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ORIGINAL PAPER

GEOSCAPE

The relation of alpine vegetation cover and geomorphic processes in the Belianske Tatra Mts. (Slovakia)

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Abstract

The geomorphic processes in high-mountain environments are crucial and often limiting factors of vegetation development. Studies based on the long-term field monitoring are still scarce, however, thus limiting our understandng to vegetation dynamics and the knowledge needed for effective conservation management. In this paper we interpret results of a 20 years long observation considering the relationship between alpine vegetation and intensity of geomorphic processes in the territory of seven permanent plots in the Belianske Tatra Mts. (Slovakia, Central Europe). In principle, these sites represent a "battle field" for ongoing geomorphic processes and vegetation. They are either gradually occupied by initial stages of ecological succession of vegetation or were occupied in the past with the vegetation being more or less destructed. The field research was combined with data collection for standard phytosociological relèves. Spatial distribution of particular tussocks or individuals on each field was drawn in detail. We observed the share of species and their spatial arrangement in relation to the control sites with uncovered substrate. Special attention was paid to measuring the intensity of geomorphic processes using various methods and carried out three times a year. The CANOCO software was used for quantitative evaluation of the phytosociological relèves data. We applied indirect gradient analysis of principal components (PCA) to find out the variability of vegetation and sites, and the direct gradient analysis (RDA) to explain the diversity of species ad the habitat characteristicsThe geomorphic processes affecting the extreme high-mountain environment were evaluated as the most crucial elements that determine the spatial distribution of vegetation, its particular species or overall nature of coppice fragmentation. The relief and mainly its spatial geomorphic attributes are therefore relevant phenomena of landscape that enable scientists to understand, for example the scale and hierarchy of vegetation arrangement. The relationship of vegetation and the intensity of geomorphic processes can be only considered and generalized on the basis of long-termed research.

Highlights for public administration, management and planning:

- We performed a 20 years long observation considering the relationship between alpine vegetation and selected geomorphic forms and processes at seven pemamanent plots in the Belianske Tatra Mts.
- We identified interesting plant species that colonize individual forms and microforms of the relief in the periglacial zone.
- We argue that long-term research represents a significant contribution to the knowledge of vulnerable high-mountain landscape and, subsequently, to its further development, conservation management, and environmental planning.

Keywords

Geomorphic processes, Alpine vegetation, Permanent plots, Belianske Tatra Mts., Slovakia

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1 Introduction

The vegetation cover of the Tatra high-mountain landscape (Slovakia, Central Europe) with its species composition, physiognomy and spatial arrangement significantly reflects the sum of the impacts of all habitat factors in specific georelief conditions. However, in addition to the prevailing combined effects of wind and snow cover depending on the georelief conditions, a significant factor limiting the localization of the vegetation cover in the high-mountain relief consists mainly in the destruction itself by certain types of predominant geomorphic processes (Midriak 1983).

For this reason, it is necessary to focus on the more detailed research of the high-mountain landscape or its functioning. Landscape consists of a mosaic of abiotic components and, together with the vegetation, these are not arranged randomly but based on certain principles and rules. Studying them helps clarify the complex relationships between the respective components and plant species, the knowledge of which is necessary for the care and management of high-mountain areas established on exact scientific basis. With respect to the global changes ongoing on our planet, improved care of high mountains, which comprise an important source of water and biodiversity, will be a significant phenomenon. Global biodiversity is being rapidly reduced with potential consequences for humankind, thus the high mountains play a key role in sustaining the planet's biodiversity potential. For this reason, in the recent decades the research has been focusing on the more detailed knowledge of high-mountain environment, as well as the utilization of knowledge obtained in this way in various types of analyses, syntheses, and assessments, e.g. when dealing with the practical issues of nature and land protection. Complex research of vegetation and site conditions brings a lot of data. In this context, application of statistical methods has an increasingly important position in geographical and environmental research (Falťan et al. 2020).

Vegetation or its individual species respond to different destructive impacts differently. Therefore, some areas are populated by typical plant communities - often with a variety of plant species. These are often also a reliable indicator of the aeolian destruction of the surface (Šmarda 1956, 1964a) and snow erosion (Kozłowska & Rączkowska 1996, 2006), displacing the vegetation cover due to avalanches, debris flows, debris shifts (Šmarda 1964b), debris creeping, the cryogenic gravitational processes, tracking out the land by tourists, etc. (Midriak 1983). The most interesting species include those that colonize individual forms and microforms of the relief, structural and frosty soil forms, edges of nivation and aeolian forms, talus and debris flow cones or flow slopes affected by solifluction, creeping of debris, avalanche falling, etc. Considering the fact that the various forms were created by several geomorphic processes (polygenetically), the vegetation is distributed according to the consequences of these processes in the soil-geest cover (Midriak 1983). These aspects were highlighted in the works of Šmarda (1956); Plesník (1956); Gerdol and Smiraglia (1990); Kotarba (2005); Kozłowska et al. (2007); Hreško and Boltižiar (2001); Boltižiar (2001, 2009); Barka (2004); Gądek et al. (2016); Rączkowska et al. (2015, 2016a,b); Piscová et al. (2023) and others. Belianske Tatry Mts., thanks to their location, were not hit by the strong windstorm disturbance in the Tatra National Park in 2004, total area of valuable alpine vegetation has changed minimally (Falťan et al. 2009, 2021).

Our research focuses on the detailed monitoring of the spatial distribution of the areas of soil-geest covers of the Belianske Tatra Mts. in relation to the effects of geomorphic processes, which appear to be key and often limiting factors of vegetation development in this environment.

2 Study area

The Belianske Tatra Mts. are located in the north part of Slovakia near the border with Poland and they are a part of the Tatra Mountains - the highest mountain range within the Carpathians (Fig 1, Table 1). They are legally protected by the establishment of the Tatra National Park (1949) in Slovakia which is jointly entered in UNESCO's World Network of Biosphere Reserves (1993).

The Belianske Tatra Mts. consist of limestones, dolomites, marls, marly slates and exceptionally also quartz sandstones. The relief is characterized by smooth surface with rock defiles and a whole series of sharp-crested ridges, hogbacks and narrow segments of transversal valleys on limestone, dolomite and quartz sandstone. On marls and marly slates, erosive-denudative furrows, saddles and widened segments of valleys were formed (Lukniš 1973). Some types of limestone present in the Tatra Mts. are particularly prone to karstification.

A considerable part of the Belianske Tatra Mts., namely from a height of 1 600 m above sea level upwards, is located within a periglacial morpho-

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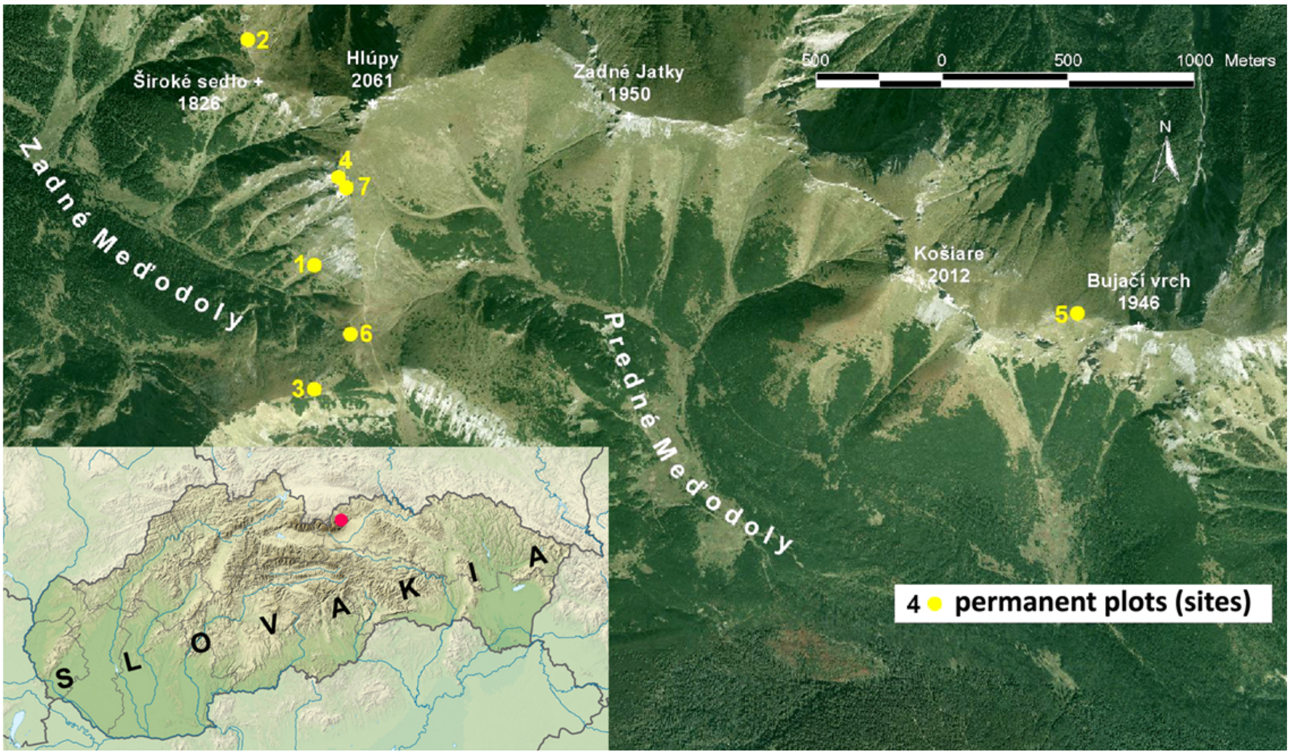

Fig. 1 Orthophoto with selected permanent plots/sites and map with localization of the study area Belianske Tatra Mountains. Source orthophoto: © Eurosense s.r.o. (2002).

climatic belt with relict periglacial landforms with some types of limestone karstify. It is typified by intensive frost weathering and formation of talus below rock walls. Relict forms comprise rock glaciers nival ramparts, debris covers, as well as large sorted circles and polygons. Most of these landforms developed in the Late Pleistocene. Other landforms - small sorted polygons, periglacial vegetation – soil features, i.e. bald soils and garland soils, patterned ground, stone-festoons, solifluction sheets and thufurs are active at present, mostly because of seasonal and diurnal oscillations of ground temperature around 0° C. The present-day geomorphic activity corresponds to the altitudinal climatic and vegetation belts, with the major importance of rapid mass movements like rockfalls, rockslides, debris flows, gelivation, solifluction, deflation, nivation, etc. (Boltižiar 2022). Snow avalanches are a special phenomenon (Rączkowska et al. 2016a; Boltižiar et al. 2016).

The morphodynamic phenomena of the high-mountain landscape are characterized by high dynamics and frequency of geomorphic processes, extreme disturbance effects on the landscape, which are remarkably reflected also in the changes of the vegetation patterns.

3 Methodology

The vegetation cover is monitored in more detail in the localities of Belianske Tatra Mts. For this purpose, 7 representative permanent observation plots (PP) of 4x4 m have been established so far in 2002. Their position and altitude were measured with GPS and integrated into GIS. The selection of the plots at the sites was also determined by comparing the current state of the sites and their state in the past, which is captured on archive aerial photographs and terrestrial photographs. Based on this comparison, it was evident that there have been changes due to the effects of geomorphic processes, as well as progressive succession. However, when subject to extreme intensive processes (e.g. catastrophic debris flows, strong deflation, avalanches, etc.), succession can be stopped or disappear for a long time, yet its progress is also influenced by species competition. The selected sample sites represent, in essence, the ”battlegrounds” of struggle between the ongoing geomorphic processes and vegetation which either gradually occupies them in the form of initial stages or possibly occupied them in the past and was/is subsequently more or less destroyed (Fig. 2).

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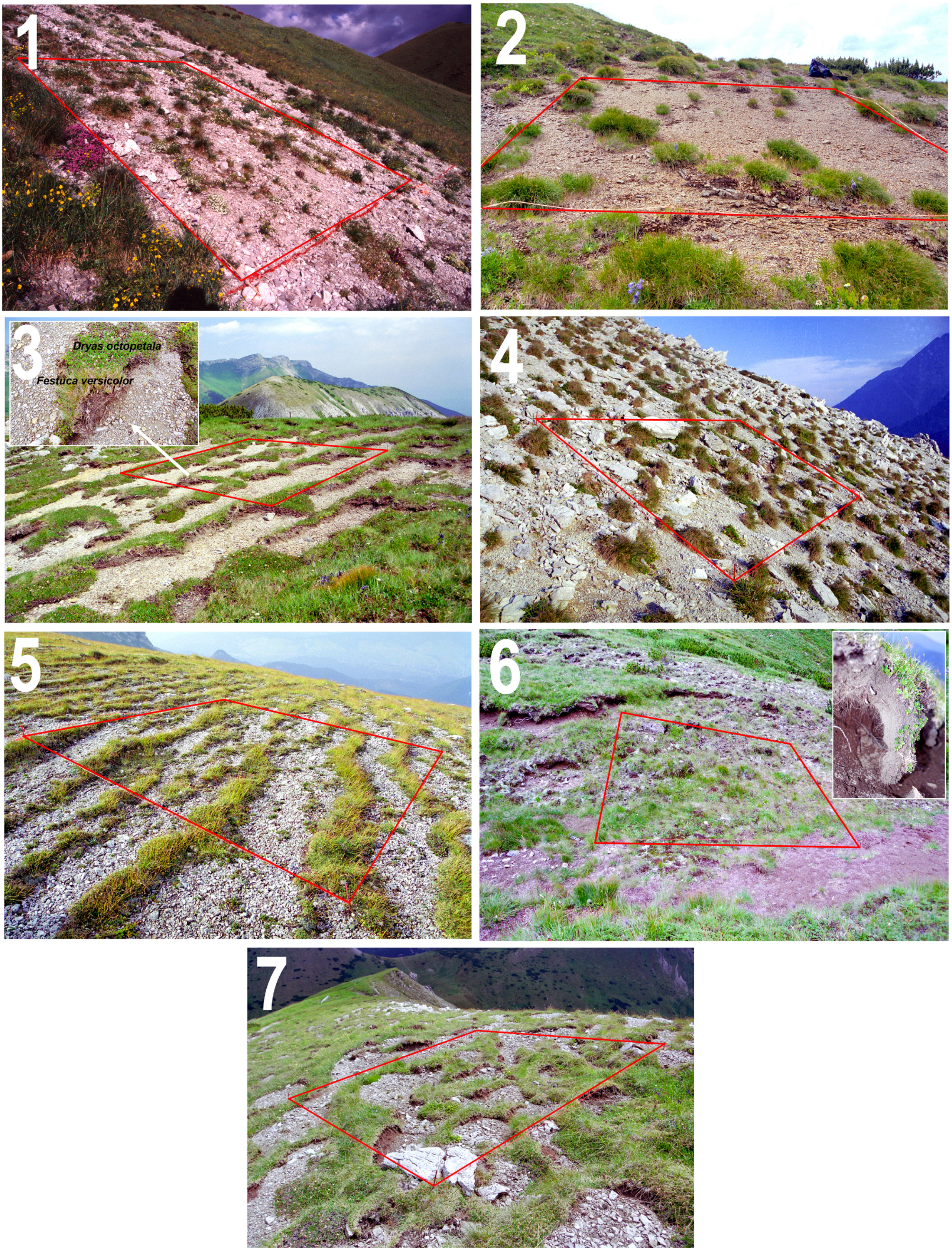

Fig. 2 Permanent sample sites in the Belianske Tatra Mountains.

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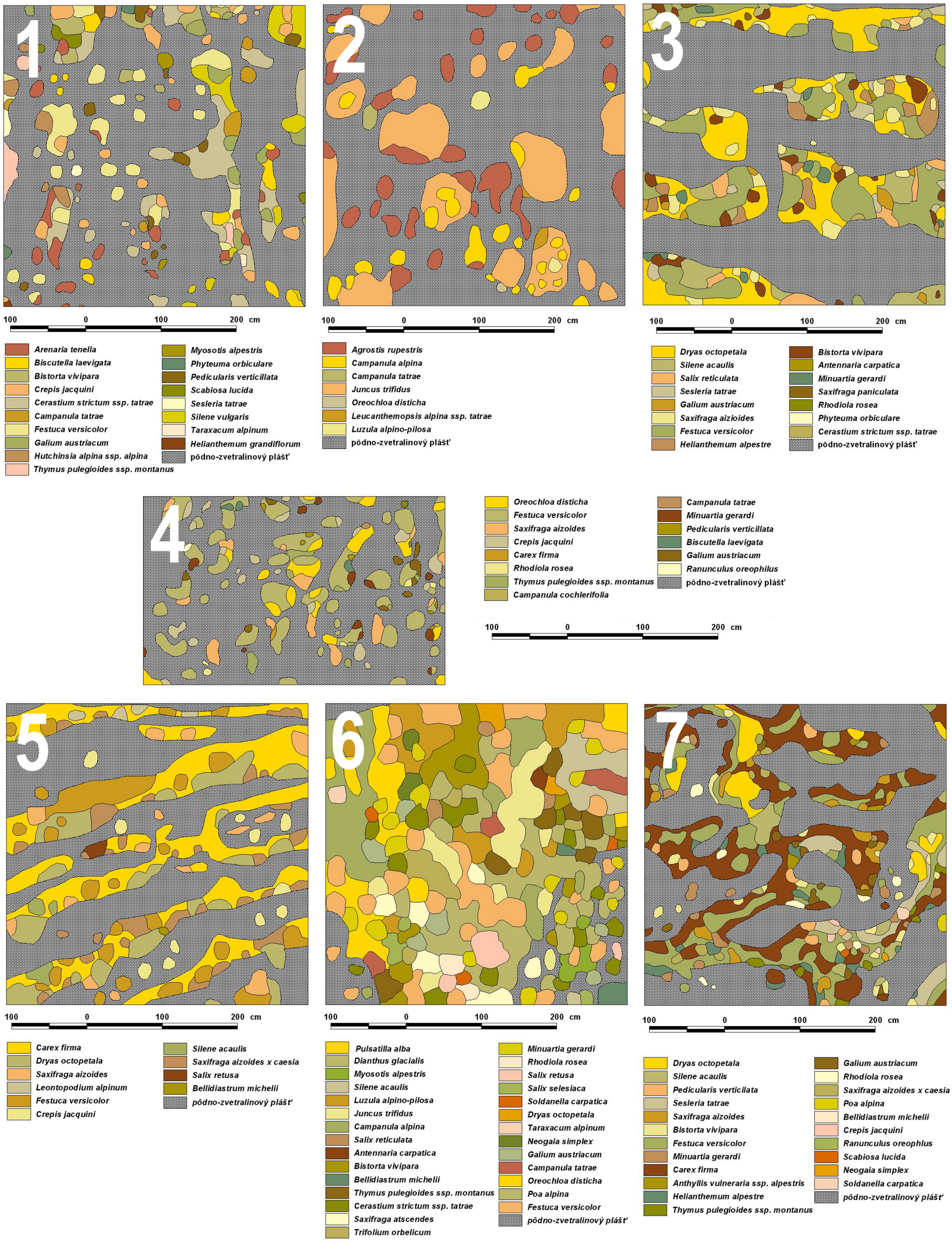

Fig. 3 Field drawings of the species distribution for the individual permanent sample sites.

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Table 1 Selected characteristics of sites (permanent plots), types of processes and their intensity per year calculated from all measurements (2002-2022).

Permament plot	altitude (m s. l.)	slope declination in ° (mean value)	exposition	type of dominant geomorphic processes	intensity in cm/ year (mean value)
PP1	1675	40	S	water-gravitational debris flow	0.5-300
PP2	1829	4	N	aeolian deflation, nivation	1
PP3	1824	2	NW	aeolian deflation	0.5
PP4	1916	48	W	gravitational creeping debris	100
PP5	1905	3	W	aeolian deflation	1
PP6	1763	7	W	aeolian deflation	0.4
PP7	1917	25	E	solifluction	4

The field research was associated with the collection of data in the form of standard phytosociological relèves of the Zurich-Montpellier school (Table 2) which we started implementing in June 2002. The species coverage was evaluated according to the combined seven-stage Braun-Blanquet scale approach (frequency-coverage), in line with the Zurich-Montpellier school, where the higher number means the higher coverage and the frequency of the given species (Table 2): 5 - coverage 75-100 %, 4 - coverage 50-75 %, 3 - coverage 25-50 %, 2 - coverage 5-25 %, 1 - coverage less than 5 % rather plentiful to scattered, + coverage insignificant, scattered, r - rare.

The field research also includes detailed mapping of spatial distribution of individual tussocks or individuals on each area. In this way, we monitor the species' share and their spatial distribution with respect to the other part of the area represented by the exposed soil-geest substrate. Such field drawings with the detailed repartition of the species on the surfaces are transferred into the digital form and into the GIS environment (Fig. 3).

For the scientific names of the taxa, the nomenclature was used according to the work of Marhold and Hindák (1998). When evaluating vegetation, we also attempted to determine the plant communities - phytocoenoses (geobotanical characteristics).

The field research was also associated with the collection of data of environmental factors (Table 1). Special attention was paid to measuring the intensity of geomorphic processes. Several methods are used. In particular, we used the method of measuring the longitudinal displacements of moving debris fragments by using colour profiles, which are applied to the surface of the debris material between the fixed steel benchmarks in certain time intervals. This method was applied especially in the measurement of the intensity of the debris flows and the gravitational creeping of the debris. Solifluction movements are measured by solid steel benchmarks that are mounted outside the active niche, while the moving point is being placed on top of a solifluction-gravity terrace (garland). The expansion of the edges of the aeolian niches or their retrograde retreat is measured between two fixed points. Fluctuant measured points are at the intersection of the edge of the plate and the rope fixed between the fixed points while only one of them has a stable location in the area. Measurements are taken 2-3 times a year and they are used to calculate the mean values of length changes. The field research also includes a rigorous photographic documentation.

For a more comprehensive understanding of the properties of the studied sites, as well as for the analysis of the relationship between the soil response and the plant species, we also investigated the soil pH which we determined after taking the samples in the field by using a standard procedure in the laboratory.

We used the CANOCO software package (Ter Braak 1988; Ter Braak & Šmilauer 1988; Ter Braak 1990), a specialized program for the analysis of phytosociological and similar data, to quantify the obtained data. Primary input data were the phytosociological relèves that were characterized by species representation. For direct methods, 7 environment characteristics recorded in the terrain were used as explanatory variables (environmental variables which included also some vegetation character - coverage) - slope of relief, altitude, soil pH, vegetation coverage, intensity of individual geomorphic processes - deflation, creeping, solifluction). For the analysis and quantitative evaluation of phytosociological data, we used direct and indirect gradient analysis according to the suitability of the evaluated sets (Lepš & Šmilauer 2000).

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Table 2 Phytosociological relèves from the 7 permanent plots/sites.

permant plots / sites (PP)	PP1	PP2	PP3	PP4	PP5	PP6	PP7
altitude (m)	1675	1829	1824	1916	1905	1763	1917
numbers of species in record	17	7	14	13	11	28	21
Agrostis rupestris		1					
Antennaria carpatica			r			r	
Anthyllis vulneraria ssp. alpestris							+
Arenaria tenella	2						
Bellidiastrum michelii					+	r	+
Biscutella laevigata	2						
Bistorta vivipara	+		2			1	1
Campanula alpina		1				1	
Campanula cochlerifolia				r			
Campanula tatrae ssp. tatrae	r	r				r	
Carex firma				+	3		3
Cerastium arvense ssp. glandulosum	2		+			1	
Crepis jacquini ssp. jacquini	+			1	+		r
Dianthus glacialis						1	
Dryas octopetala			3		2	r	2
Festuca versicolor ssp. versicolor	2		3	3	2	3	3
Galium austriacum	2		+	+		+	1
Helianthemum grandiflorum	r						
Juncus trifidus		2				2	
Leontopodium alpinum					+		
Leucanthemopsis alpina ssp. tatrae		r					
Ligusticum mutellinoides						r	r
Luzula alpinopilosa		r				2	
Minuartia gerardi			r	r		1	1
Myosotis alpestris	+			+		r	
Oreochloa disticha		r		3		r	
Pedicularis verticillata	1			r			+
Phyteuma orbiculare	r		r				
Poa alpina						1	r
Pritzelago alpina ssp. alpina	+						
Pulsatilla scherfelii						1	
Ranunculus breyninus				r			r
Rhodax alpestris			1				2
Rhodiola rosea			r	r		r	+
Salix reticulata			1			r	
Salix retusa					+	1	
Salix silesiaca						r	
Saxifraga adscendens					r	+	
Saxifraga aizoides			1	1	1		1
Saxifraga caesia					1		+
Saxifraga paniculata			r				
Scabiosa lucida							r
Sesleria tatrae	1	r	+				2
Silene acaulis			2		+	+	2
Silene vulgaris	+						
Soldanella carpatica						r	
Taraxacum tatrense						r	
Thymus pulegioides ssp. montanus	1			+		+	1
Trifolium orbelicum						r	
Trisetum alpestre	r						

4 Results and Discussions

4.1 Debris flow under the Hlúpy vrch peak

The permanent plot (PP1) was established on the SW slope of the Hlúpy vrch peak on the talus sediments of limestone and dolomite rocks and deposited in the erosion furrow of the debris flow. Based on the analysis of historical images, it is evident that the debris furrows running down from the top of the Hlúpy vrch peak have changed significantly since the end of grazing in 1954 and they are being stabilized by the succession of grass vegetation processes which, at the same time, slows down the intensity of material creeping. This site was also selected because of the previous measurements of material creeping taken by Midriak (1983). Their comparison with the new measurements could, among other things, further clarify the nature and course of these processes.

The measurement profiles for the determination of the intensity of talus creeping were established in two areas - in the transport and in the lower accumulation part of the flow. In a transport section with a slope of 45°, the measuring profile passes through an erosion furrow 10.5 m long, while the width of the actual debris flow, excluding the edges of the erosion furrow, is 3 m. If the talus do not reach an appropriate degree of watering during the rainfall, they mostly move along the surface by rolling, gliding, slow creeping or partial displacement due to smaller water flows. According to the Midriak (1983), the movement of the talus is almost exclusively on the surface. Fragments reach a diameter of 1-2 cm, while larger stones have the diameter of 1-20 cm. According to the results of the above-mentioned author, 70% of all talus were transported frontally at 0.15-21 m/year (but only by 0.6 m/year on average). Solitary larger stones moved even further. According to our measurements, since the establishment of the profile, there was an overall frontal shifting of fragments by 1-5 cm/month. Some of them (about 5 cm in diameter) were transported up to a distance of 0.5 to 2.7 m/month. After a year of measurements, however, the middle part of the colour profile (except for the margins with displacements of about 0.3-0.5 m/month) was completely absent and the fragments moved deep into the valley (more than 30 m). This fact demonstrates the high intensity of material transfer which ultimately prevents its settlement by vegetation.

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In the accumulation part of the debris flow (1675 m a.s.l.), the second measuring profile was established with a part of it forming the lower side of the square of the permanent plot. The measuring profile is 9.6 m long. During the 20 years of measurements, the intensity of the shift of most of the fragments was 5 cm/month (on the edges) to 50 cm/month (in the middle part) in the period of May - November. However, a large part (about 1/3) of fragments is washed off every year during the spring measurements almost to the bottom of the valley, probably during intensive snow melting, when the fragments exceeded the distance of almost 40 m. Midriak (1983) measured the movements of 5-7 m and 0.7 m/year on average.
The lower part of this flow is gradually settled by vegetation which is represented in particular by species typical for moving talus: Arenaria tenella, Cerastium arvense ssp. glandulosum, Biscutela laevigata and others. These species also have a relatively high coverage in the phytosociological relèves (Table 2). Vegetation can be described as a pioneer community of chamaefytes and hemicryptophytes that are syntaxonomically likely to be associated with Papaverion tatrici.

4.2 Aeolian-nivation niche in the Široké saddle

The permanent plot (PP2) is situated in the depression of the Široké saddle on the edge of this aeolian-nivation niche. Its formation is mainly subject to regular strong N and NW winds which are reinforced in these places by the jet effect of the saddle. In the spring period, nivation erosion of long-lasting snow fields is also partially active here. Degradation of this site is also influenced by in the regelate processes, as well as anthropogenic processes (surface degradation) of the past before the marked tourist trail to the Ždiarska vidla peak was closed in 1978. During deflation, which is active especially at the surface of the terrain, small particles of rocks, as well as non-consolidated fine soil, are transported from the surface and drifted to another place (Kozłowska & Rączkowska 1996, 2006). According to Midriak (1983) and Michaeli and Boltižiar (2010) for flat deflation it is necessary for the wind speed to reach 4-4.5 m.s-1. Vegetation also adapted to these conditions by its species composition (Table 2). The highest frequency and coverage is reached by the species Juncus trifidus whose deep root system enables it to survive even in such extreme conditions. Its vegetation is represented by the remains of originally continuous turfy mantle of the climax plant community Juncetum trifidi, which remained in situ after the removal of the finer material. The community can be characterized as heliophyta, xero- to mesophyta and extremely acidophyta growing on shallow and acidic soils, as confirmed by our measurements (pH 4.4). Because of the extreme living conditions, they belong to the poorest alpine communities in general. Another dominant species is Campanula alpina which is spread irregularly in the form of individuals.
To measure the intensity of deflation, the above-described method is used – measuring the spreading of edges of the niche in several directions. The results confirmed that under the influence of a strong aeolian corrasion, the edges of the terrain were abrased by about 1 cm/year indicating a relatively high intensity of winds creating the erosion.

4.3 Lysine soils under Jahňací štít peak

The permanent observation plot (PP3) is located in the extinction stage of lysine soils on the intersection of limestones and Verphenian schist and on the intersection of the High and Belianske Tatra Mts. on the ridge rising to the N from the Jahňací štít peak. The formation of lysine soils is mainly due to regular strong winds and partly to regelation. Vegetation covers only cryoplanar soil remnants in the form of irregular islands and bands or grows only in individual tussocks. The bands are diagonally oriented along the slope in the direction of the predominant winds. In the lower areas, these soils are transfered into long terraced lysine-garland soils. On this permanent plot, there is a very interesting spatial distribution of some species. A characteristic community in this plot consists in the association Festuco versicoloris-Dryadetum octopetale, where Dryas octopetala, Festuca versicolor ssp. versicolor, Silene acaulis prevail. While the first mentioned species produces loose dwarf shrubs vegetation, the other grows mainly on the windward sides of the loamy soil residues and in many places its root skeleton is exposed by strong W winds, which also gradually disrupt the upper part of the tussocks. Tussocks, however, provide protection for a wide range of other species, especially, the genus Saxifraga which overgrow from the margins to the center of the Festuca versicolor tussocks. Species such as Silene acaulis or Dryas octopetal grow behind individual cryoplanar residues where they are protected from wind. These phenomena were observed and described by several authors (Midriak 1983; Midriak and M. 1970; Plesník 1956; Šmarda 1956; Izmailow 1984b and others). Dense intact tussocks of Festuca versicolor ssp. versicolor also provide good protection for many other species in its lee side. The species Saxifraga aizoides overgrows from the edges to the center of the grass tussocks Festuca versicolor ssp. versicolor. On the contrary, the species Silene acaulis, mainly Dryas octopetala, grow on the lee side in the micro-space on the basis of individual cryoplane residues. When exposed to strong winds, usually after the disturbance of Festuca versicolor ssp. versicolor tussocks, it decays.

The intensity of aeolian erosion is measured at several places of the site. In 20 years of measurements, we found that the edges of vegetation bands receded only a few mm/year (0.3-0.7 mm) which may be interpreted as relative weak deflation intensity. When comparing the historical photographs of the same site where our permanent observation plot is located from the 60s of the last century taken by prof. Midriak and our current photographs, we can see a slight growth of the area covered by vegetation in the past and now. There are several alternatives explaining this difference (e.g. medium-term climate change, ending of grazing, etc.), however, correct conclusions cannot be drawn for the lack of accurate knowledge and measurements.

4.4 Talus slope below Hlúpy vrch peak

The permanent observation plot (PP4) is located on the Hlúpy vrch peak which is affected mainly by creeping of talus, but also by rone and intense aeolian erosion. Vegetation only sporadically takes root in tussocks and creates a unique arranged dotted structure in the direction of prevailing winds along the slope line. It is composed mainly of the species Festuca versicolor ssp. versicolor with a deep root system that helps it to survive in such extreme conditions. The other numerous species, which we recorded at the plot, were Oreochloa disticha and Sedum alpestre. The species of Carex firma, according to our observations and the observations of other authors (Midriak 1983; Plesník 1956), is applied both in the initial stages of the destructed areas on the moving talus, which are typical for our locality, and also in the developmental stages of garlands and girland-lysine soils. This community can be syntaxonomically included in the association Festucion versicolor, ev. Caricion firmae.

At the bottom part of the plot, measurements of the movement of the talus were taken using two fixed metal benchmarks and a coloured line. During the three-year measurements, there was a significant shift of the talus. Especially after the winter season during the first spring measurements, most of the colour profile is usually carried down several tens of meters. During the summer period, in the absence of more intensive rainfall, the shift of the talus amounts to an average of 0.1-1 m/year while larger stones (diameter of 10 cm) are transfered to a distance of almost 1 m. The intensity of the talus shift due to creeping, as well as surface runoff, is relatively high.

4.5 Girland-lysine soils in the saddle below the Košiare peak

This permanent plot (PP5) was established at a place of long garland-lysine soils in the saddle between the Košiare peak and the Bujačí vrch peak on the main eastern ridge of the Belianske Tatra Mts. The bare gravelly areas were created by the destruction of the vegetation cover by aeolian, cryogenic and anthropogenic processes. There are alternating bare bands of the soil-geest substrate and bands of vegetation extended in the direction of the wind to several tens of meters. The vegetation bands are predominantly a community of the Caricion firmae represented by the association of Saxifrago caesiae-Caricetum firmae. The Carex firma, Saxifraga caesia, Dryas octopetala, Festuca versicolor ssp. versicolor are predominant (Table 2). The first species forms dense firm cushions attached to the soil which is well overlaid. The second mentioned species has thin cushions which provide less protection of the soil from regellation. Its clusters, as well as the individuals of other species, try to find shelter from the destructive winds in the lee sides of Festuca versicolor and Carex firma tussocks, which also better overlay and thus protect the soil from drifting away and regellation. According to the aeolian erosion intensity measurements, it can be assumed that the vegetation, as well as the exposed substrate, are relatively strongly attacked by the effects of this erosion. As implied by field observations, in spring and autumn months the exposed areas are affected by strong effects of regellation in the form of loosening their surface by soil ice (Izmailow 1984a). The measurements show that the influence of the aeolian erosion and jet effect of the saddle cause the edges of the terrain to recede by about 1 cm/year on average.

4.6 Aeolian depression near the Kopské saddle

The plot (PP6) in the aeolian depression lies at the watershed line between Predné and Zadné Meďodoly valleys. The site was also selected on ac-

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count of the fact that the wind erosion measurements were previously carried out here by Midriak (1972). The depression was caused by the destruction of the vegetation and the soil-geest cover by deflation and consequently fluvial erosion in co-operating with cryogenic processes. Western winds hit the transverse slope, where the jet-like shaping of the relief increases their speed. By co-working with other processes, they formed falcular shape with the total length of 35 m, an average width of about 6 m (2-12 m) and a maximum depth of 1.5 m. In this relatively recent young form, the progressive destruction of grass-herbaceous stands and the spreading of the exposed soil-geest vegetation can be observed. However, the prevailing erosion factor is deflation, as evidenced by the fact that the furrow did not flow into the valley, but its lengthwise growth is, despite the high slope, faster in retrograde direction than in the slope direction. In this part Midriak (1983) measured the recess of the edges of the aeolian-nivation niche by 1-29 cm/year and by 1.9 cm/year on average. After our repeated measurements, we measured the edge recess of only a few mm/year (between 0,2 - 0,8 cm) . Also, according to the comparison of the same photographs from 1967 and 2017 (after half a century), we can see the progressive succession of grass-herbaceous and dwarf pine vegetation. We believe, however, that wind is still a heavily limiting factor limiting the succession of vegetation. It also affects the furrow during winter when the area is mostly without snow. From the effects of the wind, the lateral spreading of the edges is the most striking where the blowing of the fine earth causes the turnover of the turfy cover while overhangs are being created (Midriak 1972).
From phytosociological relèves, high species diversity (28 taxons) can be deduced. The most numerous with high coverage are predominantly grass species, such as ako Festuca versicolor ssp. versicolor, Juncus trifidus, Luzula alpino-pilosa and Poa alpina. These species have been transported here from the margins of the turfy overhangs. Despite the deflation, they survive thanks to their adaptation to such extreme habitats (deep root system, etc.). These are, in particular, the communities of the Juncetum trifidi, which grow in the wider area of the aeolian niche.

4.7 Garland soils under the Hlúpy vrch peak

The permanent plot (PP7) was established on the east slope of the Hlúpy vrch peak at the site with garland soils. These are frozen soil forms, so-called amorphous solifluction, in which terraced stone or fine-grained (loam) steps are formed with vegetation rims. The terraces themselves are formed by a finer material or a coarse-grained skeleton often affected by the regelation processes. A typical feature of garland soils is their movement along the slope due to the solifluction which is manifested in the weaving of the vegetation. The solifluction was confirmed on the plot after the year of observation by the bending of fixed benchmarks (2 cm in diameter) which were set at the depth of more than 80 cm. The bare faces are created by the vegetation cover destruction, as well as by the aeolian processes. According to our ten-year measurements, we have recorded the recession of the wind-eroded edges by about 2-6 cm/year which indicates the relatively significant effect of the western winds on the area. Moreover, the species composition (Tab. 2) suggests that there are species typical for blown sites: Festuca versicolor ssp. versicolor, Dryas octopetala. Even with these species, there is a marked spatial distribution. The tussocks of Festuca versicolor grow especially on the upper edge or on the entire upper half of continuous garlands, as well as on more or less isolithic remains of the turf bands affected by solifluction. On the other hand, Dryas octopetala creates loose cushions on the foothills of terraces, but in spome spots it also forces its way in between other species of the Caricion firmae inside the garlands. Together with this species, mosses and lichens are abundant on the garland soils. Silene acaulis vegeatation is very frequently found here, but it also grow upwards and along with the Saxifraga species they inhabit almost all of the lower half of continuous garland bands. The Carex firma also has a high coverage at the site, which is also typical for the solifluctically influenced soil-geest cover, where it has a particularly reinforcing role. It forms dense cushions firmly attached to the soil, which is well overlaid especially at the upper edge of garland terraces (Midriak 1983).

4.8 Vegetation variability

The method of indirect gradient analysis of the principal components - PCA, which affects the vegetation variability based on species composition, was used to analyse the structure of the surveyed data (sites and species). The highest value of the length of environmental gradient (calculated using DCA) was 3.898 and is therefore suitable for the use of the linear PCA method. The data matrix was represented by a table of phytosociological relèves of all species from the surveyed sites (Table 2). The combined seven-degree Braun-Blanquet scale

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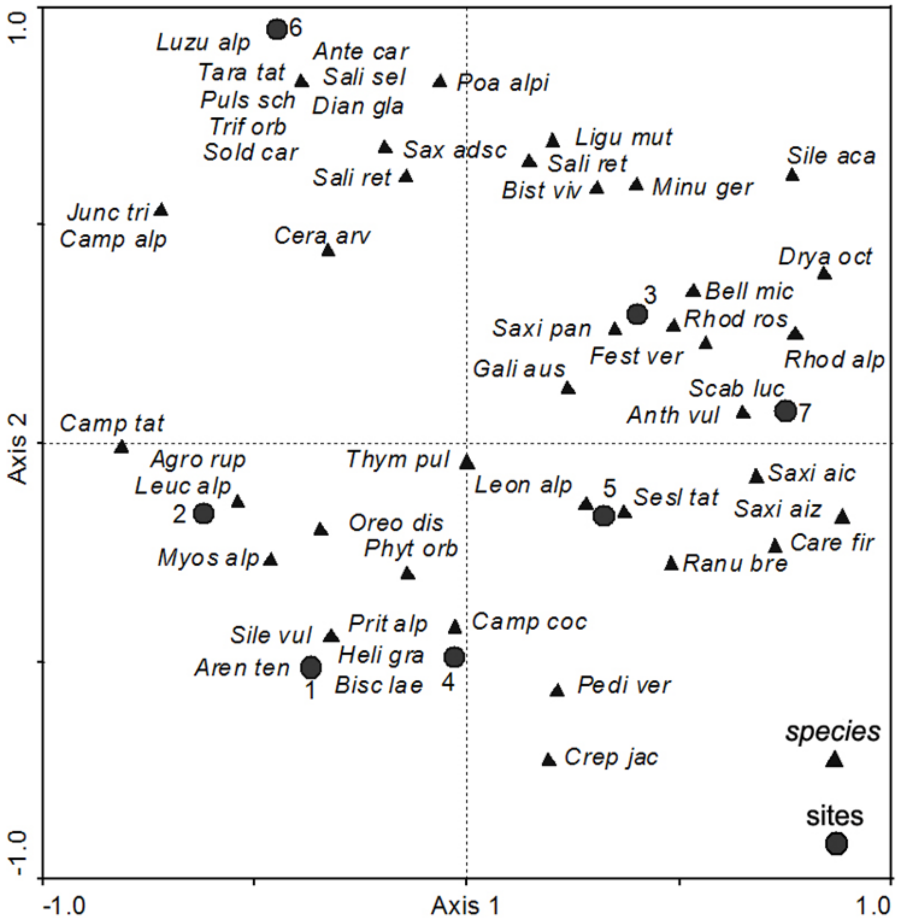

Fig. 4 PCA biplot of the species and localities/sites.

approach of abundance and dominance was converted to numerical values for the CANOCO programme using the Van der Maarel scale (Herben & Münzbergová 2002, 2003). The values prepared in this way were imported into the Cornell format and subsequently entered the CANOCA programme. After the analysis and creation of the ordination diagram (Fig. 4), we found that the surveyed data (species and sites) are structured creating several ordinal clusters. They are scattered throughout the ordination space. It may be inferred that clusters represent certain synecologically and syntaxonomically defined groups. However, PCA does not allow for gradients to be identified - the ecological characteristics of the sites with which species variability is correlated and their relation to ordination axes. The first two axes, however, account for up to 50.5% of species data variability which confirms that the factors explained by the ordination axes are significant. Species such as e.g. Dryas octopetala, Silene acaulis, Saxifraga aizides, Carex firma and others (localities 3, 5, 7) are typical for habitats with strong and frequent winds, but also for the environment affected by solifluction or with the occurrence of solifluction-gravitational garland soils. According to the mutual relation between the species and their relation to the distribution of individual records (sites), as well as on the basis of field observations, it may be assumed that the main gradient (property) explained by the first ordination axis is probably wind or solifluction. Another gradient explained by the second ordination axis can be the high slope and the associated process of creeping of dolomite-limestone talus which conditioned the formation of a cluster of species typical for the consolidation of moving talus material ((Arenaria tenella, Biscutela laevigata, Silene vulgaris, Thymus pulegioides ssp. montanus, Campanula cochleariifolia and others (sites 1 and 4). Species from site 6 (the so-called ”outlier”) are typical for climax grass alpine meadows. Many of them are also taxa of wind sites (Juncus trifidus, Campanula alpina, Pulsatilla scherfelii, Poa alpina and others). As we mentioned in the characteristics of this site, it is an aeolian depression. Its remote position in the graph (Fig. 4)

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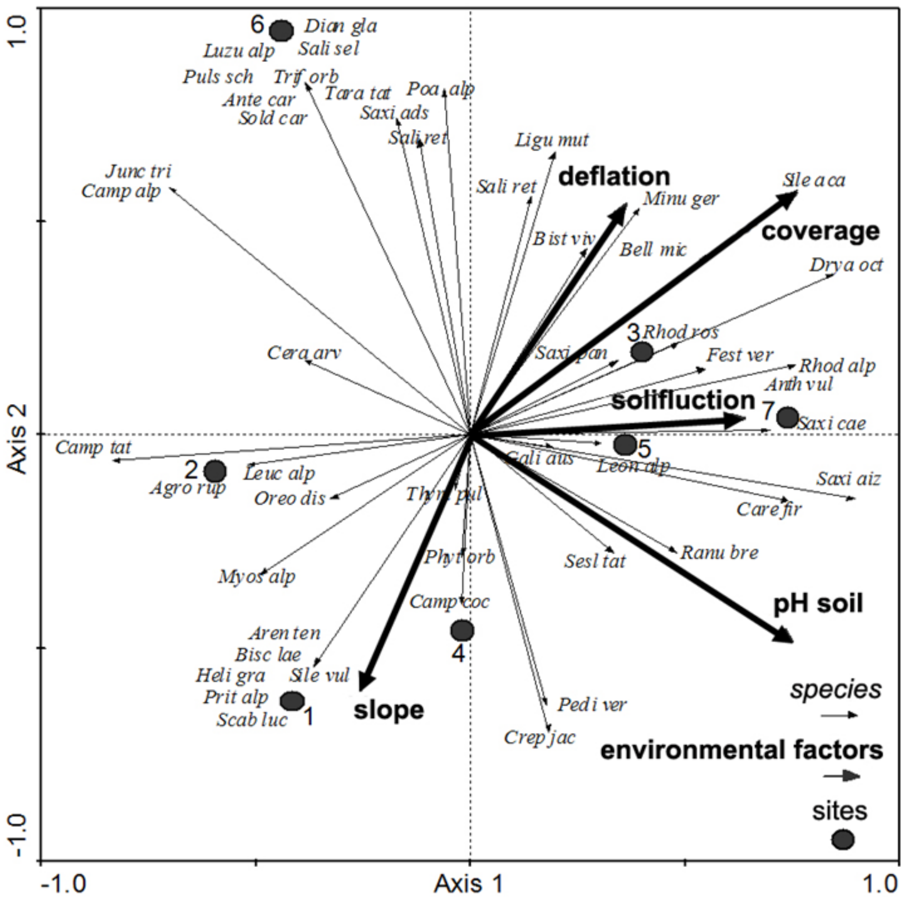

Fig. 5 RCA triplot of the species, localities/sites and environmental factors with vegetation coverage.

from other sites can be caused, for example, by different soil pH or a soil-forming substrate. Another property which causes differences in the relèves can consist in the coverage of the herb layer (E1).

4.9 Habitat variability

The nature of the environment is determined by the primary characteristics of the habitat (sites) and indirectly also by the representation of species that express the demands for light, heat, humidity, soil response, etc. To analyse the data variability in relation to explanatory variables to confirm their impact based on the above mentioned assumptions and hypotheses, we used a direct gradient analysis - RDA which explains the variability of vegetation not only based on species composition, but also based on the environment properties. As explanatory variables, 6 environmental factors (including one vegetation characteristic) entered the analysis as input data which were acquired in the field: slope, deflation (aeolian erosion), creeping of geest substrate, solifluction, soil pH, and total herbage coverage in %. The data were modified and subsequently imported into CANOCA programme. The ”inflation factor” data in the *.log file confirmed a relatively high correlation between two factors (values above 10): slope and creeping of talus. In such case, it is appropriate to exclude one of the factors with the highest value (Herben & Münzbergová 2003). In our case, it was the factor of talus creeping which is subject to higher slope values. The result of the Monte-Carlo permutation test of environmental characteristics, which tests their statistical significance, is the so-called ”p-value” - the critical value for the determination of probability level. Its calculation is based on a zero hypothesis that species are independent of explanatory variables (environmental factors). The obtained values pointed to the fact that the most important factor is the coverage of the herb layer (E1). Other factors may be considered to be less significant or irrelevant according to the obtained test values.
The ordination graph 2 (Fig. 5) shows the distribution of species (localities) and also the ordination of species in relation to environmental characteristics. The species are shown as arrowheads

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in the direction of their coverage. Environmental variables (environment factors) are displayed with arrows in the direction where their significance increases.

The first axis explains the 28.7% of variability. The solifluction correlates with it as a variable with demonstrable influence occurring at site 7, where it conditions the formation of semicircular garland soils. Solifluction is also influenced by the location of site 5 with the occurrence of garland-lysine soils. Another important variable is the coverage of the herb layer - E1. It correlates with sites 3 and 7 with higher coverage. This variable is in a negative correlation to the slope which explains the second axis of the ordinal graph. It explains 50.5% of variability.

With slope growth, the coverage of the herbal layer - E1 at sites 1 and 4 decreases, where under the influence of a high gradient (gravity), the geest material of the dolomitic limestones is creeping. Moreover, the cluster of species in the surroundings of sites 1 and 4 is represented predominantly by the species typical for the succession stages on the talus. This corresponds to the representation of the species and their distribution on the Fig. 4 (Arenaria tenela, Silene vulgaris, Biscutela laevigata, Campanula cochlerifolia, Pritzelago alpina ssp. alpina and others).

On the contrary, sites 3 and 7 have the highest overall coverage. Therefore, they are in the first quadrant of the graph. However, the location of these sites (especially site 3 with the occurrence of lysine soils) in the ordination space is also determined by the effects of wind in the form of deflation.

Near the ordination sites 1 and 4, there is also site 2 which has the lowest overall coverage (25%). Therefore it is in strong negative correlation with sites 7, 3, and 5 with the highest coverage. This site has also the lowest pH (along with site 6) compared to other sites.

The position of site 6, as well as the species in its surroundings, as we have already indicated, is determined mainly by soil reaction. For example, species such as Juncus trifidus or Campanula alpina are species typical for the acidic substrate and are in negative correlation to a vector showing the pH increase direction (alkaline reaction). Moreover, the species lying in the fourth quadrant of the graph are typical calciphytes (Sesleria tatrae, Carex firma, Leontodon alpinus and others). It has to be said that site 6 is predominantly occupied by climax grass communities of contiguous alpine meadows (Pulsatilla scherfelii, Trifolium orbelicum, Luzula alpinopilosa, Poa alpina, Taraxacum tatrense).

In conclusion, based on the analysis of ordination graph 2 as a result of the RDA method used, the above mentioned hypotheses from the indirect PCA analysis on the influence of habitat conditions on vegetation were confirmed.

5 Conclusions

In this paper, we presented initial results of the 20-years monitoring of the relation between vegetation and the intensity of the geomorphic processes from seven permanent observation plots in the Belianske Tatra Mts. The obtained vegetation data were used for the indirect gradient analysis of the major components - PCA to determine the variability of vegetation and sites. However, this method did not allow us to identify environmental variables or properties of habitats, with which species variability is correlated, and also their linkage to ordination axes. For this reason, based on the synecological properties of vegetation and the knowledge of the ecological properties of the sites, we were able to make judgements about the dominant factors of the environment that are linked to individual axes and which explain the position of species and sites in the ordination space. The main gradients are wind, solifluction, slope and soil pH according to our research. Therefore, to confirm the hypotheses from PCA analysis, we used a direct gradient analysis - RDA which explains the variability of data not only based on the species composition, but also based on the properties of the sites, which were obtained from the field measurements. It confirmed the correctness of hypotheses about the impact of environmental factors on vegetation. The most important environmental variable was solifluction correlating with the first ordination axis and explaining 28.7% of variability. Another significant variable was the vegetation coverage or herb layer (E1), with a strong negative correlation to the slope, which explained the second axis of the graph binding up to 50.5% of variability. Other environmental variables explaining the variability were the aeolian erosion and soil pH.

On the basis of the results obtained, we evaluate the geomorphic processes operating in the extreme environment of the alpine landscape as key factors that determine also spatial distribution of vegetation or its individual species or the overall character of the fragmentation of the vegetation. These views are also presented by Šmarda (1956, 1964a,b), Midriak (1983); Midriak and M. (1970), **?**Hreško and Boltižiar (2001); Hreško et al. (2003, 2008), Kotarba (2005) and others. Georelief, in particu-

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lar its spatial geomorphic attributes, are therefore relevant phenomena of the landscape which allow us to understand, among other things, the scale and hierarchy of the vegetation cover distribution (Kotarba 2007). Due to the fact that the nature of the vegetation is heavily influenced by relief and ongoing processes, without their knowledge the conventional phytosociological analysis is only a description and static capturing of a given state. These analyses deal with the causes of succession of vegetation, their development and spatial arrangement. In this respect, it is necessary for botanists and geomorphologists to cooperate (Kozłowska 2001). Only then will we correctly understand the spatial distribution of vegetation and species. An example of such cooperation can be seen in the research conducted in the Polish side of Tatra Mts. (Rączkowska & Kozłowska 1999; Rączkowska et al. 1999; Kozłowska & Rączkowska 1996; Kozłowska et al. 2007). In Slovakia, similar research was conducted by Midriak and M. (1970) and Plesník (1956). It is the similarity of Slovak and Polish sites, as well as the studied processes which confirmed our and their presented findings and conclusions not only regarding the intensity of the processes but also their influence on the spatial distribution of vegetation and its individual species.

It should be stressed that the relation of vegetation as well as the intensity of individual geomorphic processes can be considered and generalized only on the basis of longer observations, which, naturally, partially influenced our conclusions of relatively short-term stationary research. Confirming and evaluating the established and sketched relations will be the goal of our further field-oriented research which will be based mainly on the long-term observations, as well as on the comparison of results obtained from other alpine areas.

For nature conservation organisations, the paper provides knowledge on the status and development of alpine ecosystems. The results will comprise a source for the further planning and operative management of ecosystems care.

The results represent a basis for further scientific and research works of similar character. In the scope of ecosystem management of the Tatra national park, the paper offers valuable knowledge about state and development of non-forest ecosystems. The methodological procedures, analysis and evaluation used enable us to manage the further direction in the care of high-mountain landscape. Based on our results, we argue that long-term research represents a significant contribution to the knowledge of vulnerable high-mountain landscape and, subsequently, to its further development, conservation management, and environmental planning.

References

Barka I (2004) *Repartícia plôch s deštruovanou pôdnou a vegetačnou pokrývkou v Kriválnskej malej Fatre v rokoch 1992-2003*. FEE TU Zvolen, Banská Štiavnica.

Boltižiar M (2001) Evaluation of vulnerability of high-mountain landscape on example Velická valley in the High Tatras Mts. *Ekológia* 20, (4):101–109.

Boltižiar M (2009) *Vplyv georeliéfu a morfodynamických procesov na priestorové usporiadanie štruktúry vysokohorskej krajiny Tatier*. ÚKE SAV, UKF Nitra, .

Boltižiar M (2022) Unique Glacial Landscape on the Roof of the Carpathians - Tatras Mts. In: Lehotský M, Boltižiar M, (eds.) *Landscape and Landforms of Slovakia*. Springer, pp. 63–97.

Boltižiar M, Biskupič M, Barka I (2016) Spatial avalanche modelling by application of GIS on the selected slopes of Western Tatra Mts. and Belianske Tatra Mts. *Slovakia) Geographia Polonica* 89, (1):79–90.

Falťan V, Katina S, Bánovský M, Damankošová Z (2009) The influence of site condition on the impact of windstorms on forest: The case of the High Tatras Foothills (Slovakia) in 2004. _*Moravian Geographical* Reports_17(3):10–18.

Falťan V, Katina S, Minár J, Polčák N, Bánovský M, Maretta M, Zámečník S, Petrovič F (2020) Evaluation of Abiotic Controls on Windthrow Disturbance Using a Generalized Additive Model: A Case Study of the Tatra National Park, Slovakia. _*Forests*_ 11, (12). Art. No. 1259.

Falťan V, Petrovič F, Gábor M, Šagát V, Hruška M (2021) Mountain landscape dynamic after large wind and bark beetle disasters and subsequent logging – case studies from the Carpathians. *Remote Sensing* , (3873). doi: 10.3390/rs13193873.

Gerdol R, Smiraglia C (1990) Correlation between vegetation pattern and micromorphology in periglacial areas of the Central Alps. *Pirineos* 135:13–28.

Gądek B, Grabiec M, Kędzia S, Rączkowska Z (2016) Reflection of climate changes in the structure and morphodynamics of talus slopes (the Tatra Mountains, Poland. *Geomorphology* 263:39–49. doi: 10.1016/j.geomorph.2016.03.024.

Herben T, Münzbergová Z (2002) *Zpracování geobotanických dat v příkladech. Část II. Data o populační biologii*. PF UK, Praha.

Herben T, Münzbergová Z (2003) *Zpracování geobotanických dat v příkladech. Část I. Data o druhovém složení*. PF UK, Praha.

Hreško J, Boltižiar M (2001) The influence of the morphodynamic processes to landscape structure in the high mountains (Tatra Mts. *Ekológia-Bratislava* 20, Supplement 3:141–148.

Hreško J, Boltižiar M, Bugár G (2003) Spatial structures of geomorphic processes in high-mountain landscape of the Belianske Tatry Mts. *Ekológia-Bratislava* 22, Supplement 2: 341–348.

Hreško J, Bugár G, Boltižiar M, Kohút F (2008) Dynamics of recent geomorphic processes in alpine zone of the Tatra Mts. *Geographica Polonica* 81, (1):53–65.

Izmailow B (1984a) Eolian processes in alpine belts of the High Tatra Mountains, Poland. *Earth Surface Processes and Landforms* 9, (2):143–151.

Izmailow B (1984b) Eolian deposition above the upper timber line in the Gasienicowa valley in the Tara Mts., Zeszyty Naukowe UJ. *Prace Geograficzne* 61:43–59.

Kotarba A (2005) Geomorphic processes and vegetation pattern changes. Case study in the Zalené pleso Valley, High Tatra, Slovakia. *Studia Geomorphologica Carpatho-Balcanica* 39:39 – 48.

Kotarba A (2007) Geomorphic activity of debris flows in the Tatra Mts. and in other european mountains. *Geographia Polonica* 80, (2):137 – 150.

Kozłowska A (2001) Roślinność strefy przejścia między piętrem subalpejskim a alpejskim (na przykładzie wybranych obiektów w Dolinie Gąsienicowej) In: Między geografią i biologią – badania nad przemianami środowiska przyrodniczego. *Prace Geogrficzne. IGiPZ PAN* , (179):219–252.

Kozłowska A, Rączkowska Z (1996) Relacje śnieg – róslinność w obrębie form niwalnych. *Przeglad Geograficzny* 68, (1-2): 167–179.

Kozłowska A, Rączkowska Z (2006) Effect of snow patches on vegetation in the high-mountain nival gullies (Tatra Mts. *Poland). Polish Journal of Ecology* 54, (1):69–90.

Kozłowska A, Rączkowska Z, B Z (2007) Links between vegetation and morphodynamics of high-mountain slopes in the Tatra Mountains. *Geographia Polonica* 79, (1):27–39.

Lepš J, Šmilauer P (2000) *Mnohorozmerná analýza ekologických dát*. BF JU, České Budějovice.

Lukniš M (1973) *Reliéf Vysokých Tatier a ich predpolia*. Vydavateľstvo Slovenskej akadémie vied, Bratislava.

Marhold K, Hindák F, (eds.) (1998) *Zoznam nižších a vyšších rastlín Slovenska*. VEDA, Bratislava.

Michaeli E, Boltižiar M (2010) Selected Localities of Environmental Loads in the Slovak Republic. *Geographia Cassoviensis* 4, (2):114–119.

Midriak R (1972) *Deštrukcia pôdy vo vysokohorskej oblasti Belanských Tatier. Lesnícke štúdie 11-12*. Príroda, Bratislava.

Midriak R (1983) *Morfogenéza povrchu vysokých pohorí*. VEDA, Bratislava.

Midriak R, M (1970) Vegetačný kryt na deštruovaných pôdach v subalpínskom stupni Belianskych Tatier. *Lesnícky časopis* 16, (1):3–11.

Piscová V, Ševčík M, Sedlák A, Hreško J, Petrovič F, Slobodova T (2023) Resistance of Lichens and Mosses of Regenerated Alpine Communities to Repeated Experimental Trampling in the Belianske Tatras, Northern Slovakia. *Divesity-Basel* 2. doi: 10.3390/d15020128. Article Number 128.

Plesník P (1956) Vplyv vetra na vznik a vývoj niektorých foriem periglaciálnych pôd vo východnej polovici Belanskych Tatier. *Geografický časopis* 8, (1):42–64.

Rączkowska Z, Kozłowska A (1999) Pokryva śnieźna a roślinność. In: *Badania geoekologiczne w otoczeniu Kasprowego wierchu*. IGiPZ PAN, Wrocław, pp. 81–90.

Rączkowska Z, Kozłowska A, Jakomulska A (1999) Róslinność jako wskaźnik morfodynamiki stoku wysokogórskiego. In: *Badania geoekologiczne w otoczeniu Kasprowego wierchu*. IGiPZ PAN, Wrocław, pp. 91–104.

Rączkowska Z, Raczkowski W, Boltižiar M (2015) Plate V.1. Rzeźba/Reliéf/Relief. Map 1. Relief 1:100 000. In: Dąbrowska K, Guzik M, (eds.) *Atlas Tatr/Atlas Tatier/Atlas of the Tatra Mountains. Neživá Príroda/Przyroda nieoźywiona / Abiotic Nature*. Tatrzański Park Narodowy, .

Rączkowska Z, Długosz M, Rojan E (2016a) Geomorphological conditions of snow avalanches in the Tatra Mountains. *Zeitschrift für Geomorphologie* 60, (4):285–297. doi: 10.1127/zfg/2016/0289.

Rączkowska Z, Rojan E, Długosz M (2016b) The morphodynamics of slopes within the snow avalanche starting zones in the Tatras. *Geographica Polonica* 89, (1):17–29.

Ter Braak C (1988) CANOCO - a FORTRAN program for canonical community ordination by partial detrended canonocal correspondence analysis, principal, principal component analysis and renundancy analysis (version 2.1. GLW, Wageningen.

Ter Braak C (1990) *Update notes:CANOCO version 3.10*. Agricultural Mathematics Group, Wageningen.

Ter Braak C, Šmilauer P (1988) CANOCO Reference Manual and User´s Guide to Canoco For Windows. Software for Canonical Community Ordination.

Šmarda J (1956) Vegetační kryt erosí obnažených a tundrových půd v Tatrách. *Biologické práce - zväzok II* 2, (8):50.

Šmarda J (1964a) Veterná erózia na Rakúskom chrbte v Belanských Tatrách. In: *Zborník prác o TANAP* 7. Osveta, Martin, pp. 34–40.

Šmarda J (1964b) Červená hlina v Belanskych Tatrách (Príspevok k poznaniu zárastných procesov strže. In: *Zborník prác o TANAP* 7. Osveta, Martin, pp. 127–133.

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