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CHEMICAL PROPERTIES OF SOILS IN SUBALPINE GRASSLANDS UNDER DIFFERENT MANAGEMENT REGIMES

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Abstract

The aim of this study was to evaluate the soil chemical property changes under two types of grass communities (alpine grasslands) at three locations (Velký Máj, Jelení hřbet, and Břidličná) in the Jeseníky PLA. The effect of different types of intervention (burning, mineral fertilization $N_{60}PK$, sward removal, control without management) was determined in the form of small-plot trials during three years. Significant differences were found among the management treatments with respect to exchangeable soil reaction (the pH ranged between 2.33 and 3.62) and the contents of calcium, magnesium, phosphorus, and potassium; as expected, the highest levels of these nutrients were recorded in the $N_{60}PK$-fertilized treatments. The increase in soil nutrient content was 72.8% for calcium, 10.1% for magnesium, 79.7% for phosphorus, and 25.6% for potassium. The removal of vegetation, on the other hand, significantly reduced the contents of all the nutrients mentioned. The effect of burning was not as clear-cut as in the case of fertilization. Concentrations of potentially toxic elements (Cd, Pb, and Zn) in the standard aqua regia extract indicate that the so-called preventive values were exceeded for lead and cadmium. Overall, the results confirm that the soil chemistry of mountain grasslands was strongly influenced by a combination of natural factors and management practices. Extreme soil acidity represents a key factor that modifies both nutrient availability and the behavior of potentially toxic elements and should be taken into account when designing sustainable management measures.

Keywords: grass communities, soil chemical properties, small-plot trial, potentially toxic elements, fertilization, burning

INTRODUCTION

Subalpine grasslands are a distinctive component of mountain ecosystems, generally located above the upper forest boundary or in its immediate vicinity (Körner, 1999). These ecosystems are characterized by a specific species composition and play an important role in landscape hydrology and soil protection through water retention and anti-erosion functions. In many mountainous regions of Europe, however, recent decades have been associated with gradual degradation and dieback of subalpine grasslands, which has attracted growing attention from both scientific research and nature conservation.

The formation and functioning of subalpine grasslands are strongly influenced by harsh climatic conditions, including low temperatures, a short vegetation period, strong winds, and persistent snow cover (Körner, 2003; Vittoz, Rulence, 2014).

These habitats are typically associated with acidic to slightly acidic soils characterized by low nutrient availability and relatively high organic matter content in surface horizons. Vegetation cover is dominated mainly by perennial grasses, sedges, and herbaceous species that are well adapted to environmentally stressful mountain conditions.

An important factor affecting the ecological stability of subalpine grasslands is atmospheric nitrogen deposition. Elevated inputs of reactive nitrogen may lead to soil eutrophication, shifts in species composition, and the decline of species adapted to nutrient-poor environments (Bobbink *et al*., 2010). Increased nutrient availability often promotes the dominance of competitively strong grasses, which may reduce plant diversity and contribute to destabilization of the sward structure, thereby accelerating vegetation degradation.

Historically, subalpine grasslands were maintained through traditional extensive land-use practices, particularly grazing and mowing (Tasser, Tappeiner, 2002). The abandonment of these management practices in mountain regions has frequently resulted in shrub and tree encroachment, alteration of local microclimatic conditions, and accumulation of litter layers. On the other hand, locally excessive grazing pressure may cause mechanical damage to vegetation, soil compaction, and enhanced erosion processes. Both insufficient and excessive management intensity can therefore promote degradation and dieback of grassland vegetation.

Vegetation dieback in subalpine grasslands is often accompanied by changes in soil characteristics, especially reductions in soil organic matter content, deterioration of soil structure, and alterations in microbial activity (Körner, 2003; Lal, 2004a). Additionally, biotic agents such as fungal pathogens, insects, or small mammals may contribute to sward disruption when combined with environmental stressors.

The degradation of subalpine grasslands has significant ecological implications, including reduced biodiversity, increased risk of erosion and landslides, disruption of hydrological processes, and potential release of carbon stored in soils (Pauli *et al.*, 2012; Vittoz, Rulence, 2014). These impacts may extend beyond mountain ecosystems and influence downstream environmental conditions.

Among management practices affecting grassland ecosystems, vegetation burning represents a specific intervention that modifies soil chemical properties both immediately and over longer time scales. Short-term post-burning effects include an increase in soil pH, which is primarily caused by the deposition of ash containing base cations such as Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} (Neary *et al.*, 1999a; Certini, 2005). This alkalizing effect is usually temporary and gradually decreases due to leaching processes and vegetation recovery. Burning can also reduce total soil carbon and nitrogen stocks, particularly in surface soil horizons where organic matter mineralization is most intensive (Lal, 2004a; Certini, 2005). In contrast, the availability of certain nutrients, especially phosphorus and potassium, may increase temporarily after burning. Nevertheless, repeated or intensive burning may contribute to long-term depletion of soil organic matter, reduction of soil buffering capacity, and progressive soil degradation.

Grassland disturbance (in the form of sward removal) is another important driver of changes in soil chemical properties. Removal of vegetation cover may promote the accumulation of atmospheric deposition, which represents a significant source of nitrogen and trace metals in mountain environments (Kopáček *et al*., 2001; Hůnová *et al*., 2017).

Soil chemical properties are fundamental determinants of soil fertility, nutrient availability, biological activity, and overall ecosystem stability (Brady, Weil, 2017). Hence, the objective of this study was to evaluate changes in soil chemical properties under two types of subalpine grassland communities, one of which was characterized by increased accumulation of dead biomass, across three localities (Velký Máj, Jelení hřbet, and Břidličná) in the Jeseníky Protected Landscape Area. Using small-plot experiments conducted over a three-year period, the study assessed the effects of three management treatments (burning, mineral fertilization, and sward removal) on selected soil chemical characteristics.

MATERIALS AND METHODS

Site Characteristics

The research was conducted at three localities (Velký Máj, Jelení hřbet, and Břidličná), which are part of the Praděd National Nature Reserve and the Břidličná Nature Reserve in the Hrubý Jeseník Mountains. The Hrubý Jeseník Mountains belong to a cold climatic region with a mean annual temperature of 5 °C and annual precipitation of 850–1,000 mm. The study sites fall within the higher elevation regime. At higher elevations, the mean annual temperature decreases to approximately 3 °C, while annual precipitation exceeds 1,200 mm. Detailed meteorological data for the study period are presented in Tab. I.

On 24 May 2021, small-plot experimental areas were established at all three localities. At each site, a Latin square design was established in (a) undisturbed grasslands and (b) disturbed (degraded) grasslands, which were characterised by increased dead biomass. Grassland degradation was defined as a visibly increased proportion of dead biomass within the sward.

In the first year of the experiment (July), the cover of dead vegetation and the litter layer depth were assessed. This was done only in the disturbed grasslands, because litter and dead biomass were not present in the undisturbed grasslands. The highest mean cover of dead biomass was recorded at Velký

I: *Data on the meteorological conditions of the studied area during the growing season (April to October) 2021–2023*

Year	Average daily temperatures (°C)							AVG	Deviation from the long-term average (2004–2023)
	Month								
	April	May	June	July	August	September	October		
2021	-1.2	4.7	13.5	13.7	10.5	8.8	3.2	7.6	-0.7
2022	2.7	6.8	11.1	12.9	12.5	8.3	4.3	8.4	+0.1
2023	0.2	6.4	11.2	14.1	13.8	12.5	6.4	9.2	+0.9
Year	Precipitation (mm)							In total	Deviation from the long-term average (2004–2023)
	Month								
	April	May	June	July	August	September	October		
2021	92.6	128,0	77.4	182.0	213.4	73.2	32.9	799.5	+24.5
2022	71.0	122.0	134.0	136.0	120.0	115.0	78.0	776.0	+1.0
2023	123.7	62.1	77.5	104.7	300.4	42.2	72.7	783.3	+8.3

Source: Czech Hydrometeorological Institute – Šerák meteorological station

Máj (61%), followed by Jelení hřbet (30%), while the lowest proportion was observed at Břidličná (15%). The greatest litter depth occurred at Jelení hřbet (13.5 cm), followed by Velký Máj (11.5 cm), with the lowest values at Břidličná (7.3 cm).

Regarding vegetation characteristics, species-poor grasslands of the summit subalpine belt include wind-exposed communities of the association *Cetrario-Festucetum supinae* (*Juncion trifidi*), which transition into closed grasslands of *Carici bigelowii-Nardetum strictae* (*Nardo strictae–Caricion bigelowii*) or *Festuco supinae-Nardetum strictae* (*Nardion strictae*). This type of vegetation was almost the same at all monitored localities.

GPS coordinates of experimental plots:

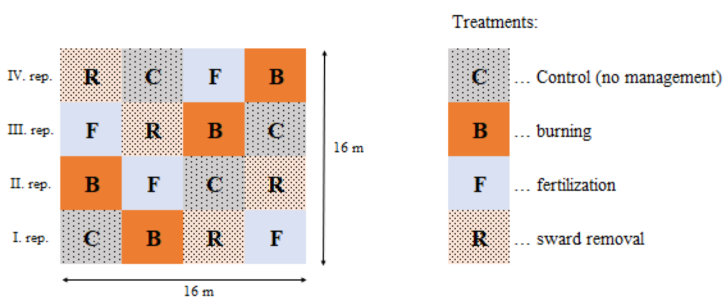
Břidličná – disturbed grasslands: N 50°01′25.2″, E 017°10′57.2″ (1 323 m a.s.l.)
Břidličná – undisturbed grasslands: N 50°01′30.5″, E 017°10′59.4″ (1 318 m a.s.l.)
Jelení hřbet – disturbed grasslands: N 50°02′23.5″, E 017°12′06.5″ (1 358 m a.s.l.)
Jelení hřbet – undisturbed grasslands: N 50°02′24.0″, E 017°12′00.8″ (1 362 m a.s.l.)
Velký Máj – disturbed grasslands: N 50°02′44.2″, E 017°13′12.1″ (1 363 m a.s.l.)
Velký Máj – undisturbed grasslands: N 50°02′45.1″, E 017°13′14.5″ (1 347 m a.s.l.)

Experimental Design

In subsequent years, various management treatments were applied to experimental plots (plot size 4 m × 4 m), each in four replications arranged in a randomized design. The experimental layout is shown in Fig. 1, and a photograph of the experimental plots at Velký Máj in 2022 is presented in Fig. 2.

Soil Characteristics

Between 2021 and 2023, basic soil chemical parameters were determined in soils beneath individual plots. A total of 96 samples per year were obtained across all replicates. Soil samples were collected using a soil auger from a depth of 2–15 cm



1: *Small-plot experimental design*
Treatments
C – Control (no management)
B – Burning (annually on July, using a gas burner)
F – Fertilization with N_{60}PK (pure nutrients), applied annually by 15 June in a single dose (fertilizers used: calcium ammonium nitrate, superphosphate, and potassium chloride)
R – Sward removal (once in the first year, July, using a mattock, the depth of the sward intervention was approximately 10 cm)

2: *View of the small-plot experiment at the Velký Máj site in 2022*

after removal of the surface sward. Each composite sample consisted of three auger cores mixed into a homogeneous sample. Air-dried samples were sieved to < 2 mm. The accredited laboratory of Agrovyzkum Rapotín Ltd. determined: the content of total organic carbon (C_{ox}) using spectrophotometry; the content of basic macronutrients (Mg, Ca, P, K) in the Mehlich-3 extractant (Mehlich, 1984); the exchangeable soil reaction (pH in 1 M $CaCl_2$); and the content of total nitrogen (N_{tot}) using the Kjeldahl method. Using the instrumental equipment of the accredited laboratory (AAS), the concentrations of potentially toxic elements (Zn, Cd, Pb in mg/kg) were also analysed in the aqua regia extract. Soil analyses were performed according to Zbíral *et al*. (2016). Evaluation criteria followed Sáňka, Materna (2004).

Statistical Analysis

Data were evaluated using analysis of variance (factorial ANOVA), followed by Tukey's HSD test (α = 0.05). The factors evaluated were treatment, year, locality, and disturbance (including their interactions). Statistical analyses were performed using STATISTICA software (StatSoft).

RESULTS

Tab. II presents summary data on exchangeable soil reaction and nutrient contents, as well as potentially toxic elements, in soil samples collected from experimental plots at individual localities between 2021 and 2023.

Soil pH values were very low at all three localities, classifying them as „extremely acidic" (pH < 4.5), which is typical of mountain soils. Correspondingly, calcium contents were „very low" (< 500 mg/kg) in all samples, and magnesium contents were mostly below 80 mg/kg, indicating „low" levels. In contrast, potassium and phosphorus contents were generally „satisfactory" (82–150 mg/kg for K; 26–50 mg/kg for P) or „good" (151–249 mg/kg for K; 51–90 mg/kg for P).

Management treatments significantly affected several soil chemical properties. Fertilization significantly increased the concentrations of calcium, phosphorus, and potassium compared with the control and other management treatments. The fertilized plots showed the highest Ca (264.7 mg/kg), P (73.5 mg/kg), and K (198.3 mg/kg) concentrations. In contrast, sward removal and burning resulted in lower Ca and K concentrations, with values similar to or slightly lower than those in the control plots. Soil pH differed significantly among treatments, with slightly higher values recorded in fertilized plots (2.99) compared with the control (2.94). No significant treatment effects were detected for nitrogen content, oxidizable carbon, lead, cadmium, or zinc.

Significant differences were also observed among years for several variables. Soil pH varied significantly over time, with the lowest value recorded in 2022 (2.68) and the highest in 2023 (3.33). Concentrations of phosphorus and potassium decreased during the study period, with the highest values observed in 2021 and lower values in the following years. Similarly, cadmium and zinc concentrations declined over time.

Locality had a strong effect on most soil chemical properties. The Jelení hřbet site showed the highest concentrations of Ca (273.6 mg/kg), Mg (85.0 mg/kg), P (73.1 mg/kg), and K (261.6 mg/kg), as well as the highest Cd and Zn concentrations. In contrast, the Břidličná site exhibited the lowest values for most nutrients and potentially toxic elements, while the Velký Máj locality showed intermediate values.

Disturbance also significantly influenced several soil properties. Disturbed plots had higher concentrations of oxidizable carbon, calcium, and phosphorus compared with undisturbed plots. In contrast, potassium concentrations were slightly higher in undisturbed stands.

Several significant interaction effects indicate that the response of soil chemical properties to management treatments was not uniform across environmental conditions. The significant

II: *Soil exchangeable reaction, nutrient content, and potentially toxic elements in soil samples collected from the individual sites in 2021–2023*

n = 288	pH ($CaCl_2$)	N_{tot} (%)	C_{org} (%)	Ca (mg/kg)	Mg (mg/kg)	P (mg/kg)	K (mg/kg)	Pb (mg/kg)	Cd (mg/kg)	Zn (mg/kg)
Means - Treatments										
Control	2.94[a]	0.98	16.53	153.2[a]	57.2[ab]	40.9[a]	157.9[a]	110.6	0.83	24.50
Fertilization	2.99[b]	0.95	16.18	264.7[b]	63.0[a]	73.5[b]	198.3[b]	114.4	0.81	25.08
Sward removal	2.96[ab]	0.92	15.45	133.2[a]	47.2[b]	36.9[a]	127.1[a]	125.4	0.72	24.15
Burning	2.96[ab]	0.93	15.55	132.9[a]	59.4[ab]	40.1[a]	153.6[a]	112.6	0.80	24.56
Means - Year										
2021	2.88[a]	1.00	16.90	168.6	67.2[a]	66.4[a]	200.7[a]	147.7[a]	1.03[a]	27.86[a]
2022	2.68[b]	0.92	15.21	185.9	58.0[b]	44.4[b]	212.0[a]	102.5[b]	0.68[b]	23.15[b]
2023	3.33[c]	0.92	15.68	158.5	45.0[c]	32.7[c]	139.9[b]	97.0[b]	0.66[b]	22.71[b]
Means - Locality										
Velký Máj	2.99[a]	0.77[a]	12.51[a]	153.7[a]	51.7[a]	42.1[a]	177.0[a]	110.3[a]	0.61[a]	23.38[a]
Jelení hřbet	2.83[b]	1.46[b]	27.73[b]	273.6[b]	85.0[b]	73.1[b]	261.6[b]	167.1[b]	1.49[b]	34.27[b]
Břidličná	3.06[c]	0.61[c]	7.55[c]	85.7[c]	33.5[c]	28.3[c]	114.1[c]	69.8[c]	0.27[c]	16.07[c]
Means - Disturbance										
Disturbed	2.93[a]	1.04[a]	18.56[a]	198.7[a]	60.2[a]	51.7[a]	169.6	121.1	0.90[a]	26.72[a]
Undisturbed	3.00[b]	0.86[b]	13.30[b]	143.3[b]	53.2[b]	44.0[b]	198.9	110.4	0.68[b]	22.43[b]
Factor	*P*-value									
Treatment	0.012	0.553	0.581	< 0.001	0.001	< 0.001	< 0.001	0.824	0.370	0.912
Year	< 0.001	0.065	0.083	0.240	< 0.001	< 0.001	0.001	0.001	< 0.001	< 0.001
Locality	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Disturbance	< 0.001	< 0.001	< 0.001	< 0.001	0.012	0.027	0.077	0.376	< 0.001	< 0.001
Year*Treatment	0.755	0.035	0.208	0.005	0.002	0.543	0.031	0.197	0.137	0.122
Locality*Treatment	0.212	0.280	0.108	0.001	0.141	< 0.001	0.002	0.399	0.184	0.679
Disturbance*Treatment	0.322	0.775	0.881	0.539	0.037	0.001	< 0.001	0.265	0.653	0.986

Legend: The values in the same column with different superscript letters are significantly different at $P < 0.05$ level for each variable (Tukey's HSD test)

treatment × locality interaction for Ca, P, and K suggests that the magnitude of fertilization effects varied among sites. In particular, increases in nutrient concentrations following fertilization were more pronounced at nutrient-richer localities, whereas sites with lower baseline nutrient status showed weaker responses.

The treatment × disturbance interaction detected for Mg and K indicates that management interventions influenced nutrient dynamics differently in disturbed and undisturbed stands. In disturbed plots, treatment effects on nutrient concentrations were generally more variable, which may reflect differences in vegetation cover, biomass turnover, and nutrient uptake intensity between the two stand conditions.

Temporal variation in treatment responses was indicated by the significant treatment × year interaction for Ca, Mg, and K. This suggests that the effects of management practices changed during the course of the experiment, likely reflecting gradual shifts in soil nutrient pools and plant–soil interactions over time.

Together, these interactions highlight that the influence of management practices on soil chemistry in subalpine grasslands is strongly modulated by local site conditions, disturbance status, and temporal dynamics.

DISCUSSION

The extremely acidic soil reaction observed at all studied localities reflects the typical characteristics of mountain soils developed on acidic parent material and exposed to high precipitation and intensive leaching of base cations (Podrázský, Remeš, 2010; Uhlířová *et al.*, 2012). Such conditions strongly influence nutrient availability and soil biological processes. In particular, the very low concentrations of calcium and magnesium represent potential limiting factors for vegetation growth and soil microbial activity (Havlin *et al*., 2014). At the same time, low soil pH enhances the mobility and bioavailability of potentially toxic elements.

Despite the strongly acidic conditions (pH < 4.5), relatively satisfactory contents of potassium and phosphorus were detected at several sites. This may be related to their stronger binding to the soil sorption complex and organic matter or to the influence of historical or current management practices (Novák *et al*., 2016). In acidic soils, phosphorus is often fixed by iron and aluminium compounds; however, the measured values indicate that its availability remains relatively stable in these systems (Frossard *et al.,* 2000). Potassium availability in grassland ecosystems may also be maintained by relatively efficient internal cycling within plant biomass and limited leaching losses (White, Karley, 2010).

Management practices significantly affected soil chemical properties in the studied grasslands. Mineral fertilization at a rate of N_{60}PK had a clear and statistically significant influence on soil nutrient status. Fertilized variants showed significantly higher contents of phosphorus, potassium, and calcium compared with control and other management treatments. These findings correspond with previous studies indicating that mineral fertilization can temporarily increase nutrient availability even in strongly acidic soils with low inherent fertility (Mengel, Kirkby, 2001; Brady, Weil, 2017). The observed increase in base cation contents suggests that fertilization may partly alleviate nutrient limitations typical of mountain soils, although this effect is likely to be temporary (Havlin *et al*., 2014).

Disturbance of grassland stands also influenced soil nutrient dynamics. Disturbed stands exhibited higher contents of nutrients and organic carbon compared with undisturbed vegetation. This pattern may partly reflect enhanced mineralization and accelerated nutrient cycling following disturbance (Six *et al*., 2002a; Lal, 2004b). However, the simultaneous accumulation of undecomposed biomass indicates that increased mineralization was not the only process involved. Higher nutrient and carbon contents may partly result from the accumulation of litter and dead biomass, redistribution of nutrients from living biomass to detrital pools following vegetation damage, and reduced plant nutrient uptake in disturbed stands (Schlesinger, 1997; Chapin *et al*., 2011; Paul, 2014).

Sward removal may temporarily increase nutrient availability through accelerated decomposition of organic residues, but this effect is usually short-lived and may be followed by gradual depletion of soil organic matter if vegetation recovery is slow (Wardle *et al*., 2004; Bardgett, Wardle, 2010). In alpine and subalpine ecosystems, where low temperatures slow soil formation and organic matter accumulation, the loss of surface organic layers may therefore have long-term consequences for soil fertility and ecosystem functioning (Körner, 2003).

Burning represents another disturbance affecting soil chemistry through thermal effects and ash deposition. Combustion of plant biomass releases base cations that can temporarily increase soil pH and nutrient availability (Neary *et al*., 1999b; Certini, 2005). At the same time, burning may reduce soil organic carbon and nitrogen due to volatilization and accelerated decomposition processes. In our experiment, however, the effect of burning on soil chemical properties was less pronounced than that of fertilization, which is consistent with studies showing that the impact of low-intensity burning is often relatively limited and short-term.

Significant differences among the studied localities confirm the strong influence of site-specific soil-ecological conditions, particularly parent material, altitude, and microclimate (Němeček *et al*., 2011). The Jelení hřbet locality showed paradoxically higher contents of nutrients and potentially toxic elements despite exhibiting the strongest soil acidity. This pattern may be explained by higher organic matter content, which increases soil sorption capacity and promotes the accumulation of both nutrients and heavy metals (Six *et al*., 2002b; McBride, 1994). Organic matter may simultaneously reduce their bioavailability through the formation of stable complexes (Stevenson, 1994).

Elevated concentrations of potentially toxic elements, particularly cadmium and lead, represent an important environmental aspect of the studied soils. Low soil pH enhances the mobility of these elements (Kabata-Pendias, 2011; Alloway, 2013), and fertilization may further increase their availability (Guo *et al*., 2010). The exceedance of preventive values observed in this study may result from a combination of factors, including historical atmospheric deposition, strongly acidic soil conditions, and high organic matter content (Kopáček *et al*., 1998; Kabata-Pendias, 2011). Geological substrate may also play an important role, as different parent materials contribute varying baseline concentrations of heavy metals to soils (Liu *et al*., 2020; Zhang *et al*., 2024).

Overall, the results demonstrate that soil chemistry in mountain grasslands is controlled by a complex interaction between natural soil-forming factors and management practices. Extreme soil acidity represents a key environmental constraint that influences both nutrient availability and the mobility of potentially toxic elements. These factors should therefore be carefully considered when designing sustainable management strategies for subalpine grassland ecosystems (Alloway, 2013; Podrázský *et al*., 2018).

These findings highlight that sustainable management of subalpine grasslands should prioritize practices that maintain soil organic matter and minimize further soil acidification. Given the naturally low buffering capacity of mountain soils, even relatively small management interventions may substantially influence nutrient cycling and the environmental behaviour of potentially toxic elements. Long-term monitoring of soil chemical properties is therefore essential for evaluating the ecological sustainability of management practices in these sensitive ecosystems.

CONCLUSION

In conclusion, the study confirmed that subalpine grassland soils in the investigated localities were characterized by extremely acidic reactions, which strongly influenced nutrient availability and the mobility of potentially toxic elements. Management interventions significantly affected soil chemical properties, with mineral fertilization ($N_{60}PK$) showing the most pronounced short-term positive effect on the contents of phosphorus, potassium, and calcium. Soil chemical conditions differed significantly among localities, indicating the strong role of site-specific ecological factors such as altitude, microclimate, and parent material. Overall, the results indicate that sustainable management of subalpine grasslands requires careful balancing of conservation measures.

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