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RESEARCH

Vegetation responses to artificial snow and abiotic factors on ski slopes in Slovakia

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Abstract

Artificial snow is increasingly used in ski resorts to compensate for declining natural snowfall, yet its ecological effects on mountain vegetation remain insufficiently understood. This study examines the impact of artificial snow on plant species composition, species traits, and environmental conditions on ski slopes in Slovakia. A dataset of 60 phytosociological relevés was collected in 2021 and 2022 across 30 ski resorts, using paired plots at topographically homogeneous sites, one on naturally snowed and one on artificially snowed slopes. Analyses showed that species composition was primarily influenced by temperature and light. Overall species composition did not form distinct groups based on snow type, but plots with artificial snow had a higher prevalence of perennial hemicryptophytes, competitive species, and plants with persistent summer green leaves, whereas higher elevation species were more frequent on naturally snowed slopes. Multiple linear regression analyses revealed that variance in plant communities' ecological indicator values is primarily driven by topographic and edaphic factors, while the presence of artificial snow showed no significant effect. Key species traits including life span, life form, strategy type, leaf persistence, and elevational affinity were significantly affected by snow type. These findings demonstrate that artificial snow induces subtle ecological shifts, likely due to its different physical and chemical properties and its effect on snow cover duration. The results provide insights relevant for vegetation management and conservation planning on ski slopes, particularly in protected areas.

Keywords Central Europe · Snow cover · Soil pH · Species traits · Vascular plants

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Introduction

The skiing industry has been identified as one of the industries that is highly dependent on ideal weather conditions. Therefore, it is tremendously vulnerable to climate change (Töglhofer et al. 2011). Over the past century, the lack of natural snow cover due to climate change resulted in declining income at ski resorts. Additional machine-made snowmaking is now required to facilitate a continuous skiing season (Fang et al. 2021). The operation of ski resorts using artificial snow starts at the beginning of the winter and lasts until the end of the skiing season in spring (Price 1972; Wipf et al. 2005). In Slovakia, this kind of management was first introduced in 1996 in the Ski Resort Jasná in Low Tatras (Smrečanský 2001). Some ski resorts facing difficulties related to the insufficient natural snow cover caused by rising temperatures have even been closed as they could not adapt to the changing management (Hamilton et al. 2003). According to some estimations, the elevation at which there is still enough natural snow for the profitable operation of ski resorts will rise by 300 m over the next 30 years (Abegg 1996).

The use of artificial snow possibly alters the plant species composition on ski slopes. For example, Wipf et al. (2005) found that the prolonged artificial snow use on ski slopes (2–15 years) resulted in higher moisture and nutrient indicator values of vegetation. Hence, the impacts of artificial snow on vegetation composition increase with time. Various surface or subsurface water sources are used to produce artificial snow, having a higher mineral content (such as nitrate, calcium ions, sulfate, and chloride ions) than rainwater (Rixen et al. 2004). Therefore, the average amount of nutrient salts and ions in the melting water is, on average, eight times higher on slopes with artificial snow (Rixen and Freppaz 2015). As a result, artificial snow can have up to 4 times higher conductivity than natural snow and thus can have fertilizer-like effects on vegetation (Rixen et al. 2002); it also provides a nutrient input during the melting of snow for about 4 weeks in late spring (Wipf et al. 2005). The addition of artificial snow and its compaction with snow-grooming vehicles delay the melting of snow for several days (17 on average), shortening the growing season (Rixen et al. 2003). Meltwater from artificially snowed ski slopes produces on average two times more runoff than natural snow because of its increased thickness and higher density (Rixen et al. 2004). In some protected areas in the world, artificial snowing is forbidden due to the danger of causing landslides (Štursa 2007; Ceccato et al. 2021) and long-lasting artificial snowing should be avoided in areas where the higher increase in the supply of water and nutrients is a concern (Wipf et al. 2005).

Ski resort management is considered to be one of the main factors causing environmental degradation in the world's mountainous areas, while the most profound impact of it takes place when the ski slope is being constructed, due to cutting forest and removal of vegetation and topsoil (Wipf et al. 2005; Pickering and Hill 2007; Klačanová et al. 2024). This causes alterations in the site's vegetation and soil characteristics. However, revegetating ski slopes afterward is a fundamental and crucial step in maintaining the stability of the mountain landscape, helping to prevent both ecological and economic harm (Kizeková et al. 2008). Commonly, revegetating makes use of non-native species, mostly graminoids, which are less expensive than native plants and can quickly establish a sufficient vegetation cover to prevent erosion. Since fast-growing grasses also tolerate disturbance, their use in revegetation poses a risk of spreading not only along the ski slopes but also into surrounding natural areas, depriving the local species of their natural habitats. Hence, the construction of ski slopes creates a new habitat type, which is maintained by management and mechanical disturbance caused by skiing (Kangas et al. 2009).

Potential detrimental effects of artificial snow on montane ecosystems may arise from the distinct chemical and physical characteristics of artificial snow when compared to the ski slope with natural snow, mainly in terms of water input and shortened growing season (Kammer 2002). Unlike high-altitude ski resorts in the Alps, ski slopes in Slovakia are situated mainly at lower elevations. This increases their sensitivity to warmer winter temperatures and enhances the dependence on artificial snow, compared to neighboring alpine countries. Therefore, the aim of this study was to evaluate how artificial snow influences vegetation and environmental conditions on ski slopes in Slovakia. We formulated the following hypotheses: (i) Floristic composition differs between artificially snowed and naturally snowed slopes due to differences in soil abiotic properties and longer snow cover at artificially snowed ski slopes. (ii) Soil reaction is altered on artificially snowed slopes compared to naturally snowed slopes as a consequence of different chemistry of artificial snow. (iii) Variability of the ecological indicator values can be explained sufficiently by a set of topographic and edaphic predictors, as well as by the presence of artificial snow. To address these hypotheses, the study focused on four main objectives: First, to assess species composition on artificially and naturally snowed slopes to detect differences in species occurrence and abundance. Second, to examine soil properties, including soil reaction, to evaluate the potential impact of artificial snow on soil conditions. Third, to analyze species traits to understand how artificial snow affects functional characteristics of plants, and fourth, to identify key environmental predictors shaping species composition, ecological indicator values, and species traits, and to determine their relative importance.

Materials and methods

Study area

The study took place in 30 different ski resorts in Slovakia (Fig. 1), situated at elevations ranging from 445 to 1435 m above sea level. The ski resorts are located in the Carpathian Mountains in submontane, montane, and subalpine climate zones. Typically, the selected ski resorts are surrounded by forests, a consequence of ski slope establishment through forest clear-cutting and artificially seeded meadows.

Vegetation sampling

Before data collection, we selected so-called twin plots, sampling two plots per ski resort (one at a naturally snowed and one at an artificially snowed ski slope) with identical or very similar topographic elements such as elevation, aspect, and slope (Bazalová et al. 2018). Plot selection was done in ArcMap 10.2 (ESRI 2011), using the Spatial Analyst toolbox with digital elevation models of Slovakia "DMR 3.5" and "DMR 5.0" provided by the Geodesy, Cartography and Cadastre Authority of the Slovak Republic. We recorded the elevation, aspect, and slope of both artificially and naturally snowed slopes within each resort and selected the most suitable areas in which to establish sampling plots. The exact locations of the plots were placed in the central parts of each slope and then were determined visually in the field by

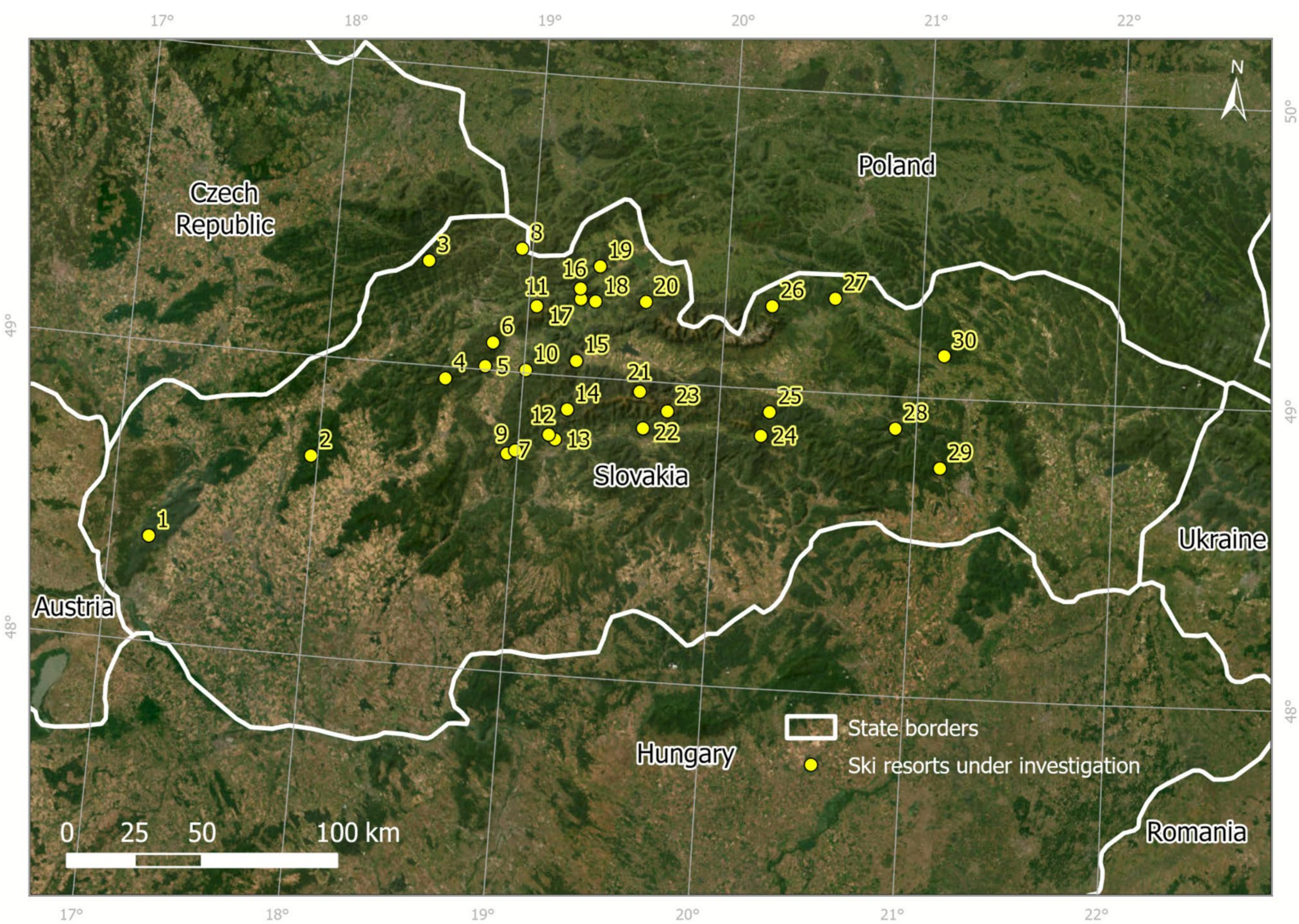

Fig. 1 Studied ski resorts in Slovakia: (1) Pezinská Baba, (2) Bezovec, (3) Makov, (4) Fačkovské sedlo, (5) Valča, (6) Martinské hole, (7) Krahule, (8) Veľká Rača, (9) Skalka, (10) Jasenská dolina, (11) Vrátna, (12) Šachtičky, (13) Selce-Čachovo, (14) Nová hoľa, (15) Malinô Brdo, (16) Hruštín, (17) Kubínska hoľa, (18) Racibor, (19) Krušetnica, (20) Zuberec, (21) Jasná, (22) Mýto pod Ďumbierom, (23) Čertovica, (24) Telgárt, (25) Vernár, (26) Ždiar, (27) Vyšné Ružbachy, (28) Plejsy, (29) Jahodná, (30) Drienica. Basemap: Ortophotomosaics of the Slovak Republic (2020–2022; provided by The Geodesy, Cartography and Cadastre Authority of the Slovak Republic)

selecting areas with similar vegetation composition between naturally and artificially snowed slopes. The twin plots were at most 200 m apart.

We conducted 60 relevés in 30 different ski resorts using the Zürich-Montpellier school of phytosociology (Braun-Blanquet 1964) and the percentage species coverage scale. Relevés were collected in the summer (June to August) of 2021 and 2022. The size of relevés was 16 m^2. The covers of the herb, moss, and lichen layer were estimated as percentage covers. The mosses and lichens were not further identified to a species level. Additionally, percentages of bare soil, litter (dead and dry organic matter), and bare rock were recorded. We also obtained environmental characteristics such as locality, coordinates, habitat, elevation, aspect, and slope.

Soil sampling

Soil sampling was conducted in autumn 2023 within the plots of the relevés. At each sampling plot, we collected one sample, which was composited from a mixture of three portions of soil (ca. 300 g of soil in total) randomly collected at 2–20 cm depth using a garden trowel. The soil portions were stored inside paper bags until arrival at the laboratory. In the laboratory, the soil portions were carefully sorted from all foreign materials, then mixed uniformly into the final samples and weighed. The samples were air-dried at room temperature, gently beaten with a porcelain pestle and mortar, and sieved through a 2-mm sieve. The prepared samples were subjected to standard soil analyses for pH using the Visocolor™ Reagent Case for Soil Analysis in our laboratory.

Topographic variables

To study the influence of topography and soil on both species diversity and plants' responses to environmental conditions (Table 1), a set of predictors (Table 2) was selected to be used in linear regression models. Values of topographic variables, such as aspect (ASP, split into eight categories), Topographic Wetness Index (TWI), and Area Solar Radiation (ASR), were obtained using ArcGIS PRO 3.1, derived from the Digital Elevation Model "DMR 3.5" with a resolution of 25 m, which is the open-source layer provided by the Geodesy, Cartography and Cadastre Authority of the Slovak Republic. Values of predictors elevation (ELEV) and slope (SLOP) were recorded during terrain research using a GPS device. Area Solar Radiation was computed for the fixed time period from 1.6.2021 to 30.9.2021, with a day interval of 7 days and the hour interval set to 4 h. Topographic Wetness Index was calculated using tangent slope and flow accumulation rasters.

Species traits

To compare the functional diversity of vegetation in different areas of ski slopes, we examined the specific biological and ecological characteristics of each species, primarily sourced from the BiolFlor database (Klotz et al. 2002); elevational

Table 1 Response variables entering linear models

Abbreviation	Variable	Type	Category
SW	Shannon-Wiener Index	Continuous	Diversity indices
EIV_M	Moisture	Continuous	Ecological indicator values
EIV_N	Nitrogen	Continuous	Ecological indicator values
EIV_R	Reaction	Continuous	Ecological indicator values
EIV_L	Light	Continuous	Ecological indicator values
EIV_T	Temperature	Continuous	Ecological indicator values

Table 2 Predictors entering linear models

Abbreviation	Variable	Type	Unit	Category
ELEV	Elevation	Continuous	m a.s.l	Topographic
SLOP	Slope	Continuous	°	Topographic
ASP	Aspect	Categorical (8)		Topographic
TWI	Topographic Wetness Index	Continuous	-	Topographic
ASR	Area Solar Radiation	Continuous	Wh/m^2	Topographic
MOIST	Soil moisture	Continuous	%	Edaphic
PH	Soil reaction	Continuous		Edaphic
ARTIF	Presence of artificial snow	Categorical (2)		Anthropogenic

belts were extracted from Key to the Flora of the Czech Republic (Kaplan et al. 2019). The selected characteristics are listed in Table 3.

When a taxon exhibits more than one category of species traits, the taxon is considered representative of each of these categories. Plant taxa nomenclature follows Marhold (1998); syntaxonomical nomenclature and characteristics follow Hegedüšová Vantarová and Škodová (2014); IUCN threat categories follow Eliáš et al. (2015); and the origin and invasiveness of taxa are according to Medvecká et al. (2012).

Data analyses

The relevés from all plots were stored in a TURBOVEG 2 database (Hennekens and Schaminée 2001) and edited in

Table 3 Studied plant species traits

Trait	Category	Description
Reproduction Type	s	reproduction by seeds
	ssv	mostly by seeds and rarely vegetatively
	sv	by seeds and vegetatively
	vvs	mostly vegetatively and rarely by seeds
	v	vegetatively
Strategy Type	c	competitors
	cr	competitors/ruderals
	cs	competitors/stress-tolerators
	csr	competitors/stress-tolerators/ruderals
	r	ruderals
	s	stress-tolerators
	sr	stress-tolerators/ruderals
Life Form*	T	therophytes
	H	hemicryptophytes
	C	chamaephytes
	G	geophytes
	P	phanerophytes**
Life Span	a	annuals
	b	biennials
	p	perennials***
Leaf Persistence****	s	summer green
	i	persistent green
Rosette	r	erosulate plants
	h	hemirosette plants
	g	rosette plants
Vegetative Propagation	ws	roots shoots
	r	runners
	b	bulbils
	rh	rhizomes
	sk	shoot tubers
	rp	rhizome-like pleiocorns
Elevational Belts of Plants	1	lowlands
	2	colline
	3	submontane
	4	montane
	5	subalpine

*Species that were not included in the BiolFlor database were determined by Dostál and Červenka (1991, 1992), who used the same (Raunkiær) classification

**Macrophanerophytes, nanophanerophytes, pseudophanerophytes and hemiphanerophytes were merged into one group

***Pluriennial-hapaxanthic and pluriennial-pollakanthic were merged into one group

****Other categories, such as spring green (v) and overwintering green (w) were not present in our dataset

JUICE software ver. 7.1 (Tichý 2002). Taxa of problematic status were merged into aggregates to minimize taxonomic bias. Classification of relevés to the level of the alliance was done using the electronic expert system for identification of grassland vegetation (Janišová 2007; Hegedüšová Vantarová and Škodová 2014). Ecological indicator values (EIV) for soil moisture, soil nitrogen, soil reaction, light, and temperature (Dengler et al. 2023), and Shannon-Wiener's diversity index (SW; Hill 1973) were calculated in JUICE. Ecological indicator values (EIVs) assign numerical scores to plant species reflecting their preferences along environmental gradients such as light, temperature, moisture, nutrients, and soil pH, allowing inference of site conditions from species composition (Ellenberg 1974; Dengler et al. 2023). All data were imported into R 4.2.0 (R Core Team 2024) for statistical analyses and visualization. Species occurrence and abundance on plots with artificial and natural snow were compared using the Wilcoxon signed-rank test as implemented in the wilcoxon.test function from stats v. 3.6.2 package (R Core Team 2024). To explore differences in community composition, we ran a detrended correspondence analysis (DCA) using the decorana() function from the vegan v. 2.6–6.1 package (Oksanen et al. 2024). To study the relationship between species composition and environmental variables, we calculated multiple regression of ecological indicator values (EIV), soil reaction (pH), Shannon-Wiener index (SW), and elevation with the first two DCA axes using the envfit() function from the vegan package. The statistical significance of regression results was tested using the resampling permutation procedure (999 permutations).

To compare artificially and naturally snowed ski slopes for a number of species with different species traits and the number of species at different elevation belts, we ran linear mixed-effects models (LMM) with ski resort as a random effect using the lmer() function from lme4 v. 1.1–35.1.1.1 package (Bates et al. 2015). To assess the influence of the random effect, we calculated marginal and conditional R^2 for each LMM using the r.squaredGLMM() function from MuMIn v. 1.47.5 package (Bartoń 2023). We performed an analysis of variance (ANOVA) using the anova() function from car v. 3.1-2.1.1 package (Fox and Weisberg 2019) with Tukey post hoc multiple comparison tests using the glht() function from multcomp v. 1.4–26.4 package (Hothorn et al. 2008). Graphics were generated using ggplot2 version 3.4.4 (Wickham 2016).

To inspect how and to what extent the environmental variables (topographic, edaphic, and the presence of artificial snow) affect species diversity and ecological indicator values (EIV), we computed multiple linear models. In these models, the response variable is described as a function of several independent variables (predictors). In total, six models were prepared. Each EIV and the Shannon-Wiener index represent a dependent variable in these models (listed in Table 1), while eight environmental variables (listed in Table 2) act as predictors. Linear models were fit using the lm() function from the stats v. 3.6.2 package (R Core Team 2024). A method of Variance Inflation Factors (VIF) was used to prevent multicollinearity, as implemented in the vif() function from the car v. 3.1-3.1.1 package (Petrie 2016), where a $VIF > 4$ indicates a high degree of multicollinearity. This was the case for ASP and ASR. Therefore, we decided to remove ASP from all the models, while keeping ASR (a continuous variable contributes to a more accurate model compared to the categorical one). The quality of model fit was estimated by the coefficient of determination (R^2). The relative importance of predictors in each model was estimated using the calc.relimp() function from relaimpo v. 2.2–7.2 package (Groemping 2006). The metric of lmg was used, which is based on the partitioning of R^2 by averaging it over orders of regressors.

Results

Species composition and vegetation characteristics

The dataset of 60 relevés consisted of 301 vascular plant taxa, of which 250 taxa occurred on artificially snowed ski slopes and 234 on naturally snowed ski slopes. For the full list of species, see Supplementary material S1. Taxa whose occurrence and abundance on plots with artificial snow was significantly higher were *Taraxacum* sect. *Ruderalia* ($p = 0.010$), *Plantago major* ($p = 0.017$), *Achillea millefolium* agg. ($p = 0.024$), *Medicago falcata* ($p = 0.028$), *Lotus corniculatus* ($p = 0.035$), *Cichorium intybus* ($p = 0.039$), and *Festuca pratensis* ($p = 0.050$). Plots with the presence of natural snow were showing higher occurrence and abundance of *Anthoxanthum odoratum* ($p = 0.004$), *Brachypodium pinnatum* ($p = 0.012$), *Vaccinium myrtillus* ($p = 0.028$), and *Stellaria graminea* ($p = 0.033$). The most frequently occurring taxa in both artificially and naturally snowed plots is to be seen in Table 4.

We recorded 11 non-native species on the ski slopes, of which eight were archaeophytes and three neophytes. In plots with artificial snow, eight archaeophytes (*Anagallis arvensis*, *Arctium tomentosum*, *Cichorium intybus*, *Convolvulus arvensis*, *Melilotus albus*, *Spergula arvensis*, *Veronica arvensis*, *Vicia tetrasperma*) and two neophytes (*Juncus tenuis* and *Trifolium hybridum*) were found. In plots with natural snow, we found four archaeophytes (*Cichorium intybus*, *Convolvulus arvensis*, *Veronica arvensis*, *Vicia tetrasperma*) and two neophytes (*Stenactis annua* and *Trifolium hybridum*). Also, a few of the IUCN Red list species were found in our studied plots: *Allium carinatum* (NT) and *Carex flava* (LC) at both artificially and naturally snowed plots, *Centaurium pulchellum* (NT), *Crocus discolor* (LC), and *Lilium*

Table 4 The most frequent taxa in studied areas of ski slopes in Slovakia (%). Only taxa with a minimum 50% frequency in any column are shown. Taxa in the first column are arranged in decreasing frequency, with frequencies over 50% marked in bold. Green shaded cells indicate the highest frequency in the column

	Habitat	
	Artificially snowed	**Naturally snowed**
Achillea millefolium agg.	**90**	**73**
Dactylis glomerata	**87**	**67**
Lotus corniculatus	**80**	**53**
Alchemilla spp.	**77**	**60**
Taraxacum sect. *Ruderalia*	**77**	**47**
Plantago lanceolata	**63**	**63**
Trifolium pratense	**63**	**50**
Poa pratensis	**60**	47
Hypericum maculatum	**57**	**60**
Leontodon hispidus	**57**	30
Festuca pratensis	**53**	47
Trifolium repens	**53**	33
Veronica chamaedrys	**53**	**63**
Vicia cracca	**53**	30
Agrostis capillaris	**50**	**53**
Pimpinella saxifraga agg.	**50**	40
Ranunculus acris	**50**	27
Cruciata glabra	43	**57**
Anthoxanthum odoratum	23	**53**

bulbiferum subsp. *bulbiferum* (NT) at artificially snowed plots, and *Gymnadenia conopsea* (LC) and *Soldanella carpatica* (LC) at naturally snowed plots.

The floristic composition of studied plots was mosaic and diverse, comprising up to eight alliances from four classes. Floristic compositions of relevés on both artificially snowed ski slopes and naturally snowed slopes contained species typical for various classes and alliances, including *Molinio-Arrhenatheretea* (*Arrhenatherion elatioris*, *Cynosurion cristati*, *Plantagini-Prunellion*, and *Polygono bistortae-Trisetion flavescentis*), *Nardetea strictae* (*Nardo strictae-Agrostion tenuis*, *Violion caninae*), *Trifolio-Geranietea sanguinei* (*Trifolion medii*), and *Calluno-Ulicetea* (*Genisto pilosae-Vaccinion*).

The alliance *Arrhenatherion elatioris* was the most prevalent in plots with artificial snow (12 relevés) and natural snow (17 relevés). This alliance is typical for mesophilic meadows consisting of tall grasses and flowering herbs, dependent on frequent mowing. Its optimum is at elevation between 600 and 800 m above sea level; montane species are absent. *Cynosurion cristati* was the second most common alliance at plots with artificial snow (9 relevés); at plots with natural snow, it was the third most common (4 relevés). This is an alliance of intensively used pastures prevalent in lower elevations, consisting of grasses and herbs adapted to trampling and grazing by livestock. The second most frequent alliance in plots with natural snow was *Genisto pilosae-Vaccinion* (5 relevés) which was completely absent in plots with artificial snow. This alliance is typical for subalpine and alpine areas with species *Calluna vulgaris* and genus *Vaccinium*. The third most frequent alliance in plots with artificial snow (3 relevés) was *Nardo strictae-Agrostion tenuis*, which we only found once in the plots with natural snow. This alliance is typically present at montane to supramontane grasslands with alpine species up to 1500 m above sea level. *Violion caninae* was the fourth most common alliance in plots with artificial snow (2 relevés) and only once represented in the plots with natural snow (1 relevé). It is an alliance that is typical for lower elevations (lowlands to submontane belt); it is relatively species-poor, with dominant oligotrophic species due to extensive grazing. *Polygono bistortae-Trisetion flavescentis* was the fourth most prevalent alliance in plots with artificial snow (2 relevés) and plots with natural snow (2 relevés). This species-rich alliance is to be found in mountain meadows growing on nutrient-rich soils and is affected by shorter vegetation seasons. *Trifolion medii* was present only once at the plots with artificial snow. This alliance of mesophilic edge communities is present at the edges of forests and anthropogenically affected habitats. *Plantagini-Prunellion* was also present only once at plots with artificial snow. This alliance typically occurs on trampled paths in shaded habitats.

The DCA plot (Fig. 2) shows how different syntaxonomical alliances are distributed in the environmental space defined by the two DCA axes. From this figure, the relative similarities between alliances can be seen. For example, the relevés of the alliances *Arrhenatherion elatioris* and *Cynosurion cristati* seem to be relatively similar, while those of the alliance *Genisto pilosae-Vaccinion* seem more distinct when compared to the first two alliances. It should be noted that the amount of relevés belonging to some alliances is too small (e.g., *Trifolion medii*, *Plantagini-Prunellion*) to infer information about their similarities with other alliances from this ordination alone. The first axis of DCA of 60 relevés (DCA1) explains 6.02% of the variance of plant species community data, and the second axis (DCA2) explains 3.78% (Fig. 3). Plots on artificially snowed ski slopes (blue points) and plots on naturally snowed ski slopes (yellow triangles) do not form distinct clusters. This could imply that artificial snowing does not have a great effect on floristic composition, but it could also be that the effect of artificial snow is masked because we included all plots of all different alliances in this DCA (Fig. 3a). The ecological indicator values with the strongest relation with floristic composition were temperature ($R^2 = 0.86$, $p < 0.001$) and light ($R^2 = 0.71$, $p < 0.001$), followed by elevation, nitrogen, pH, moisture, and Shannon-Wiener index (Table 5). All ecological indicator values, except for light, align closely with the first axis. There is a positive correlation between elevation and moisture, while temperature shows an inverse relationship with these variables. The second DCA graph (Fig. 3b) shows that species such as *Agrostis capillaris*, *Hypericum maculatum*, and *Nardus*

Table 5 Results of envfit function for DCA ordination. R^2 is the goodness of fit (coefficient of determination), and *p* shows significance of the relationship using the permutation test. The significant differences are marked with bold and with a star above with significances as **p* < 0.05, ***p* < 0.01, and ****p* < 0.001. Number of permutations: 999

Variables	DCA1	DCA2	R^2	*p*
pH	−0.99989	−0.01485	0.4579	**0.001*** **
SW	−0.98854	−0.15096	0.1918	**0.008** **
Elevation	0.99083	0.13512	0.5178	**0.001*** **
Moisture	0.99471	−0.10268	0.3824	**0.001*** **
Nitrogen	−0.96661	−0.25624	0.4993	**0.001*** **
Light	−0.83004	−0.5577	0.7143	**0.001*** **
Temperature	−0.99787	−0.06518	0.8591	**0.001*** **

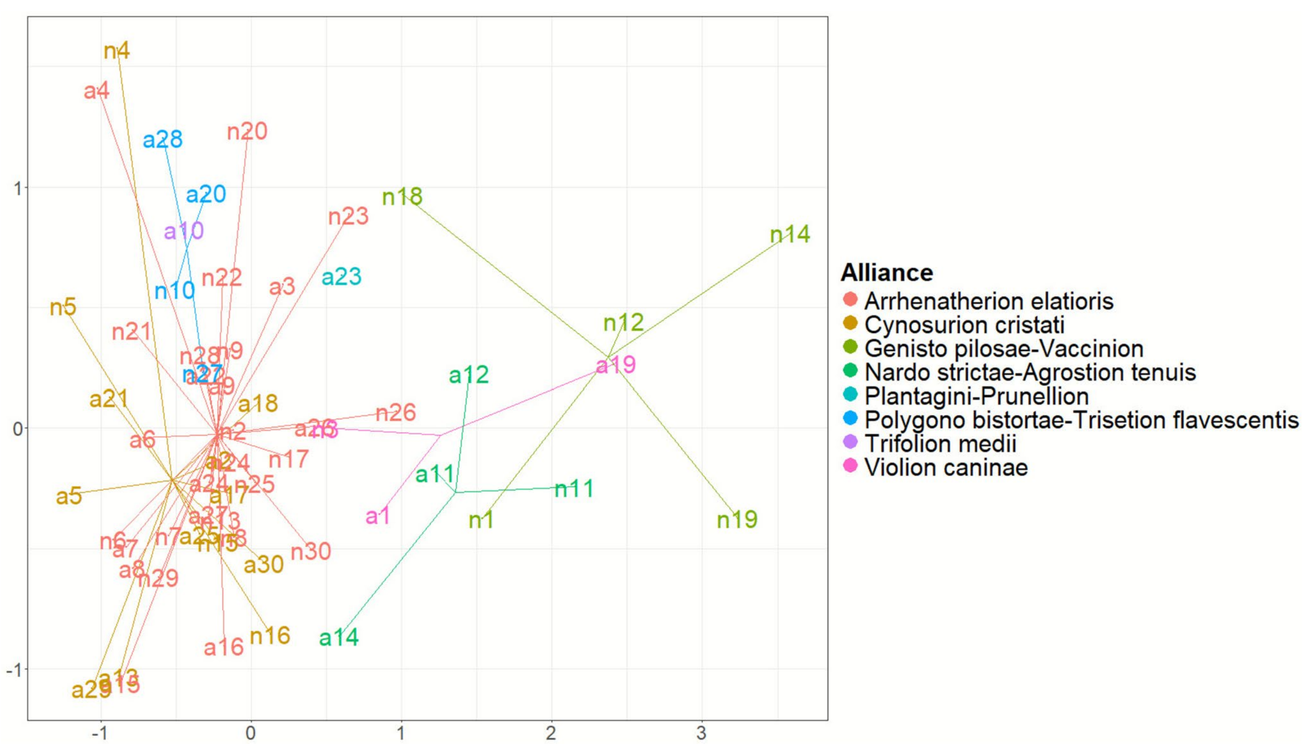

Fig. 2 Detrended correspondence analysis (DCA) of all relevés grouped by alliances. Colors represent alliances and relevés are connected to the centroid of their alliance. Numbers represent the study area, a = artificially snowed, n = naturally snowed

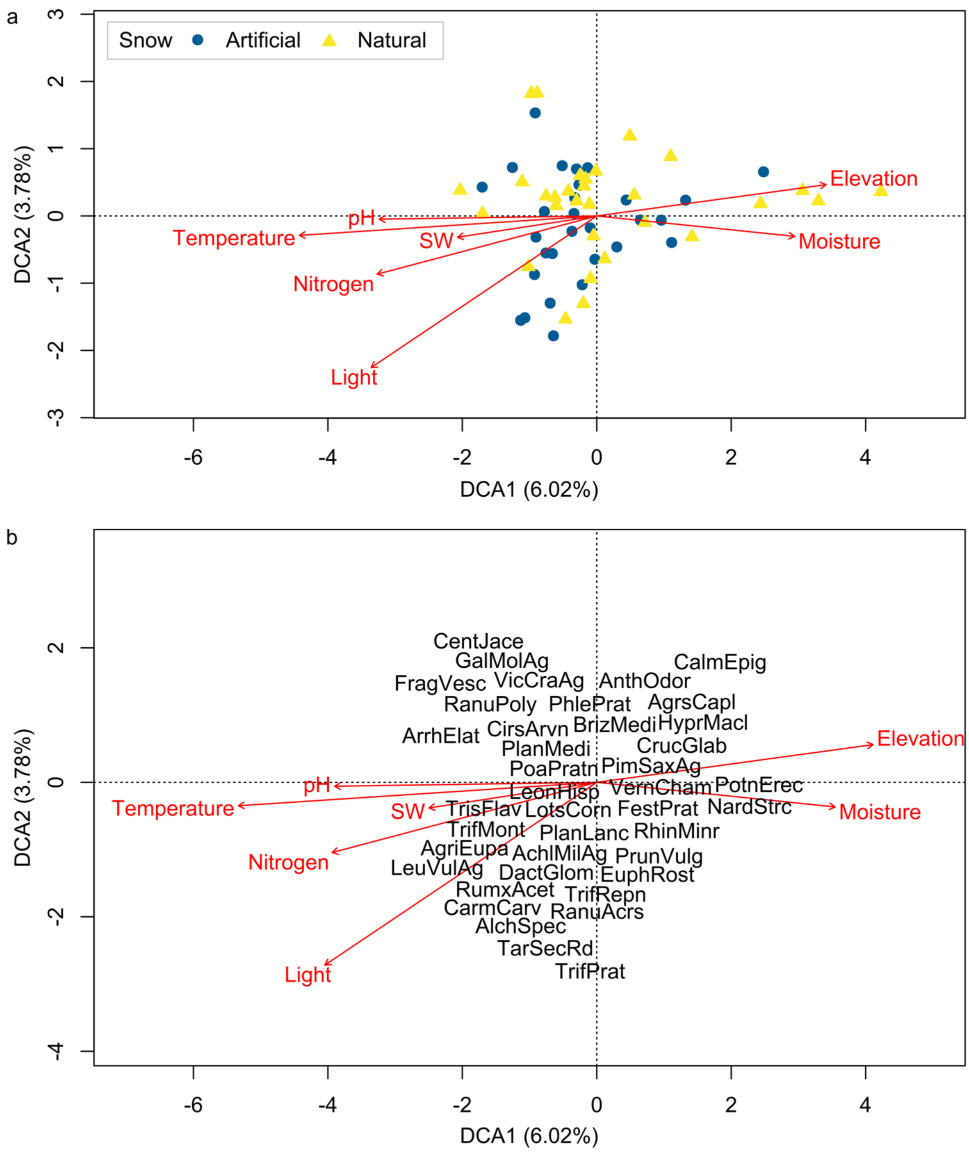

Fig. 3 Detrended correspondence analysis (DCA) of 60 relevés from artificially and naturally snowed areas of 30 ski slopes in Slovakia with ecological indicator values (EIV), Shannon-Wiener index (SW), pH, and elevation plotted onto a DCA diagram as supplementary variables, explaining 9.80% of the total variance. (**a**) Species fit was selected by frequency to 40 species. (**b**) Abbreviations of the species: AgrsCapl, *Agrostis capillaris*; AchlMilAg, *Achillea millefolium* agg.; AgriEupa, *Agrimonia eupatoria*; AlchSpec, *Alchemilla* spp.; AnthOdor, *Anthoxanthum odoratum*; ArrhElat, *Arrhenatherum elatius*; BrizMedi, *Briza media*; CalmEpig, *Calamagrostis epigejos*; CarmCarv, *Carum carvi*; CentJace, *Centaurea jacea*; CirsArvn, *Cirsium arvense*; CrucGlab, *Cruciata glabra*; DactGlom, *Dactylis glomerata*; EuphRost, *Euphrasia rostkoviana*; FestPrat, *Festuca pratensis*; FragVesc, *Fragaria vesca*; GalMolAg, *Galium mollugo* agg.; HyprMacl, *Hypericum maculatum*; LeonHisp, *Leontodon hispidus*; LeuVulAg, *Leucanthemum vulgare* agg.; LotsCorn, *Lotus corniculatus*; NardStrc, *Nardus stricta*; PhlePrat, *Phleum pratense*; PlanMedi, *Plantago media*; PimSaxAg, *Pimpinella saxifraga* agg.; PlanLanc, *Plantago lanceolata*; PoaPratn, *Poa pratensis*; PotnErec, *Potentilla erecta*; PrunVulg, *Prunella vulgaris*; RanuAcrs, *Ranunculus acris*; RanuPoly, *Ranunculus polyanthemos*; RhinMinr, *Rhinanthus minor*; RumxAcet, *Rumex acetosa*; TarSecRd, *Taraxacum* sect. *Ruderalia*; TrifMont, *Trifolium montanum*; TrifPrat, *Trifolium pratense*; TrifRepn, *Trifolium repens*; TrisFlav, *Trisetum flavescens*; VernCham, *Veronica chamaedrys*; VicCraAg, *Vicia cracca* agg.

stricta exhibit a preference for higher elevations, thriving in environments with higher humidity and acidic (low) pH conditions. Conversely, species like *Agrimonia eupatoria*, *Arrhenatherum elatius*, and *Leucanthemum vulgare* are typically found at lower elevations, where they experience reduced precipitation and are better suited to neutral or slightly alkaline soils.

Another DCA plot (Fig. 4) visually separates different elevation groups (low, medium, and high) based on the species composition of each relevé. The group of blue relevés,

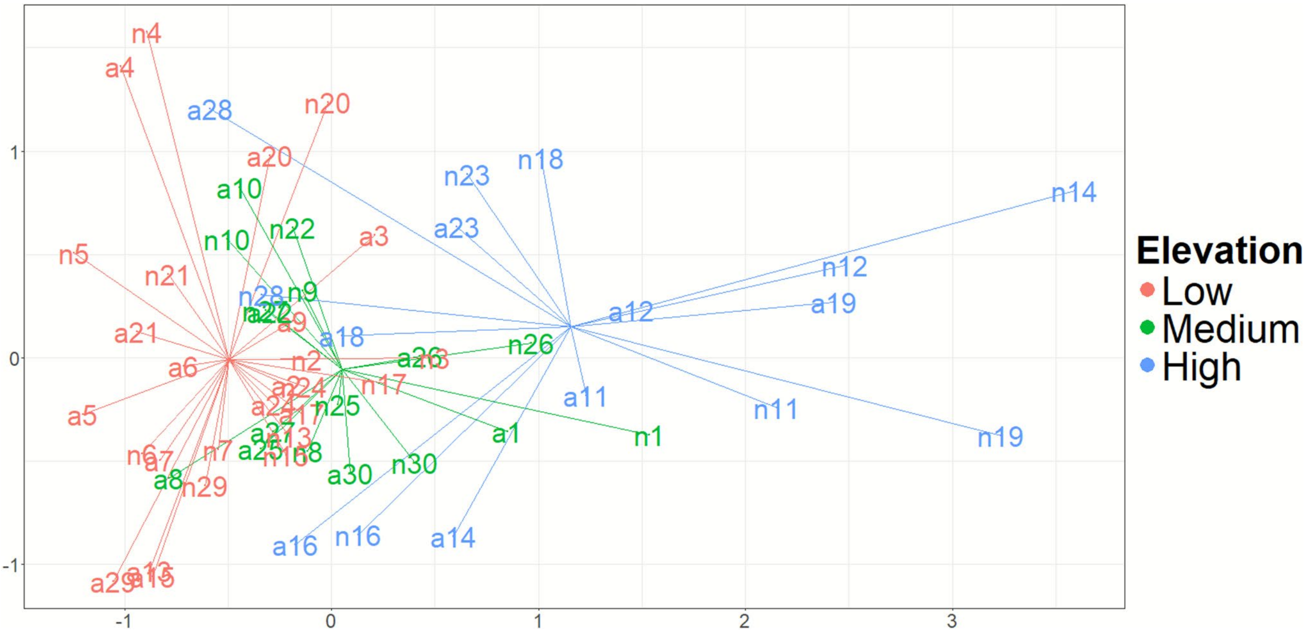

Fig. 4 Detrended correspondence analysis (DCA) of all relevés grouped into three levels of elevation: low < 799, medium 800–999 m, and high > 1000 m. Relevés are connected to the centroid of their elevation level. Numbers represent the study area, a = artificially snowed, n = naturally snowed

situated at higher elevations, is more dispersed, suggesting a broader range of variation at higher elevations.

Species traits

The presence of selected plant species traits was compared between the areas on ski slopes with different snow types (Fig. 5). From eight analyzed traits, five came out as significant: life span, life form, strategy type, leaf persistence, and elevation belt (for detailed results, see Supplementary material S2). Traits such as reproduction type, rosette, and vegetative propagation did not show significant results. Overall, perennial hemicryptophytes, with competitive strategy and with persistent summer green leaves, were most common. Plants with a perennial life span were more frequent in areas with artificial snow than in those with natural snow ($p = 0.0087$). Hemicryptophytes ($p = 0.0028$) and competitive species ($p = 0.0508$) also occurred more often on artificially snowed slopes. In terms of leaf persistence trait, the summer green leaves were more prevalent in areas with artificial snow than in areas with natural snow ($p = 0.0447$). From the elevation belts, there was a higher presence of plants belonging to lowland ($p = 0.0264$) and colline ($p = 0.0416$) elevation belts in areas with artificial snow than in the areas with natural snow. For the full list of species with their traits, see Supplementary material S1.

Variance of species diversity and ecological indicator values explained by environmental predictors

The highest R^2 score was reached in the case of temperature (EIV_T) ($R^2 = 74\%$), meaning that the selected topographic, edaphic, and anthropogenetic predictors accounted for almost three-quarters of the variation in the computed values of temperature as an ecological indicator value. A good fit was also reached in the case of ecological indicator values for soil reaction (EIV_R) ($R^2 = 67\%$) and for light (EIV_L) ($R^2 = 60\%$). The lowest explanatory power was achieved in the case of Shannon-Wiener Index (SW) ($R^2 = 23\%$). All values are listed in Fig. 6.

With the strongest R^2 contribution, elevation (ELEV) and soil reaction (pH) were found to be the most important predictors in all the models. On the contrary, the presence of artificial snow (ARTIF) did not perform significantly in any case (Fig. 6). The ecological indicator values of temperature (EIV_T) and soil reaction (EIV_R) were found to be strongly negatively affected by the increasing elevation (ELEV) (more than 30% of response variance). Soil reaction (pH) was the most important variable, especially in terms of its positive impact on temperature (EIV_T) and light (EIV_L). The importance of all the other predictors was relatively low (up to 10% of response variance; see Fig. 6).

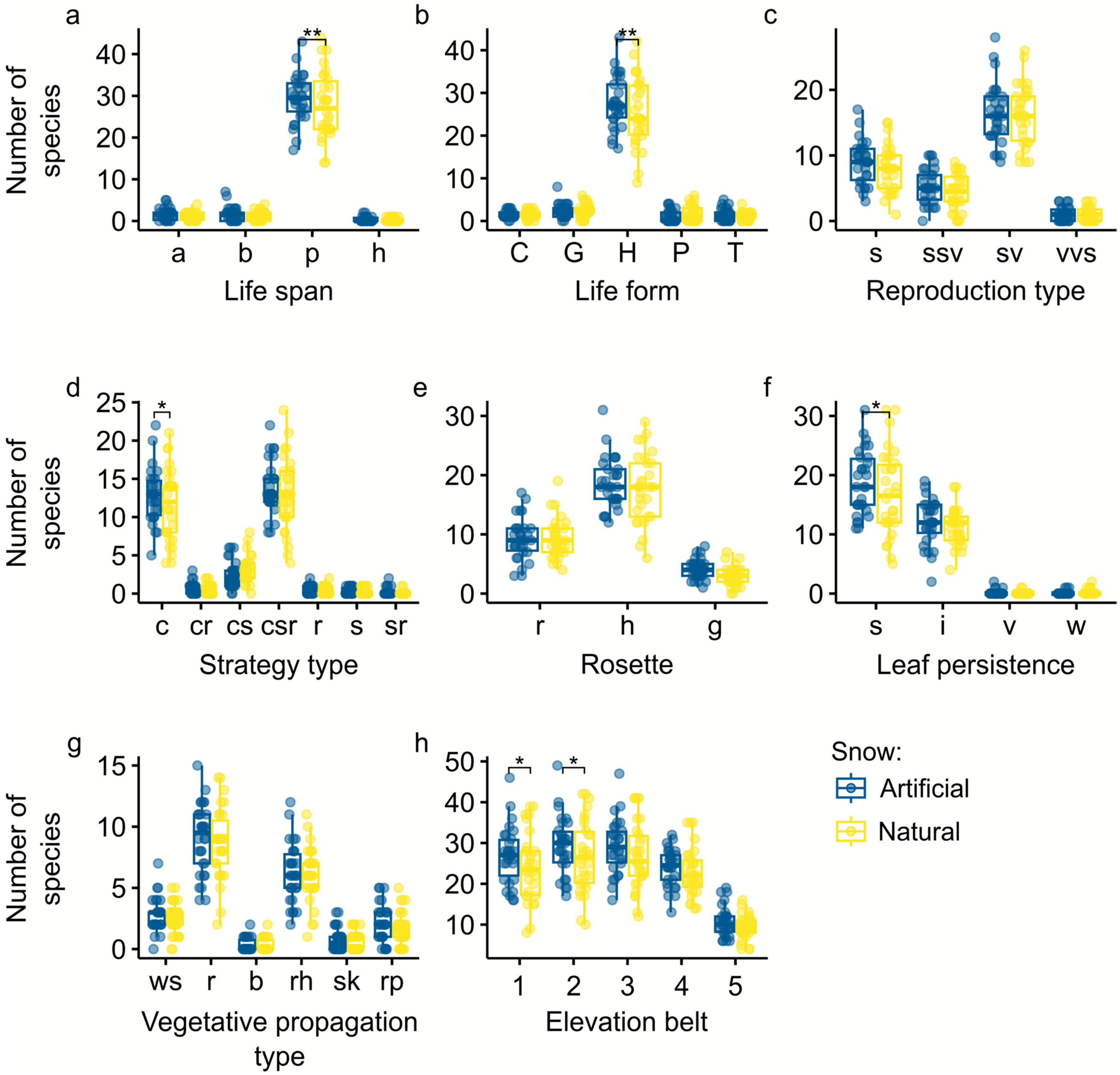

Fig. 5 Boxplot showing the comparison of selected species traits between artificially and naturally snowed areas of 30 ski slopes in Slovakia: life span (**a**), life form (**b**), reproduction type (**c**), strategy type (**d**), rosette (**e**) leaf persistence (**f**), vegetative propagation type (**g**), elevation belt (**h**). For abbreviations of species traits, see Table 3. Individual data points show species recorded for each trait; the medians are shown as a bold horizontal line; boxes represent upper and lower quartiles. The significant differences are marked with a star above with significances as $*p<0.05$ and $**p<0.01$

Discussion

Our results indicate that species composition on Slovak ski slopes is primarily influenced by temperature, light, elevation, and soil reaction, while artificial snow had little direct effect on overall community composition. Plots with artificial snow were more often dominated by perennial hemicryptophytes, competitive species, and plants with persistent summer green leaves, whereas higher elevation species were more frequent on naturally snowed slopes.

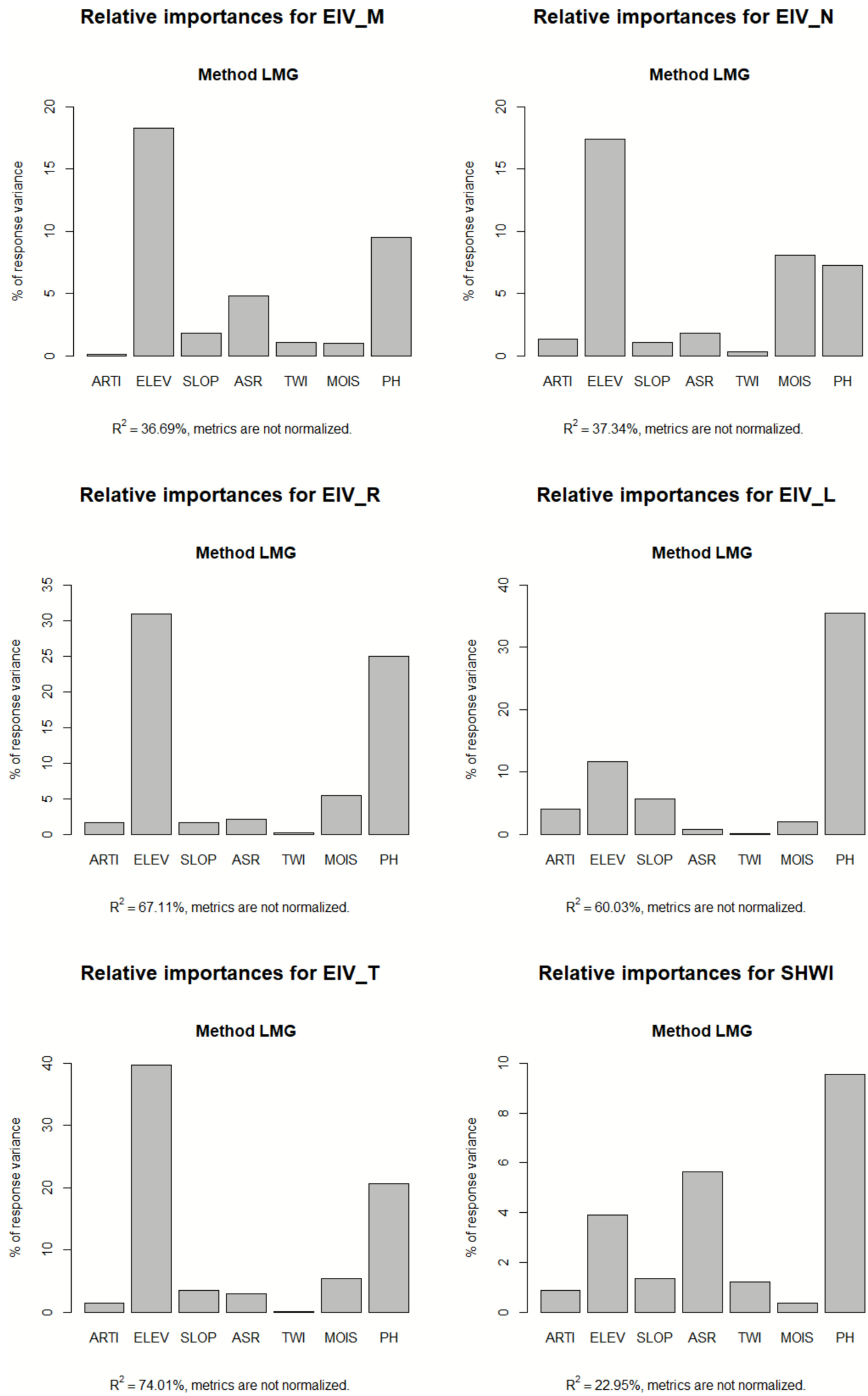

Fig. 6 Relative importance of predictors in regression models estimated by the LMG. Codes of variables are explained in Table 2

Key species traits including life span, life form, strategy type, leaf persistence, and elevational affinity showed significant responses to snow type. Variation in ecological indicator values was largely explained by topographic and edaphic factors rather than by artificial snow.

Species composition and vegetation characteristics

Our results did not support the first hypothesis as species composition did not differ significantly between ski slopes with artificial snow and those with only natural snow. This is consistent with earlier studies reporting little or no effect of artificial snow on vegetation composition (Pohl et al. 2009; Roux-Fouillet et al. 2011), but contrasts with findings from other Slovak studies where changes in floristic composition or evenness were observed (Šeffer and Stanová 1999; Mikloš et al. 2018). Also, our results do not directly support the hypothesis that artificial snow alters soil reaction, as the presence of artificial snow was not a significant predictor of soil pH (EIV_R). However, the higher occurrence of species typical of more nutrient-rich, less acidic soils on artificially snowed slopes may indicate indirect soil changes consistent with chemical inputs from snowmaking, which was also one of the findings of Rixen et al. (2003). According to the analysis of prevalent community alliances, it is clear that the plots with artificial snow are dominated by grassland-type grazed communities, as a result of a different management regime. The vegetation at these plots is nutrient-rich and acidic and richer in species diversity, while the plots with natural snow consist mostly of vegetation belonging to *Genisto pilosae-Vaccinion*, which is an alliance comprising vegetation that is the closest to the natural state of the area that would be present if there is no management.

Differences in ecological indicator values (EIV) between artificially and naturally snowed ski slopes are consistent with previous studies, which have shown that artificial snow generally prolongs snow cover and delays plant phenology (Stoeckli and Rixen 2000; Rixen et al. 2001, 2003, 2008; Smith et al. 2012). Wipf et al. (2005) further demonstrated that long-term use of artificial snow increases soil moisture and nutrient availability, with impacts accumulating over time.

Species traits

The higher prevalence of perennial plants on ski slopes with artificial snow compared to those with natural snow can be attributed to several ecological and environmental factors. Artificial snow is denser and melts more slowly, delaying the onset of the growing season (Rixen et al. 2003). This favors perennials, which can utilize stored energy from their roots to survive shorter growing seasons, unlike annuals that rely on rapid germination and growth (Wipf et al. 2005). Hemicryptophytes are more prevalent on ski slopes with artificial snow than on those with natural snow due to their adaptive growth forms and resilience to disturbances caused by artificial snow production. Artificial snow increases snow density and delays melting, which can shorten the vegetation season (Wipf et al. 2005; Barni et al. 2007). In combination with its higher water and nutrient content, this can favor species adapted to these conditions, such as perennials with competitive strategies and summer green leaves, as observed in our study. These changes may lead to subtle shifts in species composition on artificially snowed slopes, although overall community composition remains largely similar to naturally snowed areas. Furthermore, ski slope construction and maintenance activities, such as grading and grooming, alter soil properties and vegetation composition, influencing which plant strategies are favored under disturbed conditions (Burt and Rice 2009; Burt and Clary 2016). The higher prevalence of species with summer green leaves on ski slopes with artificial snow compared to those with natural snow can be attributed to the altered microclimatic and soil conditions created by artificial snow. Artificial snow leads to prolonged snow cover duration and delayed snowmelt, which shifts the growing season to later in the summer (Rixen et al. 2008). This delay favors species with summer green leaves that can rapidly take advantage of the shorter growing season after snowmelt. The mechanical disturbance from grooming and compacting ski slopes by grooming vehicles is beneficial for lowland species, as they tend to have better adaptability to disturbed environments than native alpine flora (Körner 1999).

Variance of species diversity and ecological indicator values explained by environmental predictors

Using multiple linear regression modelling, we found that the variability of the ecological indicator values can be explained by the selected topographic and edaphic characteristics, but not by the presence of artificial snow.

Elevation emerged as the most important predictor of ecological indicator values for moisture, reaction, and temperature, which corresponds with the understanding of this variable as the proxy for some climatic characteristics (Kőrner 2007; Stokes et al. 2021; Yang et al. 2022). Similar can be claimed about the other strong predictor, soil reaction, that is also significantly determined by the air temperature and precipitation, which have an impact on the process of the organic matter decomposition (Rengel 2011). Therefore, we assume that the variability of the EIVs can be explained particularly by the climatic variables and their proxies, rather than by the artificial snow presence.

Furthermore, we tested the explanatory power of these predictors in relation to the Shannon-Wiener diversity index, but the low score of the variance explained confirmed the findings of Liu et al. (2021) and He et al. (2023), describing the species diversity as a complex function of a wide range of environmental factors.

Conclusion and recommendation

In conclusion, this study demonstrates that the effects of snow type were relatively subtle compared to the stronger influence of topographic and environmental factors like temperature, light, and elevation. No clear clustering of plots based on snow type emerged from the analyses, indicating that while artificial snow may have an influence, its effect could be masked by other factors such as environmental variables included in the study. Temperature and light were identified as the strongest environmental factors influencing the floristic composition, with elevation and soil reaction also playing significant roles. Regarding plant traits, plots with artificial snow exhibited a higher presence of perennial hemicryptophytes, competitors, and plants with persistent summer green leaves. In contrast, plots with natural snow supported more species from higher elevation belts. Environmental predictors such as elevation and soil reaction were the most influential, whereas the type of snow (artificial or natural) had little explanatory power in the models. It would be beneficial for future research to establish permanent monitoring plots at some ski resorts situated at similar elevation to thoroughly study the impact of artificial snow on species composition on ski slopes.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10113-025-02500-y.

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Data Availability Data is available from the authors upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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