a stop for measurement, collection of point data; Fig. 2) applied in April 2000. Complete data for the whole snowpatch were collected in a regular network by the "stop and go method" in a later period of spring when the snow cover was safe enough for surveying. Subsequent construction of the snow surface model was performed for data sets belonging to each year. Data for the construction of the snow-free ground surface model were collected after the snow melting in mid-August 2000. We used the line measurements in a plot 400 m × 250 m in size, which covered the entire snowbed area. For the creation of digital elevation models (DEMs), the TOPOGRID command in ArcGis 8.3 (ArcInfo) was used, which generated a grid of elevations from 3-D point, line, and polygon data. This interpolation method, specifically designed for the creation of a hydrologically correct DEM, was based on the ANUDEM program developed by Hutchinson (1988, 1989) for hydrological research. All parameters in this tool were used in default. These two digital models (snow surface model and snow-free ground surface model) were both overlaid and after a simple arithmetical operation in the GRID extension of ArcInfo, the snow depths for each relevé were obtained and snow maps constructed accordingly.

MELTING RATE

The snow melting rate was recorded every year at weekly intervals in two ways. (1) In four transects, situated downward across the whole snowbed, we measured the distance of the snow-free area between the upper and bottom edge of the snowbed; wooden poles were used to indicate the margin of the snow cover each week; the GPS was used for the poles' position after complete snow recession. (2) Alteration of the outline of the melting snowbed was recorded with the GPS while walking around the snowbed. Both methods were applied every spring, starting in April 2000 and finishing after the snow disappearance in 2003.

FIGURE 2. Kinematic GPS measurement by "stop and go" method on the investigated snowbed in May 2000; each point was recorded in the course of 30 sec; antenna height of the GPS receiver was 2 m.

PLANT SPECIES COMPOSITION

Phytosociological relevés were recorded along the same four transects as where the snow melt gradients were measured. Plant cover was estimated in percentages in 2 m × 2 m square plots in September 2000. Altogether, 111 relevés were recorded in the investigated area. Nomenclature of vascular plant species follows Kubat et al. (2002).

SOIL CHARACTERISTICS

The depths of the soil profile and the litter horizon were recorded using a soil probe in all 111 plots. The soil skeleton ratio (gravel and stones) was estimated from excavated material in the soil probes according to weight share. Part of the investigated area becoming snow-free relatively early was covered by Quaternary quartzite debris. The rest of the study site with leptosols and lithosols was strongly affected by processes of nivation (Fig. 3).

DATA ANALYSIS

To evaluate multivariate vegetation data and their relation to explanatory (environmental in Canoco terminology) variables, we used Canonical Correspondence Analysis (CCA) followed by the Monte Carlo permutation test. We used the unimodal method because of the great length of the environmental gradient; all environmental data, with the exception of the relevé position only, were of continuous character. Vegetation data variability explained by a single environmental variable was used as its explanatory power measure. We used restricted

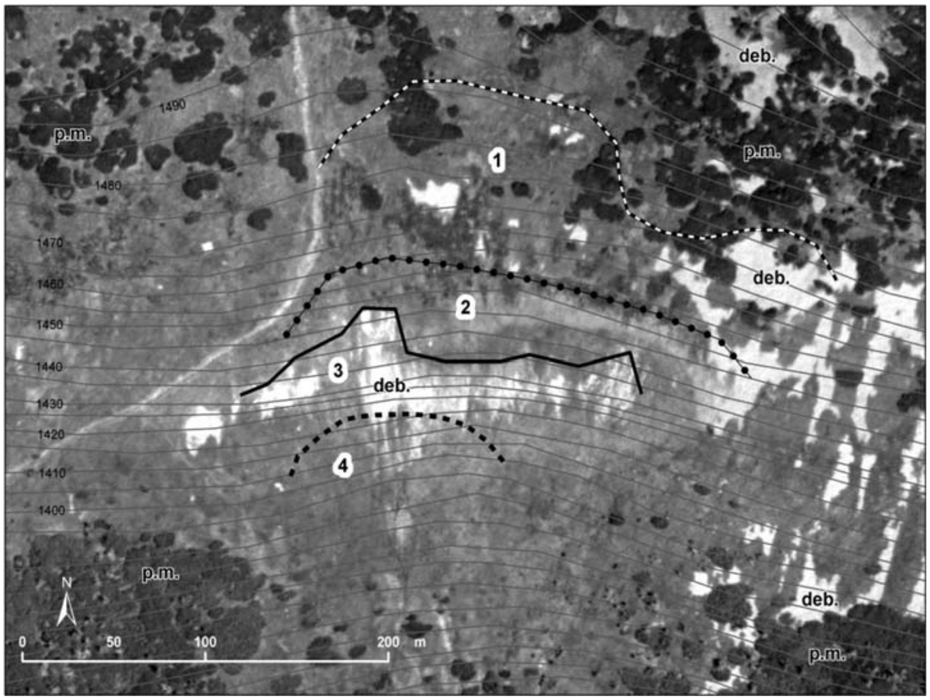

FIGURE 3. Orthophotomap of the investigated area with four zones demarcated in the nivation depression and its surrounding. (1) Zone of small depressions; white patches are Quaternary debris patches surrounded by *Calluna vulgaris*, *Vaccinium vitis-idaea*, *V. myrtillus*, and *V. uliginosum*. (2) Upper part of the nivation depression with undisturbed ground surface; the dominant plant species *Nardus stricta*, and patches of *Molinia caerulea* below Quaternary debris. (3) Main zone of active processes of nivation, with the dominant plants *Avenella flexuosa*, *Deschampsia cespitosa*, and *Gnaphalium supinum*. (4) Zone of solifluction lobes and slope debris, with *Juncus filiformis*, *Viola palustris*, and *Deschampsia cespitosa* in waterlogged soil with periodical flows. Contour interval is 5 m. The white line in the upper left hand corner is an abandoned summer footpath. Abbreviations: deb.—debris fields, on the right side of the figure Quaternary debris fields; p. m.—plants of dwarf pine (*Pinus mugo*).

permutations and a cyclic shift of samples because the data were collected in transects. Altogether 499 permutations were performed and the results of these analyses were illustrated in the form of ordination diagrams in the Canodraw program. All multivariate analyses were performed in the Canoco for Windows (ver. 4.5) program (ter Braak and Šmilauer, 1998). Spearman correlation and regression analyses were performed in the STATISTICA (ver. 6.0) program.

Results

SNOW COVER MEASUREMENTS

In the Map of the Republic snowbed, depths of the snowpack and date of snow melting were highly positively correlated. The obtained regression coefficient was 0.97 and the relationship was significant ($P > 0.001$; Fig. 4). In the center of the snowbed, the snow depth was 15.7, 6.1, 13.4, 7.6, and 14.2 m in 2000, 2001, 2002, 2003, and 2004, respectively. The depth of the snowpack depended on the winter weather, as seen in the comparison of maximum snow depths in the Map of the Republic and respective maxima at Lucni Bouda chalet (Table 1). At both localities the deepest snowpack was recorded in 2000, while the minimum depth occurred in 2001 and 2003. Despite the high yearly variability of the snow depth, the pattern of snow accumulation remained relatively stabilized, as shown in Figure 5. Maximum snow depth was recorded in the first week of April 2000, but the snow cover model in Figure 5 is from May 2000, when the snowpack was relatively shallow. Obviously, a part of the variability of the snowpack depth within individual years was caused by the date of actual snow measurements, but unfavorable weather prevented us from eliminating this factor. The depth of accumulated snow depended not only on the total amount of snow precipitation in particular winters, but also on wind direction and wind speed during and after the snowfalls. Northern and northwestern winds were favorable for snow accumulation at this locality.

The effects of snow cover on the cover of vascular plants was significantly negative ($P = 0.014$; $R^2 = -0.296$; Fig. 4). Mean vegetation cover in the early melting sites was 85%, with a high variability caused by the substrate, while only 17% cover was found in the center of the snowbed loaded with the maximum amount of snow. The low degree of vegetation cover in some early melting sites was caused particularly by the presence of quartzite debris fields of Quaternary origin.

VEGETATION STRUCTURE

Twenty-seven vascular plant species were recorded in our 111 phytosociological relevés covering the area of the Map of the Republic. According to the dominant species, we determined several vegetation units. The *Calluna vulgaris* unit (1) was present in the marginal zone of early melting edges situated on stony debris of Quaternary origin. The *Molinia caerulea* unit (2) was represented by grassland patches distributed below the zone of quartzite debris; this grass species was present only in a zone with a thick layer of rough humus emerging relatively early from the snowpack; *Polygonum bistorta* grew jointly with *M. caerulea*; this unit was predominately present above the snowbed in more favorable moisture conditions caused by water drained from the debris fields. The *Nardus stricta* unit (3) was a type of grassland tolerating a relatively high snow accumulation and a short snow-free period; a small patch dominated by this grass was developed

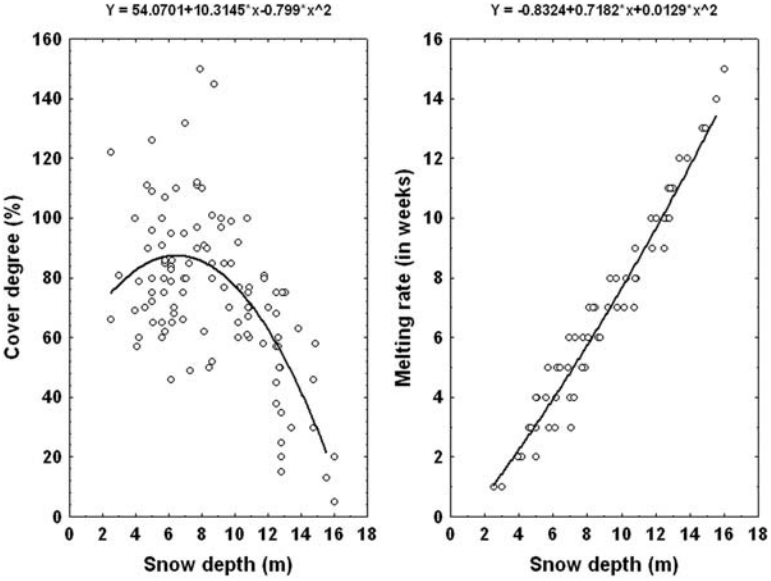

FIGURE 4. Cover degree of vascular plants (left) and melting rate in weeks from emergence of the snowbed from continuous snow cover (right) as a function of the snow depth in April 2000.

above the central part of the snowbed, in a position lacking dense vegetation. This unit evidently remains unaffected by disturbances of creeping snow and landslides (Fig. 3); *Avenella flexuosa*, *Anthoxanthum alpinum*, *Carex bigelowii*, and *Solidago virgaurea* subsp. *alpestris* with a low cover degree were associated with *Nardus stricta*. The *Avenella flexuosa–Deschampsia cespitosa* unit (4) included grasses growing on the edges of the scarcely vegetated central part of the nivation niche; optimum growth conditions of *Deschampsia cespitosa* occurred at the bottom of the snowbed, i.e., in a zone of more favorable moisture conditions caused by water running from the melting snow. The *Gnaphalium supinum* unit (5) was represented by this single forb species and occurred in the central part of the snowbed or in the area where the upper soil horizons were destroyed by landslides; the soil skeleton amounted to more than 90%, and fine earth was missing. The *Vaccinium vitis-idaea–V. uliginosum* unit (6) occurred on the debris emerging relatively early from the snow above the upper margin of the snowbed where a fermented litter horizon was only found; *Vaccinium myrtillus* formed a belt of only a few meters broad, at the bottom margin of the snowbed where less than 9–10 m of snow was recorded.

In CCA, all investigated environmental variables explained together 23.1% of the species data variability (Table 2; An. 1). Results of this analysis are illustrated in the form of an ordination diagram (Fig. 6). Depth of the litter horizons explains 10.5%, and soil skeleton present in the soil profile reflects 10.2% of the species data variability.

Snow depth explained 3.8% and the snow melting rate 3.7% of the species data variability only (Table 2; An. 5 and 6). In the ordination diagram, the relationship of plant species to environmental variables is visible: *Vaccinium vitis-idaea*, *V. uliginosum*, *Calluna vulgaris*, *Trientalis europaea*, and *Hieracium alpinum* agg. were species more common above the central part of the snowbed, where the amount of soil skeleton was high and where an early date of melting, shallow snowpack, and shallow soil profile were recorded. *Calamagrostis villosa* differs from this group by preferring deeper soils with a smaller share of soil skeleton. In Figure 6, the overlap of the arrow for depth of litter horizons (H) and triangle for *Molinia caerulea* indicates occurrence of this grass in places with favorable moisture and geomorphological conditions for litter accumulation. *Galium saxatile* and *Gentiana asclepiadea* were species more common below the snowbed (Fig. 6), where relatively deep soils developed without obvious disturbances of ground surface. *Juncus filiformis* grew below snow accumulation only where waterlogging during snow melting was present. *Viola palustris* occurred on the banks of small periodical water flows below the snowbed where fine soil particles were washed out.

Discussion

SNOW COVER MEASUREMENTS

Detailed measurements of the snow cover in the area of the Map of the Republic had never been performed, and comparable data are missing even in other regions. Earlier attempts were not successful, e.g., those undertaken with wire probes or a fixed steel pole by Messner (in Vrba, 1964). According to the experienced team of the Mountain Rescue Service in the Giant Mountains, collapsible avalanche probes serve as a reliable tool for snow measurements down to 3 m depth only. As witnessed by Billings and Bliss (1959), Stursa et al. (1973), or Klimesova (1993), wire probes can be successful in measurements of a relatively shallow snowpack. In a deep snowpack, a rapid increase of the estimation error must be expected due to the probe's flexibility and deviation from the investigated direction. For that reason we verified our GPS measurements by comparison with a probe down to 3 m, a snow depth found at the edge of the studied snowbed only. We

TABLE 1

Maximum snow depths, dates of snow disappearance, and differences between the date of disappearance of continuous snow cover, and dates of complete melting of the snowbed (in months).

	Lucni Bouda chalet		Map of the Republic		Difference between continuous snow cover and disappearance of the snowbed
Winter season	Maximum snow depth (m)	Disappearance of continuous snow cover	Maximum snow depth (m)	Disappearance of snow	
99/00	2.30	10 May	15.7	1st week of August	3 months
00/01	1.45	4 May	6.1	3rd week of June	1.5 months
01/02	2.40	17 May	13.4	2nd week of August	3 months
02/03	1.45	30 April	7.6	3rd week of June	>1.5 months

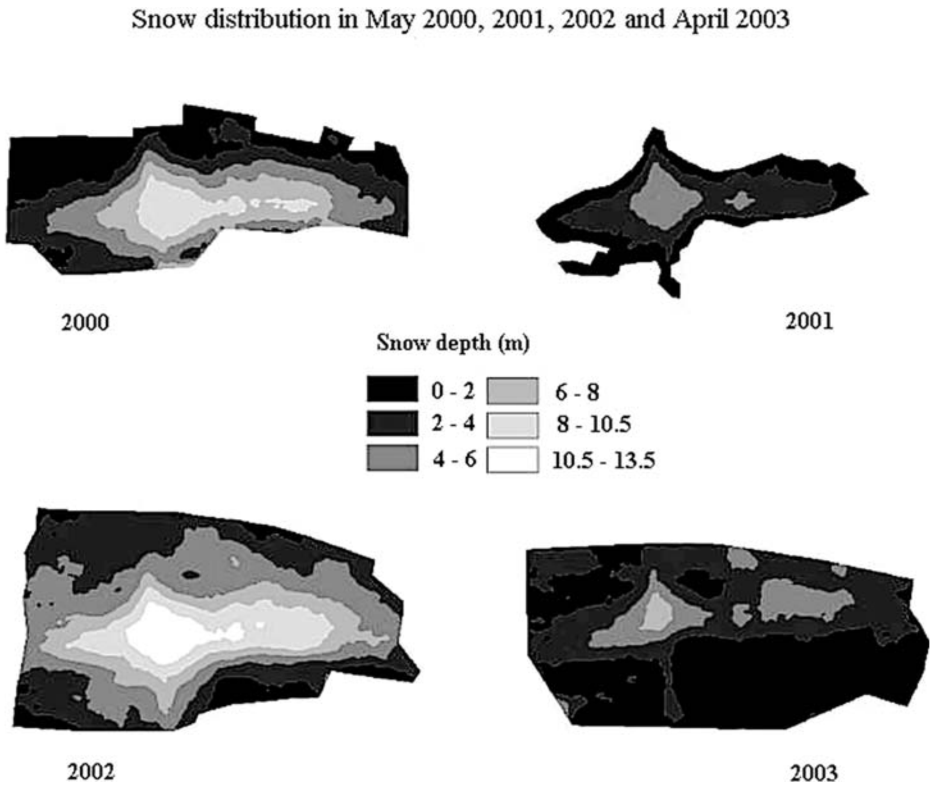

FIGURE 5. Snow cover models of the snowbed, based on snowpack depth measurement in four consecutive winter seasons in 2000, 2001, 2002, and 2003.

consider the depths obtained from our model as "fairly precise" because differences between measurements performed by a wire probe and those recorded with our new method were less than 10 cm. Verification of the snow depths in central parts of the snowbed was impossible, but realistically no decrease of precision with increasing snow depths could be expected. Indirect support for the feasibility of our measurements is the repeated yearly coincidence of highest snow thickness and place of latest melting. The human factor is evidently more decisive for the model's reliability than the centimeter accuracy level of the kinematic carrier phase–based GPS measurements; we consider the insufficient density of collected data in the dissected ground surface and changes in antenna height due to movement difficulties in the mountain landscape to be human-induced factors (Fig. 2). The advantages of our new method are (1) computation of the snow depth without decrease of precision in thick snow accumulations, (2) recording of snow depth for each point of an area, and their subsequent attribution to each vegetation relevé, and (3) quantification of snow volume and therefore water storage in the investigated snowbed.

TABLE 2

Results of CCA analyses of the cover estimates. An.—number of analyses; Expl. var.—explanatory (environmental in Canoco terminology) variables; % ax 1 (all)—species variability explained by canonical axis 1 or by all axes (measure of explanatory power of the environmental variables); *F* 1 (all)—*F* statistics for the test of the particular analysis; *P* 1 (all)—corresponding probability value obtained by the Monte Carlo permutation test. Abbreviations of the environmental variables: H—litter horizons, Ah—soil profile depth, S—soil skeleton in %, D—snow depth, M—melting rate in weeks from the emergence of the snow-bed from the continuous snow cover, P—position of the particular relevé (above or below the central part of the snow-bed).

An.	Expl. var.	Covariables	% ax 1 (all)	*F* 1 (all)	*P* 1 (all)
1	H, Ah, S, M, D, P		12.6 (23.1)	14.28 (6.1)	0.002 (0.002)
2	Litter horizons	S, Ah, M, D, P	10.5	12.48	0.002
3	Soil skeleton	H, Ah, M, D, P	10.2	12.01	0.002
4	Soil profile depth	H, S, M, D, P	7.8	8.97	0.002
5	Melting rate	H, S, Ah, D, P	3.7	4.11	0.002
6	Snow depth	H, S, Ah, M, P	3.8	4.17	0.002
7	Position	H, S, Ah, M, D	5.6	6.25	0.002

Accessibility of satellite signals was the only limitation in our procedure. If this method is applied in a narrow mountain valley surrounded by steep slopes, data collection must in many cases be limited to a time of day when a sufficient number of satellites is available for high precision measurements. According to our experience, GPS data collection can in many cases be performed without walking or skiing on dangerous slopes; in several cases we fixed the GPS receiver on a sledge driven by a rope from a safe site above the snow-patch where no avalanche hazard exists.

The majority of snowbed studies were based only on the melting rate or length of the snow-free period, irrespective of actual snow depth measurements (Stanton et al., 1994; Kudo and Ito, 1992; Tomaselli et al., 2003). A high correlation of melting rate and snow depth, found in our study, indicates that both these environmental variables gave similar results if used in an analysis of vegetation structure as explanatory variables.

A surprising feature of the Map of the Republic is the relatively high durability and stability of snow accumulation on the south-facing slope. In spite of occasional slab avalanches with a highly destructive effect recorded by Jenik (1958), these events are not frequent or regular. Spusta et al. (2003a, 2003b) recorded one avalanche moving on the ground and nine slab avalanches there within a period of 42 years from winter season 1961/1962 to 2002/2003. Most avalanches were caused by a new snow fracture during or following several days after heavy snowfall attended by strong northern or northwestern winds. Accumulation of snow from east and west is prevented by the presence of neighboring mountains ridges. Wind ripples and rills directed north–south in the snow were a direct evidence of accumulation due to snow transport from the northern etchplain. These ripples and rills, often more

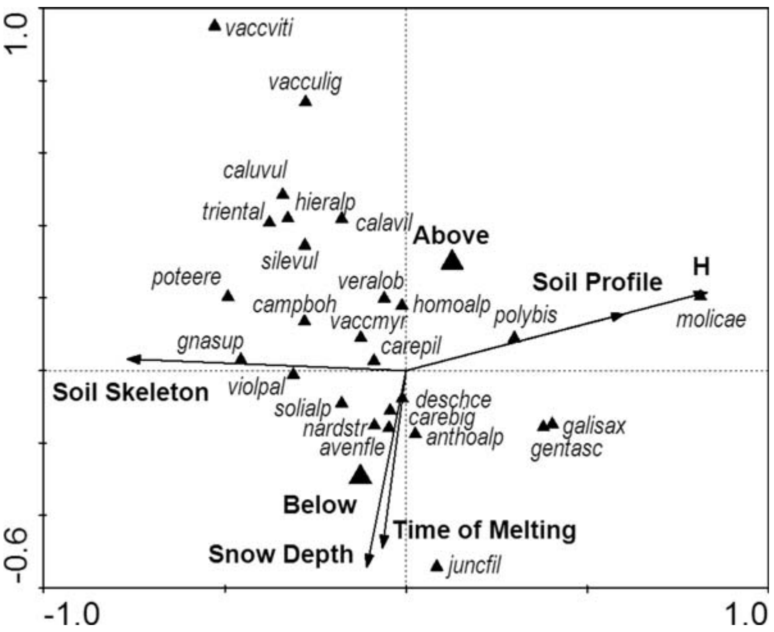

FIGURE 6. Ordination diagram showing the results of the CCA analysis (analysis no. 1 in Table 2). Environmental variables: Soil Profile—depth of the soil profile; H—litter horizons; Soil Skeleton—share of gravel and stones in %; Above, Below—position of the relevé in relation to the central part of the snowbed; Snow Depth—snow depth in meters; Time of Melting—melting rate recorded in week intervals. Species abbreviations: anthoalp—*Anthoxanthum alpinum*, avenfle—*Avenella flexuosa*, calavil—*Calamagrostis villosa*, caluvul—*Calluna vulgaris*, carebig—*Carex bigelowii*, carepil—*Carex pilulifera*, campboh—*Campanula bohemica*, deschce—*Deschampsia cespitosa*, galisax—*Galium saxatile*, gentasc—*Gentiana asclepiadea*, gnasup—*Gnaphalium supinum*, hieralp—*Hieracium alpinum*, homoalp—*Homogyne alpina*, juncfil—*Juncus filiformis*, molicae—*Molinia caerulea*, nardstr—*Nardus stricta*, polybis—*Polygonum bistorta* (syn. *Bistorta major*), poteere—*Potentilla erecta*, silevul—*Silene vulgaris*, solialp—*Solidago virgaurea* subsp. *alpestris*, triental—*Trientalis europaea*, vacculig—*Vaccinium uliginosum*, vaccmyr—*Vaccinium myrtillus*, vaccviti—*Vaccinium vitis-idaea*, veralob—*Veratrum album* subsp. *lobelianum*, violpal—*Viola palustris*.

than 0.5 m deep, were present above the investigated snowbed. It is obvious that the thickness of snow accumulation is a result of both regular snowfall and successive wind loading. The last big avalanche in 1985 resulted from a snow storm accompanied by a NNW wind blowing at a speed of 140 km h^{-1} on the day preceding the event; the crown fracture of the avalanche was 180 m long and 4 m high; snow density was 440 kg m^{-3} (Spusta and Kocianova, 1998).

VEGETATION STRUCTURE

We have determined a negative relationship between the cover of vascular plants and snowpack thickness. The negative relationship is in accordance with findings of Galen and Stanton (1999). The low regression coefficient indicates a high variability in the data and relative weakness of the relationship in the Map of the Republic. In places with a shallow snow cover, total plant cover was lower than in places with average snow depths (Fig. 4). This was predominately caused by the substrate, not by a low protective effect of the snowpack. Under a shallow snowpack, the recorded high variability of total vegetation cover degree was an undisputable proof of the variability of the substrate. Low plant cover degree was revealed on the edge of Quaternary debris fields. On the other hand, a high total cover of plants was recorded in places with a deep soil profile. Also, the depth of snow cover on the neighboring etchplain is around 2 m, and a dense plant cover is developed there. The threshold limit for the decrease of herb layer cover are snowpack depths of 1 m, providing a low protective effect and enabling plant communities of wind-exposed stands to occur there (Jenik, 1961).

The main factors causing the variability in the cover degree of vascular plants was a high soil diversity across the snowpatch, caused mainly by nivation processes and snow creeping generated by thick snow layers. Landslides disturbed the soil surface in a range of areas differing in snow depth, namely in the upper part of the snowbed. *Gnaphalium supinum* was strictly restricted to these sites, with a low participation of the other species. Surprisingly, *Salix herbacea*, a typical snowbed willow in the Central European mountains, does not grow in the study area despite its scattered occurrence in the surrounding area; unlike *Gnaphalium supinum*, the smallest willow evidently prefers snowbeds with a relatively stable soil surface. The preference of *Salix herbacea* for "stable nivation niches" is in agreement with a study performed in the Apennines by Tomaselli (1991).

The share of plant species variability explained by melting rate or by snowpack depth gradient was surprisingly small, in contrast to the high variability explained by soil parameters. Evidently, one explanation could be a high variability of the soil, and a high degree of soil disturbance created by solifluction, snow creeping, and especially by snow and firn erosion. The low explanatory power of the melting rate is in sharp discrepancy with findings of Stanton et al. (1994). The snowpack thickness gradient is obviously decisive for vegetation development in snowbeds with a quiet, stabilized ground surface, which is not the case in the Map of the Republic with high dynamic nivation processes on a sloping ground surface. We should not forget, however, that the majority of soil variability in the snowbed was caused by nivation; to divide strictly the effect of snow and soil parameters is simply impossible, and all environmental parameters determining plant growth must be evaluated jointly. Another factor probably responsible for the weakness of the snow gradient as a predictor of plant responses was the absence of specialized snowbed species in our study, in comparison with other studies performed in extensive tundra or alpine environments (see Hirano and Kudo, 2004; Komarkova, 1993; Sandvik and Heegaard, 2003; Sandvik et al., 2004;

Vanderpuye et al., 2002). In our locality, changes in plant composition in relation to the snowpack gradient were thus in many cases just quantitative, not qualitative.

Presence of *Agrostis rupestris* was recorded in the central part of the snowpatch Map of the Republic, yet this species was excluded from our analyses because of its low abundance in the transects. A stand dominated by *Nardus stricta* was restricted to the area of medium melting date, on the ground surface obviously lacking any mechanical disturbance. *Nardus stricta* is evidently able to cope with a deep snowpack and short growing season, but it is unable to regenerate under frequent disturbances, in contrast to the grasses *Avenella flexuosa* and *Deschampsia cespitosa*. In similar conditions, *Nardus stricta* is a frequent snowbed species also in other European mountains, from the Mediterranean to Scandinavia (Jenik, 1961; Krahulec 1985; Palacios et al., 2003; Thebaud and Etlicher, 1997; Tomaselli, 1991).

A similar case of *Nardus*-dominated patches and the distribution of other vegetation patches including *Molinia caerulea*, *Gnaphalium supinum*, *Deschampsia cespitosa*, and *Avenella flexuosa* in relation to snow cover were first described by Jenik (1958). He used a different method in data collection and therefore his chosen statistical approach was inappropriate to compare with ours. In spite of this, it is evident that after nearly half a century the vegetation structure of the Map of the Republic snowbed has remained stabilized. The vegetation pattern and soil disturbance are evidently long-term features as confirmed by similar vegetation and substrate patterns recorded in the area in 1954 and 2003.

Conclusions

We tested a new method for measuring snowpack thickness based on GPS data collection and its procession in a GIS environment. Further we showed the applicability of snow depth data in the research of snowbed vegetation. We consider our method to be a satisfactory procedure to measure snowpack depths and quantify snow volume with a high accuracy even over a large area. Snowpack depth and melting rate were highly positively correlated, thus indicating their similar explanatory power if used in the analysis of vegetation patterns. In the case of our snowbed, soil parameters explained the highest share of vegetation variability. Distribution of soils was strongly affected by snow accumulation due to processes of nivation. Based on comparison with earlier observations published by Jenik (1958), vegetation pattern and soil features are long-term phenomena of snow-rich areas.

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References Cited

Billings, W. D., and Bliss, L. C., 1959: An alpine snowbank environment and its effects on vegetation, plant development and productivity. *Ecology,* 40: 388–397.

Galen, C., and Stanton, M. L., 1999: Seedling establishment in alpine buttercups under experimental manipulations of growing-season length. *Ecology,* 80: 2033–2044.

Goudie, A. (ed.), 1994: *The Encyclopedic Dictionary of Physical Geography.* Second edition. Oxford: Basil Blackwell Ltd.

Gough, L., Shaver, G., Carroll, J., Royer, D., and Laundre, J., 2000: Vascular plant species richness in Alaskan arctic tundra: the importance of soil pH. *Journal of Ecology,* 88: 54–66.

Hejcman, M., and Dvorak, I. J., 2001: Kolik snehu lezi na Mape republiky? *Krkonose,* 37(1): 8–9.

Hirano, A. S., and Kudo, G., 2004: Landscape genetics of alpine-snowbed plants: comparisons along geographic and snowmelt gradients. *Heredity,* 93: 290–298.

Hutchinson, M. F., 1988: Calculation of hydrologically sound digital elevation models. *Third International Symposium on Spatial Data Handling*, Sydney. Columbus, Ohio: International Geographical Union.

Hutchinson, M. F., 1989: A new procedure for gridding elevation and stream line data with automatic removal of spurious pits. *Journal of Hydrology,* 106: 211–232.

Janssen, V., and Rizos, C., 2003: A mixed-mode GPS network processing approach for deformation monitoring applications. *Survey Review,* 37(287): 2–19.

Jenik, J., 1958: Geobotanical study of the avalanche field in Modry dul valley in the Giant Mountains. *Acta Universitatis Carolinae Biologica,* 5(1): 47–91.

Jenik, J., 1961: *Alpine vegetation of the Giant Mountains, Kralicky Sneznik, and Hruby Jesenik Mountains.* Praha: Academia.

Jirasek, F. J., 1915: *Heimatkunde des Hohenelber Bezirkes*, Bd. III.: 250–350, Vrchlabi.

Klimesova, J., 1993: Alpine plant communities with *Nardus stricta* in the Hruby Jesenik Mountains. *Preslia,* 65: 63–75.

Komarkova, V., 1993: Vegetation type hierarchies and landform disturbance in arctic Alaska and alpine Colorado with emphasis on snowpatches. *Vegetatio,* 106: 155–181.

Krahulec, F., 1985: The chorologic pattern of European *Nardus*-rich communities. *Vegetatio,* 59: 119–123.

Kubat, K., Hrouda, L., Chrtek, J., jun., Kaplan, Z., Kirschner, J., and Stepanek, J. (eds.), 2002: *Key to the Flora of the Czech Republic.* Praha: Academia.

Kudo, G., 1991: Effects of snow-free period on the phenology of alpine plants inhabiting snow patches. *Arctic and Alpine Research,* 23(4): 436–443.

Kudo, G., and Ito, K., 1992: Plant distribution in relation to the length of the growing season in the Taisetsu Mountains, northern Japan. *Vegetatio,* 98: 165–174.

Palacios, D., Andres, N., and Luengo, E., 2003: Distribution and effectiveness of nivation in Mediterranean mountains: Penalara (Spain). *Geomorphology,* 54: 157–178.

Sandvik, S. M., and Heegaard, E., 2003: Effects of simulated environmental changes on growth and growth form in a late snowbed population of *Pohlia wahlenbergii* (Web. et Mohr) Andr. *Arctic, Antarctic, and Alpine Research,* 35: 341–348.

Sandvik, S. M., Heegaard, E., Elven, R., and Vandvik, V., 2004: Responses of alpine snowbed vegetation to long-term experimental warming. *Ecoscience,* 11: 150–159.

Sebesta, J., 1978: Snow patches on the Czech side of the Giant Mountains. *Opera Corcontica,* 15: 25–49.

Soukupova, L., Kocianova, M., Jenik, J., and Sekyra, J. (eds.), 1995: Arctic-alpine tundra in the Krkonose, the Sudetes. *Opera Corcontica,* 32: 5–88.

Spusta, V., and Kocianova, M., 1998: Avalanche cadastre in the Czech part of the Krkonose Mts. (Giant Mts.) during winter seasons 1961/62–1997/98. *Opera Corcontica,* 35: 3–205.

Spusta, V., sen., Spusta V., jun., and Kocianova M., 2003a: Snow deposition on leeward slopes of the Czech part of the Giant Mountains (Tundra zone). *Opera Corcontica,* 40: 87–104.

Spusta, V., sen., Spusta V., jun., and Kocianova M., 2003b: Avalanche cadastre and winter condition in summit area of the Giant Mountains (Czech part) during 1998/99–2002/2003. *Opera Corcontica,* 40: 108–102.

Stanton, M. L., Rejmanek, M., and Galen, C., 1994: Changes in vegetation and soil fertility, a predictable snowmelt gradient in the Mosquito Range, Colorado, U.S.A. *Arctic and Alpine Research,* 26: 364–374.

Stursa, J., 1998: Research and management of the Giant Mountains' arctic-alpine tundra. *Ambio,* 27: 358–360.

Stursa, J., Jenik, J., Kubikova, J., Rejmanek, M., and Sykora, T., 1973: Snow cover of the Western Giant Mountains in the abnormal winter 1969/1970, and its ecological meaning. *Opera Corcontica,* 10: 111–146.

ter Braak, C. J. F., and Šmilauer, P., 1998: *CANOCO Release 4. Reference manual and user's guide to Canoco for Windows: Software for Canonical Community Ordination.* Ithaca: Microcomputer Power.

Thebaud, G., and Etlicher, B., 1997: *Nardus* communities on the Monts du Forez (France) and their snow patch environment. *Acta Botanica Gallica,* 144: 217–230.

Tomaselli, M., 1991: The snow-bed vegetation in the Northern Apennines. *Vegetatio,* 94: 177–189.

Tomaselli, M., Bernardo, L., and Passalacqua, N., 2003: The vegetation of the *Ranunculo-Nardion* in the Southern Apennines (S Italy). *Phyton-Anales Rei Botanicae,* 43: 39–57.

Vanderpuye, A. W., Elvebakk, A., and Nilsen, L., 2002: Plant communities along environmental gradients of high-arctic mires in Sassendalen, Svalbard. *Journal of Vegetation Science,* 13: 875–884.

Vrba, M., 1964: Snehova akumulace v lavinove oblasti Modreho dolu v Krkonosich. *Opera Corcontica,* 1: 55–70.

Wijk, S., 1986: Performance of *Salix herbacea* in an Alpine snow-bed gradient. *Journal of Ecology,* 74: 364–375.

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