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The impact of coniferous vegetation on properties of podzolic soils in the Tatra Mountains, southern Poland

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Abstract

The main aim of this study was to determine the impact of upper montane coniferous forests and dwarf pine communities on the physical and chemical properties of podzolic soils in the Tatra Mountains. Ten soil profiles were excavated, including five from the upper montane forest zone and five from the subalpine zone. The results indicate that the studied soils exhibit generally similar properties. All the podzolic soils investigated displayed characteristics typical of mountainous podzols. Soil mineral composition was comparable in both vegetation zones and reflected a granitoid parent material. The only statistically significant differences between the two soil groups were observed in particle-size distribution (sand, silt, and clay content). Soils from the upper montane forest zone had a finer texture compared to those from the subalpine zone. This may indicate differences in weathering intensity or variations in the genesis of the parent material between the two vegetation zones. Mean values of soil pH, soil organic carbon (SOC), total nitrogen (TN), C/N ratio, water-extractable organic carbon (WEOC), water-extractable total nitrogen (WETN), amorphous forms of Fe, Al, and Si, podzolization index, and optical density of oxalate extract (ODOE) were similar and did not differ significantly between the studied zones. These findings suggest that environmental conditions controlling the development and transformation of podzolic soils are largely comparable in the upper montane forest and subalpine zones of the Tatra Mountains.

1. Introduction

The relationship between soil and vegetation is a dynamic interaction that plays a crucial role in ecosystem development, particularly in forested mountain landscapes. Tree species influence soil properties through the delivery of litter of different quantity and quality, root exudates, and nutrient uptake, which in turn affect soil organic matter composition, nutrient cycling, and chemical soil characteristics, such as pH and C/N ratio (Norris et al., 2012; Aponte et al., 2013; Han et al., 2021). Coniferous vegetation produces needle litter with high lignin content and slower decomposition rate compared to broad-leaved species, leading to distinct organic matter signatures and often more acidic soils (Segura et al., 2019). These processes are integral to the formation and evolution of podzolic soils, which typically form under boreal and temperate coniferous forests and are characterized by low nutrient availability, acidic conditions, and pronounced horizon differentiation due to soil leaching and organic matter translocation downward (Bednarek and Skiba, 2015).

Podzolic soils have been studied in several mountains of the temperate zone such as the Alps (D'Amico et al., 2008, 2014; Egli et al., 2009), the Rocky Mts. in the USA (Valerio et al., 2016), the Stołowe Mts. in Poland (Waroszewski et al., 2015), and Rondane Mts. in Norway (Stützer, 1999). Podzolic soils in the Tatras have been also frequently studied with emphasis on mineral composition (Skiba, 2001, 2007; Skiba et al., 2011; Kuligiewicz et al., 2024), concentration of trace elements (Kowalska et al., 2021) and sulphur (Zadrożny and Miechówka, 2008).

Many studies, starting as early as 1926, have been conducted on soils in the Tatra Mountains (Komornicki et al., 1975, 1984a, b; Komornicki and Skiba 1996; Drewnik et al., 2021). Soils in the Tatra Mountains have been extensively studied with regards to the influence of climate on their genesis (Oleksynowa and Skiba, 1977; Skiba, 1983, 1985) as well as the influence of geomorphic processes on soil cover (Drewnik, 2008). In addition, soil mineral composition (Skiba, 2007; Skiba et al., 2011; Kuligiewicz et al., 2024) and soil pollution with trace elements and radionuclides was also studied (Kubica et al., 2002, 2007; Miechówka and Niemyska-Łukaszuk, 2004; Ciarkowska and Miechówka, 2022). Niemyska-Łukaszuk (1977), Miechówka and Ciarkowska (1998), Drewnik (2006) and Wasak and Drewnik (2015, 2016) have been studied soil organic matter and its properties as well as transformation and decomposition rate in various soils in the Tatra Mts. However, there are no detailed comparative studies related to the influence of coniferous species of the upper montane coniferous forest zone and dwarf pine communities of the subalpine zone on the genesis and properties of podzolic soils in this region.

Podzolic soils cover about 30% of the soil cover in the Polish part of the Tatra Mountains (Skiba, 1995) and develop mainly from acidic granitoid moraines and the weathering products of granitoids, gneisses, and metamorphic schists (Komornicki and Skiba, 1996). A significant proportion of Tatra podzolic soils occurs under upper montane coniferous forests (*Plagiothecio-Piceetum tatricum*) and dwarf pine community (*Pinetum mugo*), due to high precipitation and acidophilic coniferous vegetation (Komornicki and Skiba, 1996). The subalpine zone with prevalence of dwarf pine community, occurring at higher altitude, is thus characterized by a higher mean annual precipitation than the upper montane coniferous forest zone (Hess, 1996). The harsher climatic conditions, slower organic matter turnover (Drewnik, 2006), combined with the input of strongly acidic needle litter should promote more intensive podzolization in the subalpine soils of the Tatra Mountains in relation to the soils under upper montane coniferous forests (Weichmann, 1983; Wang et al., 1986; Lundstrom et al., 2000; Sauer et al., 2007).

The main aim of this study was to determine the impact of upper montane coniferous forests (*Plagiothecio-Piceetum tatricum*) and dwarf pine community (*Pinetum mugo*) on the morphology, physical and chemical properties of podzolic soils in the Tatra Mountains. The hypothesis that podzolization is more advanced under dwarf pine community (*Pinetum mugo*) in the subalpine zone than under upper montane coniferous forests (*Plagiothecio-Piceetum tatricum*) due to more acidic litter supply to the soil and higher precipitation in the subalpine zone was tested in this study.

2. Study area

The Tatra Mountains are the highest mountain range in the entire Carpathians, rising to over 2600 m a.s.l., with the highest peak (Gerlach) at 2655 m a.s.l. The highest parts of the Tatras consist mainly of Paleozoic metamorphic and granitoid rocks that form a crystalline core (Piotrowska et al., 2015). On the northern side of the mountains, this core is covered with Mesozoic sedimentary rocks, primarily carbonate formations from the Triassic, Jurassic, Cretaceous, and Tertiary periods, such as limestones, dolomites, and marls, along with smaller amounts of non-carbonate sedimentary rocks such as sandstones and shales (Jach et al., 2014). The landscape of the Tatra Mountains shows an alpine character, largely shaped by their high elevation and the effects of Pleistocene glaciations in the upper parts of the massif (Klimaszewski, 1988).

Climatic conditions vary greatly depending on altitude. The average annual air temperature ranges from –4°C in the highest parts of the mountains to 6°C at the mountain foothills. The annual total precipitation ranges from 1100 mm to 1800 mm (Błażejczyk, 2019). Clear vegetation zones occur in the Tatras due to vertical differences in climate, landforms, and soils. The lowest elevations are mainly covered with beech forests (*Dentario glandulosae-Fagetum*) or spruce forests (*Plagiothecio-Piceetum tatricum*), particularly on granitoid moraines in the High Tatras. The higher parts of the Tatras are dominated by upper montane spruce forests (*Plagiothecio-Piceetum tatricum*). Above the upper tree line, dwarf pine (*Pinetum mugo*) communities prevail, followed higher up by alpine grasslands. The highest parts of the Tatras are characterized by very poor vegetation cover dominated by lichens and single vascular plants (Piękoś-Mirkowa and Mirek, 1996).

The soil cover of the Tatra Mountains is very heterogeneous, resulting from the differences in geological structure, relief, climatic and hydrological conditions as well as vegetation cover (Skiba, 1995). In the lower parts of the Western Tatras, various variants of rendzinas (Rendzic Leptosols) and brown soils (Cambisols) occur primarily. Podzols dominate on weathered non-carbonate rocks in the upper montane zone covered with spruce forests and in the lowest zone of the High Tatras. In the dwarf pine zone, Podzols and Leptosols mainly occur. The highest parts of the Tatras are characterized by shallow, weakly developed soils such as Leptosols, Regosols, and in some places also Podzols (Skiba, 1995).

3. Materials and methods

A field study was conducted in summer 2020 and 432 soil profiles were located and numbered according to a grid of 500 × 500 m squares across the forested area of the Western Tatra Mountains. The soils were then excavated, described and sampled (Drewnik et al., 2021). Representative 10 profiles from all the 432 sites were selected for the purpose of this study (Fig. 1). Five soil profiles (TPN103, TPN134, TPN172, TPN192, TPN198) were excavated under upper montane coniferous forests (*Plagiothecio-Piceetum tatricum*) and five soil profiles (TPN42, TPN44, TPN90, TPN91, TPN201) under the dwarf pine community (*Pinetum mugo*). The soils were all located on slopes varying from 13° to 41°. A total of 47 soil samples were analyzed in this study. The soil samples were air-dried at room temperature, gently crushed, and sieved through a 2 mm mesh sieve. Soil color was determined in dry and moist conditions according to Munsell Color Soil Charts. Particle-size distribution was determined by the sieve method (sand fraction) and hydrometer method (silt and clay fractions) (Gee and Bauder, 1986). Mineral composition of the soils was determined using the X-ray diffraction technique using a benchtop diffractometer MiniFlex600 (Rigaku, Japan) equipped with a vertical goniometer, 1.25° divergence slit, 2.5° incident- and diffracted-beam Soller slits, 1.25° anti-scatter slit, 0.3 mm receiving slit, graphite diffracted-beam monochromator, scintillation counter and a Cu X-ray lamp operated at 40 kV and 15 mA. Random powder specimens were X-rayed from 2 to 65°2θ at a counting speed of 0.02°/1 s. Soil pH was measured using the potentiometric method at a soil-to-deionized water ratio of 1:2.5 (Thomas, 1996). Total carbon and total nitrogen contents were determined using a CHN VarioMicro Cube elemental analyzer (Elementar, Hanau, Germany). The total carbon was assumed as soil organic carbon (SOC), because none of the analyzed samples contained

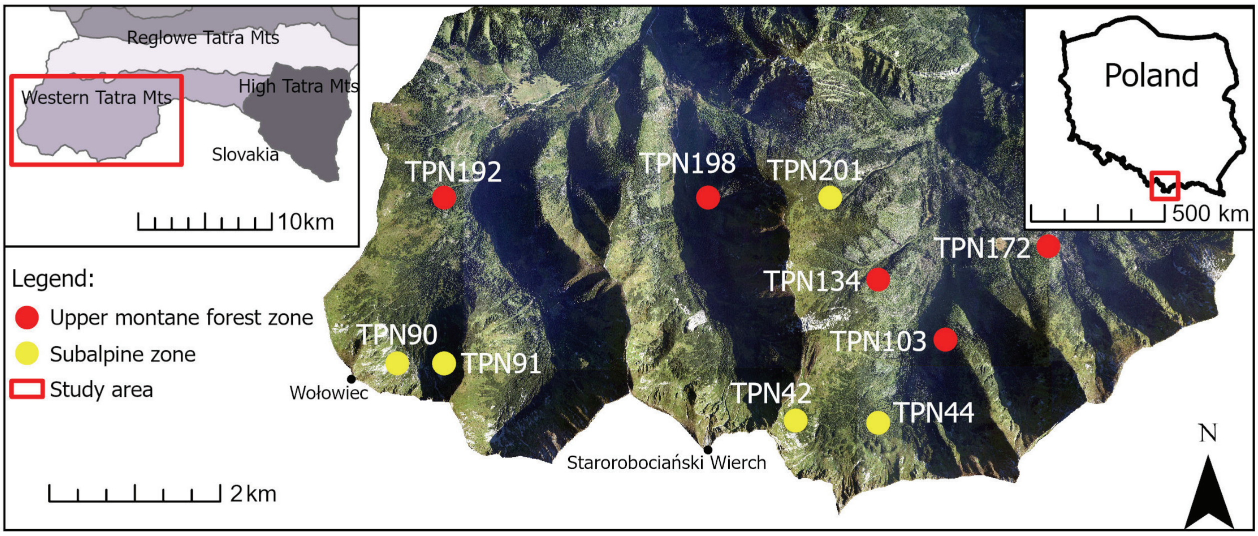

Fig. 1. Location of the study area and the studied soil profiles

carbonates (no reaction with 10% HCl was observed). A Specord 50 UV–Vis spectrophotometer (Analytik, Jena) was used to determine optical density of the ammonium oxalate extract (ODOE). Concentrations of ammonium oxalate extractable iron (Fe_o), aluminium (Al_o), and silicon (Si_o) were determine using an Inductively Coupled Plasma – Emission Spectrometry (ICP-ES) (Van Reeuwijk, 2002). To determine water extractable organic carbon (WEOC) and water extractable total nitrogen (WETN) concentration, 100 ml of deionized water was added to 1.00 g of soil material, which was previously ground in a mortar, and shaking for 24 h using a rotational shaker. Then, the suspension was filtered using qualitative filters (WHATMAN) and subsequently filtered through 0.45 μm prewashed polyethersulphone (PES) membrane filters. Determination of WEOC and WETN concentration was done via infrared detection of CO_2 after the combustion of extracts in high temperature by means of a TOC analyzer (VarioTOCcube, Elementar, Hanau, Germany) and via chemiluminescence detection of NO_x after the combustion of extracts in high temperature using a TOC analyzer (VarioTOCcube, Elementar, Hanau, Germany), respectively. Mean values of the studied soil properties were obtained by averaging all samples from the given vegetation

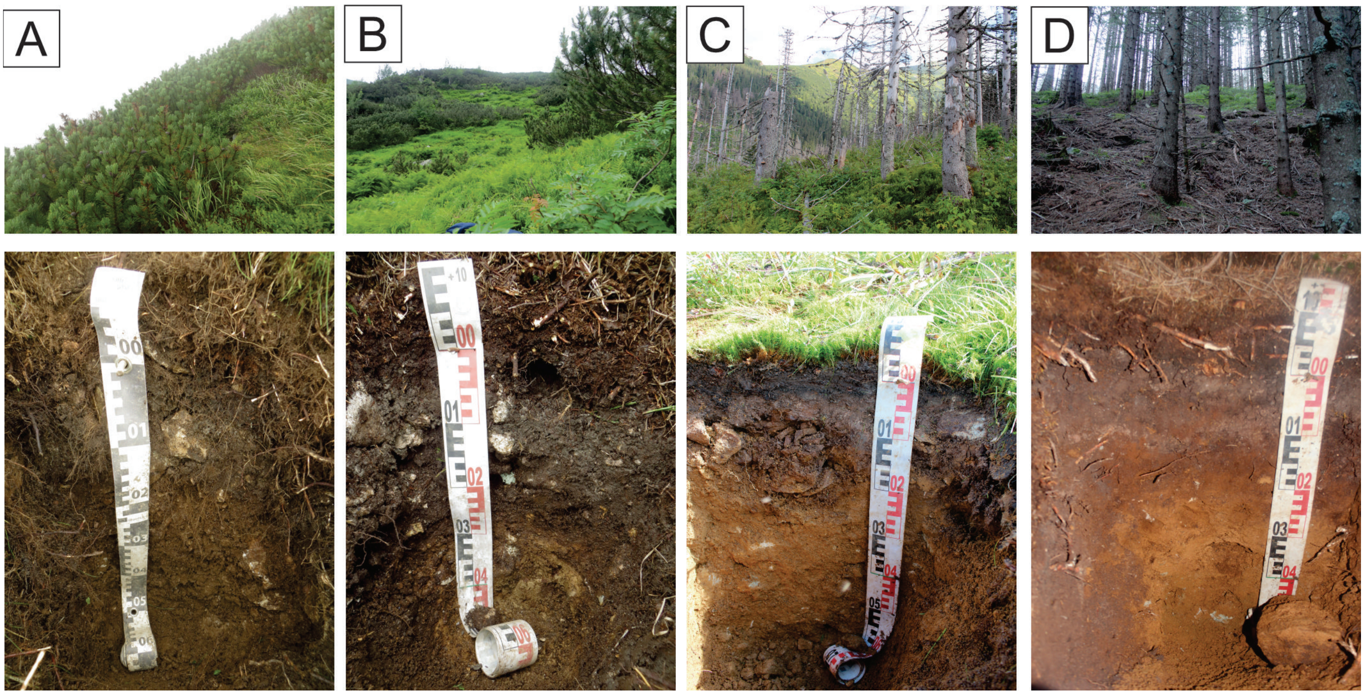

Fig. 2. Selected soil profiles and surrounding vegetation: A – Profile TPN42 (dwarf pine), B – Profile TPN90 (dwarf pine), C – Profile TPN103 (upper montane forest), D – Profile TPN172 (upper montane forest)

zone. Mean values of spodic horizons were calculated as an average of all the samples from the spodic horizons (B) from the given vegetation zone. Significance of differences in physical and chemical properties between soils from the subalpine zone and from upper montane coniferous forests was checked using the U Mann-Whitney test. All statistical analyses were done using STATISTICA 13 software.

4. Results

4.1. Classification and morphology of the soils

All the studied soils were classified as Podzols according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2022), based on the presence of a spodic horizon within 200 cm of the soil surface.

The soil profiles were excavated to depths ranging from 50 to 70 cm. In the upper montane forest zone, the mean thickness of the O horizon was 10 cm, whereas in soils from the subalpine zone it was 9 cm. The mean thickness of the A horizon was 5 cm in soils from the upper montane forest zone and 7 cm in soils from the subalpine zone. The combined AE and E horizon thickness averaged 9 cm in soils from the upper montane forest zone and 12 cm in soils from the subalpine zone. The mean thickness of the B horizon was 35 cm in soils from the upper montane forest zone and 24 cm in soils under dwarf pine. Overall, the total thickness of soil horizons was comparable between the upper montane forest and subalpine soils, with the greatest difference in the thickness of the B horizon.

In the upper montane forest zone, the dominant soil structures were subangular blocky and angular blocky with occasional occurrence of granular and single grain structures. In contrast, soils from the subalpine zone (*Pinetum mugo* community) were predominantly characterized by granular and subangular blocky structures. Roots were observed in all the studied soil profiles, with abundance generally decreasing with depth. Soil consistence ranged from friable to firm and most soil profiles exhibited increasing firmness with depth. Rock fragments increased with depth in all the studied soil profiles; however, they were more abundant in soils under the dwarf pine, reaching up to 90% in the deepest horizons (Table 1).

Table 1
Morphology of the studied soils

Horizon	Depth (cm)	Color moist	Structure	Roots	Consistence	Rock fragments (%)
Profile TPN103 *Skeletic Albic Podzol (Loamic)*						
Oi	1–0	7.5YR 3/4	fibrous	absent	friable	0
A	0–6	7.5YR 2/2	subangular blocky	+++	friable	0
E	6–10	7.5YR 3/3	subangular blocky	+++	moderately firm	40
Bhs	10–20	7.5YR 4/6	subangular blocky	+++	moderately firm	50
Bs	20–45	7.5YR 4/6	subangular blocky	++	firm	50
BCg	45–70	10YR 4/6	subangular blocky	++	firm	50
Profile TPN134 *Rustic Podzol (Loamic, Folic)*						
Oi	25–22	7.5YR 2/3	fibrous	absent	friable	0
Oe	22–15	7.5YR 2/1	fibrous/spongy	+++	friable	0
Oa	15–0	7.5YR 2/2	granular/spongy	++	friable	0
A	0–10	7.5YR 2/2	granular	++	friable	10
AE	10–22	7.5YR 2/3	angular blocky, granular	++	friable	10
Bhs	22–40	7.5YR 3/4	angular blocky	+	moderately firm	20
Bs	40–55	7.5YR 3/4	angular blocky	+	moderately firm	20
BC	55–80	10YR 4/6	granular blocky, single grain	absent	firm	40
Profile TPN172 *Albic Podzol (Loamic)*						
Oi	9–8	7.5YR 3/2	fibrous	+++	friable	0
Oe	8–4	7.5YR 3/2	fibrous	+++	friable	0
Oa	4–0	10YR 1/1	granular	+++	friable	0
E	0–8	7.5YR 2/3	angular blocky	+++	friable	20
Bhs	8–22	7.5YR 2/3	angular blocky	+++	moderately firm	30
Bs	22–40	7.5YR 4/6	angular blocky	+++	moderately firm	30
BC	40–60	7.5YR 4/6	angular blocky	absent	moderately firm	50

Table 1 – continue

Profile TPN192 *Albic Podzol (Loamic)*						
Oi	5–0	7.5YR 3/2	fibrous	+++	friable	0
A	0–6	7.5YR 2/3	granular, subangular blocky, angular blocky	+++	moderately friable	10
E	6–12	7.5YR 2/3	granular, subangular blocky, angular blocky	++	moderately friable	15
Bhs	12–35	7.5YR 3/4	granular, angular blocky, subangular blocky	++	moderately firm	30
Bs	35–65	7.5YR 3/4	granular, angular blocky, subangular blocky	+	moderately firm	50
BC	65–75	7.5YR 3/4	granular, angular blocky	few	firm	70
Profile TPN198 *Albic Podzol (Arenic)*						
Oi/Oe	7–2	7.5YR 2/1	crumb	+++	friable	0
Oa	2–0	n.a.	crumb	+++	friable	0
Ah	0–4	7.5YR 1.7/1	angular blocky	+	friable	2
E1	4–9	7.5YR 2/3	angular blocky	+	moderately firm	15
E2	9–17	7.5YR 3/3	angular blocky	+	moderately firm	15
Bhs	17–25	7.5YR 3/4	angular blocky	few	firm	15
Bs	25–40	7.5YR 3/4	angular blocky	few	very firm	20
BC	40–60	7.5YR 4/6	angular blocky	few	extremely firm	40
Profile TPN42 *Skeletic Podzol (Loamic, Folic)*						
Oi	14–0	7.5YR 2/3	fibrous	+++	friable	10
A	0–6	10YR 2/2	granular, subangular blocky	+++	friable	30
AE	6–16	10YR 2/3	granular, subangular blocky	+++	moderately firm	40
Bhs	16–35	7.5YR 3/4	granular, subangular blocky	++	moderately firm	40
BC	35–50	7.5YR 3/4	granular, subangular blocky	+	moderately firm	50
Profile TPN44 *Leptic Podzol (Arenic, Folic)*						
Oi	10–0	7.5YR 2/3	fibrous	absent	friable	0
A	0–10	7.5YR 2/2	angular blocky, granular	++	friable	5
AE	10–15	7.5YR 3/3	angular blocky, granular	+++	friable	10
Bs	15–30	7.5YR 4/4	granular, single grain	+++	moderately firm	30
BC	30–45	7.5YR 4/4	granular, single grain	++	moderately firm	50
C	45–60	10YR 5/4	granular, single grain	+	moderately firm	70
Profile TPN90 *Skeletic Albic Podzol (Arenic)*						
Oi	9–0	n.a.	n.a.	+++	friable	0
A	0–5	7.5YR 2/1	granular, subangular blocky	+++	friable	30
E	5–15	7.5YR 2/2	granular, subangular blocky	+++	moderately firm	50
Bhs	15–28	7.5YR 2/2	granular, angular blocky, subangular blocky	+	moderately firm	40
Bs	28–40	7.5YR 3/4	granular, angular blocky	few	firm	70
BC	40–55	10YR 4/4	granular, angular blocky	absent	firm	80
Profile TPN91 *Skeletic Albic Podzol (Arenic)*						
Oi	1–0	7.5YR 2/3	fibrous	absent	friable	0
A	0–6	7.5YR 2/2	granular, subangular blocky	+++	friable	10
E	6–27	7.5YR 5/3	granular, subangular blocky	++	moderately firm	30
Bhs	27–40	7.5YR 3/4	granular, subangular blocky	++	firm	70
Bs	40–55	7.5YR 3/4	granular, subangular blocky	few	firm	90
Profile TPN201 *Skeletic Podzol (Folic)*						
Oi	12–10	7.5YR 2/3	fibrous	+++	friable	0
Oe	10–0	7.5YR 2/2	fibrous	+++	friable	0
A	0–6	7.5YR 2/2	granular, subangular blocky	+++	moderately firm	10
EA	6–20	7.5YR 3/3	granular, subangular blocky	+	moderately firm	40
Bhs	20–40	7.5YR 2/3	granular	+	moderately firm	70
Bs	40–55	10YR 4/4	granular	absent	moderately firm	80

n.a. – not analyzed

4.2. Mineral composition of the soils

X-ray diffraction results from the TPN172 profile located in the upper montane forest zone indicated a mineral composition dominated by quartz (Fig. 3). Mica, potassium feldspar, plagioclase, kaolinite, chlorite, and vermiculite occurred throughout the profile. Mixed-layer minerals, including most likely mica–vermiculite and mica–smectite, together with chlorite, were particularly evident in the upper and middle soil horizons (Fig. 3). Vertical variations in mineral composition were low, with a slight decrease in the intensity of mixed-layer mineral reflections with depth, while kaolinite and chlorite reflections remained distinct in deeper horizons.

X-ray diffraction analyses of the TPN90 profile from the subalpine zone revealed quartz as the dominant mineral in all soil horizons (Fig. 4). Plagioclase and potassium feldspar were

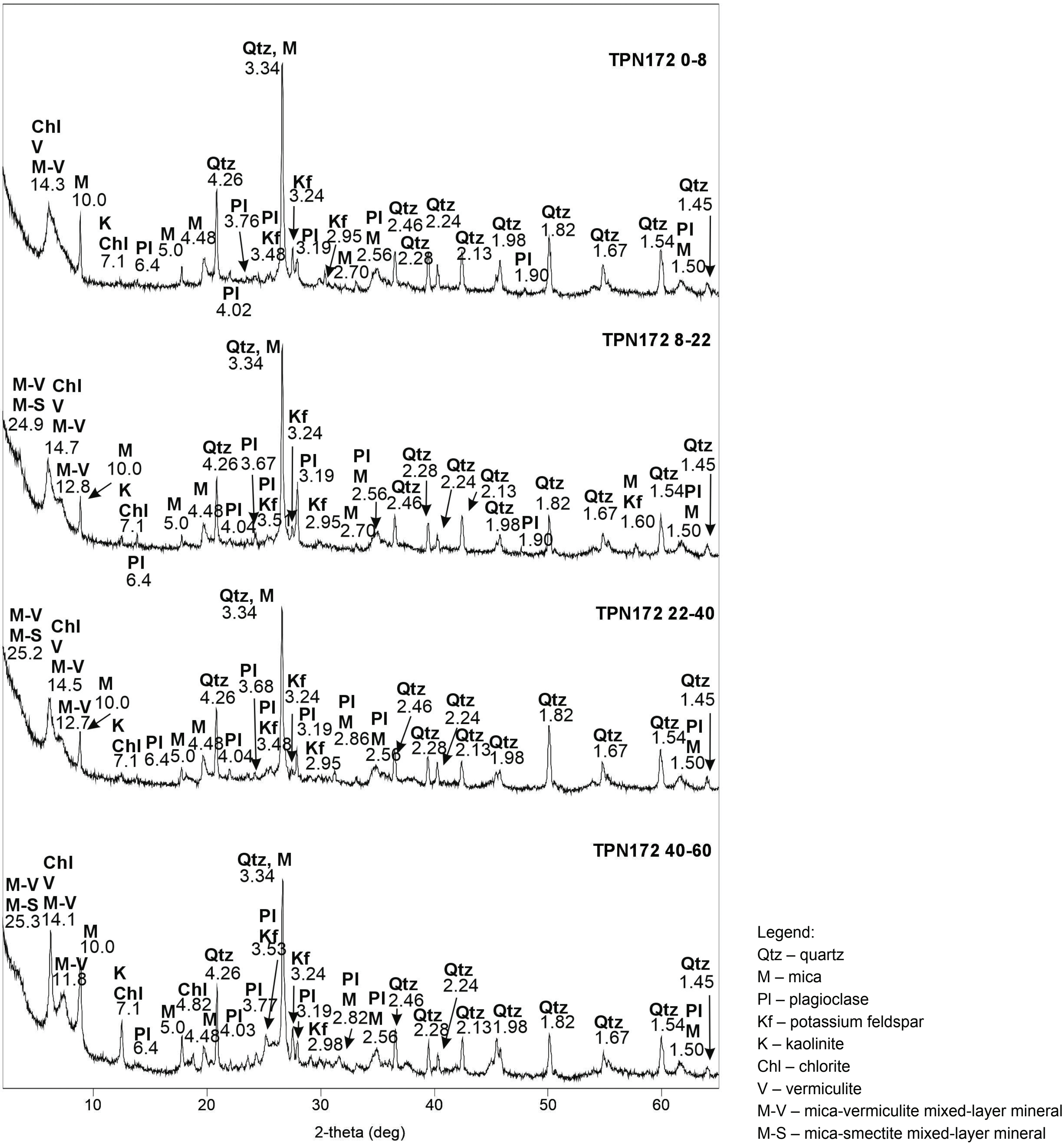

Fig. 3. X-ray patterns for soil horizons of profile TPN172: 0-8 – E, 8-22 – Bhs, 22-40 – Bs, 40-60 – BC

also common and exhibited relatively stable intensities with depth. Mica was present in all soil horizons. Kaolinite, chlorite, vermiculite, and mica–vermiculite were identified in the illuvial horizons (Fig. 4). With increasing depth, a slight decrease in the intensity of mixed-layer mineral reflections was observed, accompanied by more distinct chlorite and kaolinite peaks in the lower horizons. Overall, the mineral composition of TPN90 profile remained relatively uniform throughout the profile and was very similar to the mineral composition of the profile TPN172.

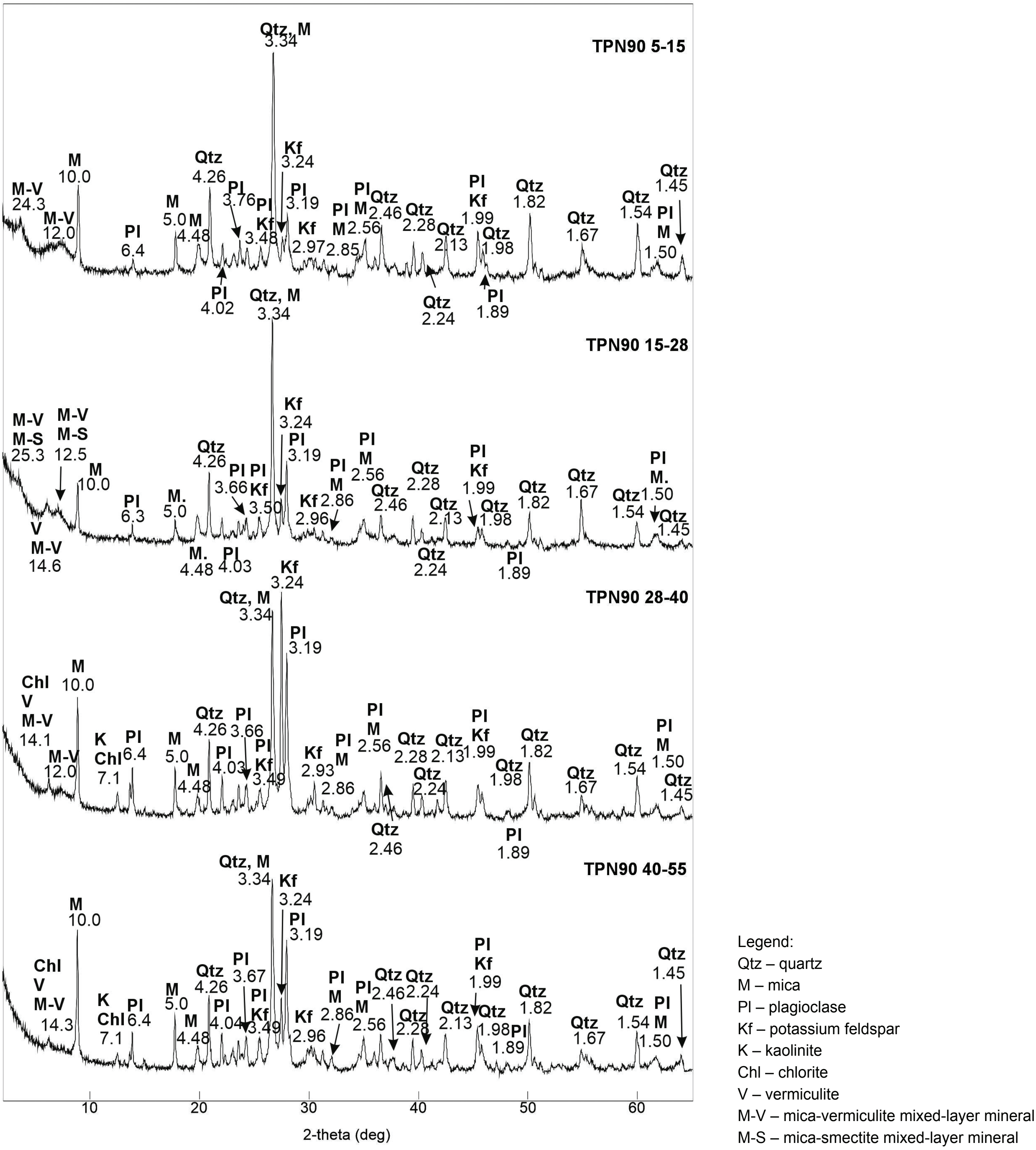

Fig. 4. X-ray patterns for soil horizons in profile TPN90: 5-15 – E, 15-28 – Bhs, 28-40 – Bs, 40-55 – BC

4.3. Physical and chemical properties of the soils

Texture of the studied soils was classified either as sandy loam or loamy sand. Sandy loam was the dominant texture class in the upper montane forest zone, whereas loamy sand prevailed in the subalpine zone (Table 2). In soils from the upper montane forest zone, sand content varied between 48% and 78%, averaging 67% (Tables 2 and 3). Corresponding values for silt were 21–49%, with a mean of 32%, while clay content reached a maximum of 5% and averaged only 1%. In the subalpine zone, soils contained

Table 2
Selected physical and chemical properties of the studied soils

Horizon	Depth (cm)	pH (H_2O)	SOC (%)	TN (%)	C/N	WEOC (mg l^{-1})	WETN (mg l^{-1})	Sand (%)	Silt (%)	Clay (%)	Texture
Profile TPN103 *Skeletic Albic Podzol (Loamic)*											
Oi	1–0	4.20	32.39	1.16	28	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
A	0–6	3.43	36.17	1.74	21	16.92	0.97	n.a.	n.a.	n.a.	n.a.
E	6–10	3.84	7.01	0.46	15	52.30	2.75	68	31	1	Sandy loam
Bhs	10–20	4.20	6.51	0.40	16	274.98	11.22	64	36	0	Sandy loam
Bs	20–45	4.88	4.78	0.24	20	65.09	3.59	48	49	3	Sandy loam
BCg	45–70	6.05	2.36	0.09	26	55.09	3.24	55	44	1	Sandy loam
Profile TPN134 *Rustic Podzol (Loamic, Folic)*											
Oi	25–22	4.59	43.67	1.69	26	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Oe	22–15	3.46	41.10	1.51	27	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Oa	15–0	3.24	20.74	1.04	20	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
A	0–10	3.82	13.63	0.75	18	25.51	1.42	n.a.	n.a.	n.a.	n.a.
AE	10–22	4.17	10.63	0.52	21	17.02	0.99	63	37	0	Sandy loam
Bhs	22–40	4.64	10.53	0.38	28	78.27	4.20	64	35	1	Sandy loam
Bs	40–55	4.82	8.35	0.28	30	57.54	3.24	64	36	0	Sandy loam
BC	55–80	5.17	1.41	0.04	38	32.23	1.95	67	31	2	Sandy loam
Profile TPN172 *Albic Podzol (Loamic)*											
Oi	9–8	4.65	43.60	1.62	27	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Oe	8–4	3.67	38.57	1.63	24	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Oa	4–0	3.16	31.85	1.50	21	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
E	0–8	3.44	7.67	0.40	19	21.57	1.35	72	27	1	Loamy sand
Bhs	8–22	3.86	6.10	0.30	21	14.64	0.91	67	31	2	Sandy loam
Bs	22–40	4.37	3.14	0.12	26	72.50	3.47	55	40	5	Sandy loam
BC	40–60	4.79	1.67	0.06	29	27.02	1.24	66	32	2	Sandy loam
Profile TPN192 *Albic Podzol (Loamic)*											
Oi	5–0	3.84	38.41	1.66	23	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
A	0–6	3.25	12.02	0.74	16	133.78	6.52	n.a.	n.a.	n.a.	n.a.
E	6–12	3.58	8.76	0.56	16	81.95	4.25	77	23	0	Loamy sand
Bhs	12–35	4.26	5.67	0.29	20	35.37	1.91	63	36	1	Sandy loam
Bs	35–65	4.64	7.18	0.28	25	26.98	1.68	67	32	1	Sandy loam
BC	65–75	4.73	7.61	0.32	24	28.80	1.57	n.a.	n.a.	n.a.	n.a.
Profile TPN198 *Albic Podzol (Arenic)*											
Oi/Oe	7–2	3.69	38.02	1.64	23	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Oa	2–0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ah	0–4	3.25	21.94	1.73	13	123.91	7.14	n.a.	n.a.	n.a.	n.a.
E1	4–9	3.60	6.26	0.36	18	63.14	3.28	72	27	1	Loamy sand
E2	9–17	3.87	6.34	0.32	20	48.86	2.56	76	24	0	Loamy sand
Bhs	17–25	4.25	4.96	0.23	22	28.88	1.62	77	23	0	Loamy sand
Bs	25–40	5.37	3.49	0.15	24	23.93	1.21	78	21	1	Loamy sand
BC	40–60	5.09	2.06	0.07	29	18.03	1.13	74	24	2	Loamy sand

Table 2 – continue

Profile TPN42 *Skeletic Podzol (Loamic, Folic)*											
Oi	14–0	4.11	23.69	1.36	17	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
A	0–6	3.62	24.69	1.17	21	171.24	7.74	n.a.	n.a.	n.a.	n.a.
AE	6–16	3.84	7.48	0.39	19	75.82	3.80	n.a.	n.a.	n.a.	n.a.
Bhs	16–35	4.75	9.81	0.46	21	42.17	2.86	72	27	1	Loamy sand
BC	35–50	4.86	4.55	0.28	16	32.81	2.19	69	30	1	Sandy loam
Profile TPN44 *Leptic Podzol (Arenic, Folic)*											
Oi	10–0	4.13	41.99	2.24	19	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
A	0–10	3.92	7.36	0.51	14	82.30	4.40	n.a.	n.a.	n.a.	n.a.
AE	10–15	4.56	2.77	0.18	15	34.14	2.09	77	22	1	Loamy sand
Bs	15–30	4.94	3.12	0.12	26	24.46	1.23	80	19	1	Loamy sand
BC	30–45	5.21	0.83	0.02	40	15.69	0.95	81	17	2	Loamy sand
C	45–60	5.30	0.79	0.03	33	13.24	0.91	75	21	4	Loamy sand
Profile TPN90 *Skeletic Albic Podzol (Arenic)*											
Oi	9–0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
A	0–5	3.57	13.61	0.65	21	91.15	4.71	n.a.	n.a.	n.a.	n.a.
E	5–15	3.69	5.69	0.30	19	58.24	3.28	n.a.	n.a.	n.a.	n.a.
Bhs	15–28	4.08	8.45	0.41	21	48.47	2.41	74	25	1	Loamy sand
Bs	28–40	4.53	2.38	0.09	26	22.28	1.27	75	23	2	Loamy sand
BC	40–55	4.8	2.09	0.07	28	19.49	1.24	n.a.	n.a.	n.a.	n.a.
Profile TPN91 *Skeletic Albic Podzol (Arenic)*											
Oi	1–0	4.03	43.22	2.02	21	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
A	0–6	3.71	11.26	0.72	16	118.20	6.00	n.a.	n.a.	n.a.	n.a.
E	6–27	4.20	2.06	0.15	14	31.84	1.96	56	37	7	Sandy loam
Bhs	27–40	4.85	11.12	0.45	25	29.42	1.88	78	18	4	Loamy sand
Bs	40–55	4.91	1.22	0.05	25	28.82	1.72	n.a.	n.a.	n.a.	n.a.
Profile TPN201 *Skeletic Podzol (Folic)*											
Oi	12–10	5.12	46.21	1.92	24	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Oe	10–0	3.35	40.35	1.55	26	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
A	0–6	3.35	8.83	0.55	16	150.30	6.55	n.a.	n.a.	n.a.	n.a.
EA	6–20	3.63	2.26	0.15	15	52.43	2.52	81	16	3	Loamy sand
Bhs	20–40	4.28	6.00	0.36	17	54.25	2.78	n.a.	n.a.	n.a.	n.a.
Bs	40–55	5.00	2.46	0.12	20	27.63	1.51	n.a.	n.a.	n.a.	n.a.

n.a. – not analyzed

56–81% sand (mean 74%), 16–37% silt (mean 23%), and 1–7% clay (mean 2%) (Tables 2 and 3). Statistical analysis revealed significantly lower mean sand and clay contents, but significantly higher mean silt content in soils from the upper montane forest zone compared with those from the subalpine zone (Table 3).

All studied soils were acidic. In the upper montane forest zone, pH values ranged from 3.25 to 6.05, with a mean of 4.29 (Tables 2 and 3). Soils from the subalpine zone exhibited a slightly narrower pH range of 3.35–5.30 and a mean value of 4.35. Despite this difference, the mean soil pH values of the two vegetation zones did not differ significantly (Table 3).

Soil organic carbon (SOC) content showed substantial variability within both vegetation zones. In the upper montane forest zone, SOC values ranged between 1.41% and 36.17%, with a mean of 8.25% (Tables 2 and 3). The corresponding values for the subalpine zone were 0.79–24.60% and 6.31%, respectively. Total nitrogen (TN) content varied from 0.04% to 1.74% in the upper montane forest zone and from 0.03% to 1.17% in the subalpine zone, with mean values of 0.43% and 0.33%, respectively. The C/N ratio ranged from 13 to 38 in soils from the upper montane forest zone and from 14 to 40 in soils from the subalpine zone. Mean C/N ratios in the soils from the two vegetation zones studied were similar, amounting to 22 and 21, respectively. None of the differences in mean content of SOC and TN as well as C/N ratio between the soils from the two vegetation zones were statistically significant (Table 3).

Water-extractable organic carbon (WEOC) concentrations in soils from the upper montane forest zone ranged between

Table 3
Mean values of the studied soil properties from the upper montane forest zone and subalpine zone. Values in brackets are standard errors (n = 47). For a given line, mean values with different letters significantly differ at $p < 0.05$ based on the Mann-Whitney U test

Soil property	Unit	Upper montane forest zone	Subalpine zone
pH	(H_2O)	4.29 (0.14) a	4.35 (0.13) a
SOC	(%)	8.25 (1.46) a	6.31 (1.19) a
TN	(%)	0.43 (0.09) a	0.33 (0.06) a
C/N		22 (1.15) a	21 (1.39) a
WEOC	(mg/l)	56.97 (11.08) a	55.65 (9.23) a
WETN	(mg/l)	2.94 (0.48) a	2.91 (0.40) a
Sand	(%)	67 (1.78) a	74 (1.99) b
Silt		32 (1.66) a	23 (1.73) b
Clay		1 (0.28) a	2 (0.53) b
Fe_o	(%)	1.26 (0.14) a	0.87 (0.18) a
Al_o		0.98 (0.17) a	0.80 (0.18) a
Si_o		0.09 (0.02) a	0.07 (0.02) a
Podzolization index	$Al_o + 0.5Fe_o$	1.61 (0.21) a	1.24 (0.27) a
ODOE		1.03 (0.14) a	0.83 (0.15) a

14.64 and 274.98 mg l^{-1} and averaged 56.97 mg l^{-1} (Tables 2 and 3). In the subalpine zone, WEOC concentrations were slightly less variable (13.24–171.24 mg l^{-1}), with a mean value of 55.65 mg l^{-1}. Water-extractable total nitrogen (WETN) concentrations varied from 0.91 to 11.22 mg l^{-1} in the upper montane forest zone and from 0.91 to 7.74 mg l^{-1} in the subalpine zone. Mean WETN concentrations were nearly identical in the soils from the two vegetation zones studied, amounting to 2.94 and 2.91 mg l^{-1}, respectively. Differences in mean WEOC and WETN concentrations among the vegetation zones were not statistically significant (Table 3).

The concentration of ammonium oxalate-extractable iron (Fe_o) in soils from the upper montane forest zone ranged between 0.28% and 2.63%, with a mean value of 1.26% (Tables 3 and 5). In the subalpine zone, Fe_o concentrations varied from 0.08% to 2.85% and averaged 0.87%. Ammonium oxalate-extractable aluminium (Al_o) concentrations reached 0.22–3.16% in the upper montane forest zone and 0.12–2.97% in the subalpine zone, with corresponding mean values of 0.98% and 0.80%. The concentration of ammonium oxalate-extractable silicon (Si_o) ranged from 0.01% to 0.35% in the upper montane forest zone and from 0.01% to 0.31% in the subalpine zone. Mean Si_o concentrations were 0.09% and 0.07%, respectively. None of the observed differences in mean Fe_o, Al_o, and Si_o concentrations between the two vegetation zones were statistically significant (Table 3).

The podzolization index ($Al_o + 0.5Fe_o$) varied between 0.41 and 4.24 in soils from the upper montane forest zone and between 0.16 and 4.17 in soils from the subalpine zone (Table 5). Mean values amounted to 1.61 and 1.24, respectively (Table 3). ODOE values in soils from the upper montane forest zone ranged from 0.17 to 3.19, with an average of 1.03. In the subalpine zone, ODOE values ranged between 0.11 and 2.04 and averaged 0.83. Statistical analysis showed no significant differences in the podzolization index and ODOE values between soils from the upper montane forest zone and those from the subalpine zone (Table 3).

4.4. Differences in physical and chemical properties between albic and spodic horizons

In the upper montane forest zone, soil pH averaged 3.75 in the albic horizon and 4.53 in the spodic horizon. Slightly higher values were recorded in the subalpine zone, where mean pH reached 3.98 and 4.67 in the albic and spodic horizons, respectively (Table 4). The mean SOC content in the upper montane forest zone was 7.78% in the albic horizon and 6.07% in the spodic horizon. In contrast, the subalpine zone showed lower SOC concentrations in the albic horizon (4.05%), while the spodic horizon contained 5.57% SOC on average. Total nitrogen concentrations followed a similar pattern. In the upper montane forest zone, mean TN content was 0.43% in the albic horizon and 0.27% in the spodic horizon. Corresponding values in the subalpine zone were lower, averaging 0.23% and 0.26%, respectively (Table 4). The average C/N ratio ranged from 18 in the albic horizon to 23 in the spodic horizon of the upper montane forest zone. Identical values for the spodic horizon and slightly lower values for the albic horizon were observed in the subalpine zone, where the mean C/N ratio equalled 16 and 23, respectively (Table 4). Water-extractable organic carbon concentrations differed between vegetation zones. In the upper montane forest zone, mean WEOC concentrations were 47.47 mg l^{-1} in the albic horizon and 67.82 mg l^{-1} in the spodic horizon. By comparison, the subalpine zone exhibited mean values of 50.49 mg l^{-1} and 34.69 mg l^{-1}, respectively. Mean WETN concentrations reached 2.53 mg l^{-1} in the albic horizon and 3.30 mg l^{-1} in the spodic horizon of the upper montane forest zone, whereas lower values of 2.73 mg l^{-1} and 1.96 mg l^{-1} were recorded in the subalpine zone (Table 4). The particle-size distribution was dominated by sand in both vegetation zones. In the upper montane forest zone, the albic horizon contained on average 71% sand, 28% silt and 1% clay, while the spodic horizon consisted of 65% sand, 34% silt and 1% clay. In the subalpine zone, mean sand, silt and clay contents were 71%, 25% and 4% in the albic horizon and 76%, 22% and 2% in the spodic horizon, respectively (Table 4). Marked differences between horizons were observed for oxalate-extractable elements. Mean Fe_o, Al_o and Si_o concentrations in the upper montane forest zone increased from 0.91%, 0.44% and 0.02% in the albic horizon to 1.76%, 1.43% and 0.11% in the spodic horizon. A comparable pattern was found in the subalpine zone, where average concentrations rose from 0.38%, 0.29% and 0.02% to 1.51%, 1.48% and 0.13%, respectively (Table 4). The mean podzolization index was substantially higher in spodic than in albic horizons. In the upper montane forest zone, values increased from 0.90 to 2.30, while in the subalpine zone they rose from 0.48 to 2.23 (Table 4). Differences between horizons were also reflected in ODOE values. In the upper montane

Table 4
Comparison of mean values of the studied soil properties between the albic (E) and spodic (B) horizons from the upper montane forest zone and subalpine zone. Values in brackets are standard errors (n = 31). For a given line, mean values with different letters separately for the two zones significantly differ at $p < 0.05$ based on the Mann-Whitney U test

Soil property	Unit	Upper montane forest zone		Subalpine zone	
		Albic	Spodic	Albic	Spodic
pH	(H_2O)	3.75 (0.11) a	4.53 (0.14) b	3.98 (0.17) a	4.67 (0.12) b
SOC	(%)	7.78 (0.69) a	6.07 (0.71) a	4.05 (1.08) a	5.57 (1.35) a
TN	(%)	0.43 (0.04) a	0.27 (0.03) b	0.23 (0.05) a	0.26 (0.06) a
C/N		18 (0.89) a	23 (1.31) b	16 (1.19) a	23 (1.21) b
WEOC	(mg/l)	47.47 (10.10) a	67.82 (24.07) a	50.49 (8.13) a	34.69 (4.22) a
WETN	(mg/l)	2.53 (0.49) a	3.30 (0.95) a	2.73 (0.35) a	1.96 (0.23) a
Sand	(%)	71 (2.14) a	65 (2.83) a	71 (7.84) a	76 (1.34) a
Silt		28 (2.10) a	34 (2.53) a	25 (6.24) a	22 (1.72) a
Clay		1 (0.22) a	1 (0.50) a	4 (1.76) a	2 (0.58) a
Fe_o	(%)	0.91 (0.21) a	1.76 (0.15) b	0.38 (0.16) a	1.51 (0.32) b
Al_o		0.44 (0.10) a	1.43 (0.31) b	0.29 (0.09) a	1.48 (0.36) b
Si_o		0.02 (0.00) a	0.11 (0.04) b	0.02 (0.01) a	0.13 (0.03) b
Podzolization index	$Al_o + 0.5Fe_o$	0.90 (0.19) a	2.30 (0.31) b	0.48 (0.17) a	2.23 (0.51) b
ODOE		1.05 (0.24) a	1.31 (0.26) a	0.39 (0.15) a	1.41 (0.21) b

Table 5
Ammonium oxalate extractable forms of iron (Fe_o), aluminium (Al_o), silicon (Si_o), and optical density of oxalate extract (ODOE) in the studied soils

Horizon	Depth (cm)	Fe_o (%)	Al_o	Si_o	Podzolization index $Al_o + 0.5Fe_o$	ODOE
Profile TPN103 *Skeletic Albic Podzol (Loamic)*						
Oi	1–0	n.a.	n.a.	n.a.	n.a.	n.a.
A	0–6	0.58	0.36	0.02	0.65	0.71
E	6–10	1.07	0.35	0.02	0.88	0.57
Bhs	10–20	2.09	0.70	0.03	1.74	0.95
Bs	20–45	0.95	1.44	0.33	1.92	0.29
BCg	45–70	1.45	0.52	0.02	1.25	2.10
Profile TPN134 *Rustic Podzol (Loamic, Folic)*						
Oi	25–22	n.a.	n.a.	n.a.	n.a.	n.a.
Oe	22–15	n.a.	n.a.	n.a.	n.a.	n.a.
Oa	15–0	n.a.	n.a.	n.a.	n.a.	n.a.
A	0–10	2.19	1.09	0.06	2.19	0.64
AE	10–22	1.65	0.88	0.03	1.71	1.90
Bhs	22–40	2.16	3.16	0.18	4.24	3.19
Bs	40–55	1.33	3.11	0.33	3.78	1.91
BC	55–80	0.29	0.95	0.21	1.09	0.21
Profile TPN172 *Albic Podzol (Loamic)*						
Oi	9–8	n.a.	n.a.	n.a.	n.a.	n.a.
Oe	8–4	n.a.	n.a.	n.a.	n.a.	n.a.
Oa	4–0	n.a.	n.a.	n.a.	n.a.	n.a.
E	0–8	0.29	0.27	0.01	0.41	0.48
Bhs	8–22	2.63	0.64	0.02	1.95	1.58
Bs	22–40	1.67	0.77	0.02	1.61	0.60
BC	40–60	0.61	0.69	0.10	0.99	0.25

Table 5 – continue

Profile TPN192 *Albic Podzol (Loamic)*						
Oi	5–0	n.a.	n.a.	n.a.	n.a.	n.a.
A	0–6	0.41	0.22	0.02	0.43	0.65
E	6–12	0.89	0.31	0.02	0.75	0.97
Bhs	12–35	1.44	0.82	0.03	1.54	1.04
Bs	35–65	2.06	1.94	0.11	2.97	1.44
BC	65–75	1.54	2.59	0.35	3.36	1.35
Profile TPN198 *Albic Podzol (Arenic)*						
Oi/Oe	7–2	n.a.	n.a.	n.a.	n.a.	n.a.
Oa	2–0	n.a.	n.a.	n.a.	n.a.	n.a.
Ah	0–4	0.28	0.29	0.02	0.42	0.17
E1	4–9	0.37	0.30	0.01	0.49	0.71
E2	9–17	1.22	0.53	0.02	1.14	1.65
Bhs	17–25	1.71	0.70	0.03	1.56	1.17
Bs	25–40	1.55	0.96	0.06	1.74	0.90
BC	40–60	0.98	0.86	0.18	1.35	0.40
Profile TPN42 *Skeletic Podzol (Loamic, Folic)*						
Oi	14–0	n.a.	n.a.	n.a.	n.a.	n.a.
A	0–6	0.52	0.52	0.02	0.78	1.51
AE	6–16	0.48	0.31	0.02	0.55	0.68
Bhs	16–35	1.84	2.04	0.12	2.96	2.04
BC	35–50	2.04	1.70	0.08	2.72	1.59
Profile TPN44 *Leptic Podzol (Arenic, Folic)*						
Oi	10–0	n.a.	n.a.	n.a.	n.a.	n.a.
A	0–10	0.38	0.33	0.02	0.53	0.85
AE	10–15	0.97	0.63	0.04	1.11	0.81
Bs	15–30	1.47	1.09	0.10	1.83	0.81
BC	30–45	0.21	0.42	0.06	0.52	0.15
C	45–60	1.11	0.39	0.10	0.95	0.18
Profile TPN90 *Skeletic Albic Podzol (Arenic)*						
Oi	9–0	n.a.	n.a.	n.a.	n.a.	n.a.
A	0–5	0.09	0.12	0.01	0.16	0.12
E	5–15	0.08	0.12	0.01	0.16	0.16
Bhs	15–28	0.99	0.57	0.02	1.07	2.00
Bs	28–40	0.61	0.37	0.02	0.67	0.69
BC	40–55	0.44	0.56	0.06	0.78	0.40
Profile TPN91 *Skeletic Albic Podzol (Arenic)*						
Oi	1–0	n.a.	n.a.	n.a.	n.a.	n.a.
A	0–6	0.26	0.17	0.02	0.29	0.17
E	6–27	0.27	0.26	0.01	0.40	0.16
Bhs	27–40	2.85	2.57	0.15	3.99	1.64
Bs	40–55	2.39	2.97	0.31	4.17	1.44
Profile TPN201 *Skeletic Podzol (Folic)*						
Oi	12–10	n.a.	n.a.	n.a.	n.a.	n.a.
Oe	10–0	n.a.	n.a.	n.a.	n.a.	n.a.
A	0–6	0.10	0.16	0.01	0.21	0.11
EA	6–20	0.09	0.14	0.01	0.18	0.14
Bhs	20–40	1.83	1.76	0.17	2.67	2.00
Bs	40–55	0.14	0.44	0.12	0.51	0.67

n.a. – not analyzed

forest zone, mean ODOE amounted to 1.05 in the albic horizon and 1.31 in the spodic horizon. In the subalpine zone, the corresponding values were 0.39 and 1.41, respectively (Table 4).

Across both vegetation zones, spodic horizons were characterized by higher mean pH values, wider C/N ratios, greater concentrations of Fe_o, Al_o and Si_o, and higher podzolization index values than albic horizons (Table 4). By contrast, mean SOC, WEOC and WETN contents, as well as particle-size fractions, varied only slightly between the two horizons.

Statistical analyses confirmed significant differences between albic and spodic horizons for pH, C/N ratio, Fe_o, Al_o, Si_o and the podzolization index in both vegetation zones. Significant differences in TN content were detected only in soils of the upper montane forest zone, whereas ODOE values differed significantly between horizons exclusively in the subalpine zone (Table 4).

4.5. Physical and chemical properties of spodic horizons

Spodic horizons from the upper montane forest zone showed less mean sand content and more mean content of silt than spodic horizons from the subalpine zone (Table 6). Mean clay content was similar in both zones. Mean soil pH values were comparable, as were SOC and TN content and the C/N ratio (Table 6). Mean WEOC and WETN concentrations in spodic horizons were slightly higher in the upper montane soils than under the dwarf pine (Table 6). Mean concentrations of Fe_o, Al_o and Si_o also showed only minor differences between both vegetation zones. Mean values of the podzolization index and ODOE were also similar (Table 6).

Statistical analysis showed that only sand and silt contents differed significantly between spodic horizons of the two vegetation zones. All remaining physical and chemical properties, including pH, SOC, TN, WEOC, WETN, Fe_o, Al_o, Si_o, podzolization index and ODOE, did not differ significantly (Table 6).

Table 6
Mean values of the studied soil properties from the upper montane forest zone and subalpine zone in the spodic (B) horizons. Values in brackets are standard errors (n = 18). For a given line, mean values with different letters significantly differ at $p < 0.05$ based on the Mann-Whitney U test

Soil property	Unit	Upper montane forest zone	Subalpine zone
pH	(H_2O)	4.53 (0.14) a	4.67 (0.12) a
SOC	(%)	6.07 (0.71) a	5.57 (1.35) a
TN	(%)	0.27 (0.03) a	0.26 (0.06) a
C/N		23 (1.31) a	23 (1.21) a
WEOC	(mg/l)	67.82 (24.07) a	34.69 (4.22) a
WETN	(mg/l)	3.30 (0.95) a	1.96 (0.23) a
Sand	(%)	65 (2.83) a	76 (1.13) b
Silt		34 (2.53) a	23 (1.41) b
Clay		1 (0.50) a	2 (0.49) a
Fe_o	(%)	1.76 (0.15) a	1.51 (0.32) a
Al_o		1.43 (0.31) a	1.48 (0.36) a
Si_o		0.11 (0.04) a	0.13 (0.03) a
Podzolization index	$Al_o + 0.5Fe_o$	2.30 (0.31) a	2.23 (0.51) a
ODOE		1.31 (0.26) a	1.41 (0.21) a

5. Discussion

Mountain podzolic soils are usually characterized by a high content of rock fragments, substantial content of organic matter favored by a cool and humid climate, high acidity, and elevated concentration of mobile iron and aluminium compounds (D'Amico et al., 2008; Egli et al., 2009; Kabała et al., 2012; Drewnik et al., 2021; Musielok et al., 2021; Kuligiewicz et al., 2024). The soils analyzed in this study show all these typical characteristics.

The mineral composition of the studied soils reflects their parent material, consisting of granitoid moraines and weathered granitoid regolith. X-ray diffraction analyses revealed quartz as the dominant mineral phase in the studied soils, with feldspars and mica also present throughout the soil profiles (Figs. 3–4). This mineral composition is characteristic of granitoid substrate and confirms the lithological uniformity of the investigated sites. The obtained results are aligned with mineralogical data reported by other authors (Skiba, 2001, 2007; Kuligiewicz et al., 2024). It should be stressed that the overall similarity of mineralogy of the two soil groups studied (i.e. upper montane forest zone *vs.* subalpine zone) allow to study the impact of vegetation and climatic conditions on advancement of podzolization process in these soils.

The texture of the soils was classified as sandy loam or loamy sand, which is typical for podzols formed from granitoids (Borkowski et al., 2005; Kabała et al., 2012). The obtained difference between the texture of podzolic soils from the upper montane forest zone and the subalpine zone is not high (Table 2). However, the difference between mean content of sand, silt, and clay from the whole soil profiles and spodic horizons are statistically significant (Tables 3 and 6). The texture of the podzolic soils from subalpine zone is coarser and was predominantly classified as loamy sand, while the soils from upper montane forest zone exhibit a finer texture and were mostly classified as sandy loam (Table 2). Most likely, the obtained differences in soil texture between soils from upper montane forest zone and subalpine zone is related to differences in genesis of the parent material (granitoid moraine in forest zone *vs. in situ* residues in subalpine zone) or it may be connected with differences in weathering between the zones (i.e. more intensive weathering in forest zone *vs.* subalpine zone). Similar relationships between parent material, weathering intensity and the development of podzolic properties have been reported in alpine environments in the western Alps, where variations in substrate characteristics and soil development stages influenced the degree of podzolization and horizon differentiation (D'Amico et al., 2008; Egli et al., 2009).

All the studied soils are acidic (Tables 2, 3, and 6). Podzolic soils typically exhibit low or very low pH throughout the profile due to intensive leaching and the high organic acids input originating from coniferous litter (Lundström et al., 2000). Downward translocation of organo-metal complexes leads to base cation (Ca^{2+}, Mg^{2+}, K^+, Na^+) depletion from the upper soil horizons, contributing to progressive acidification of surface horizons (Lundström et al., 2000; Sauer et al., 2007). This explains the increase in pH with depth observed in all the studied soil profiles (Table 2) and this is consistent with findings from other podzols in the Tatras (Drewnik et al., 2021; Kuligiewicz et al., 2024). Similar strongly acidic conditions throughout podzol profiles have been documented in alpine and subalpine environments of the western Alps, Scandinavia and the Rocky Mountains, where intensive leaching and accumulation of organic matter contribute to low soil pH values in surface horizons (Stützer, 1999; D'Amico et al., 2008; Egli et al., 2009; Valerio et al., 2016). Mean soil pH values are slightly lower in the upper montane zone than in subalpine zone (Tables 3 and 6). The marginally lower mean soil pH in the upper montane forest zone than in subalpine zone (4.29 *vs.* 4.35) may reflect greater inputs of acidic litter and higher root activity in forest stands compared to shrub-dominated subalpine vegetation (Augusto et al., 2002). However, these differences were not significant, indicating comparable conditions in both studied vegetation zones.

Podzolic soils are generally characterized by relatively slow organic matter turnover and the substantial accumulation of SOC in subsurface horizons, which is strongly controlled by climate, vegetation type, and microbial activity (Lundström et al., 2000). In the present study, the mean SOC and TN contents as well as the C/N ratio, are slightly higher in soils from the upper montane forest zone than in soils from the subalpine zone dominated by *Pinus mugo* (Tables 3 and 6). Similarly, the mean WEOC and WETN concentrations are slightly higher in soils from the upper montane forest zone than in subalpine zone (Tables 3 and 6). This contradicts the higher SOC content and C/N ratio in the subalpine soils than in the upper montane forest soils reported previously by Drewnik (2006), as well as Wasak and Drewnik (2015). However, it should be noted that all these differences are statistically insignificant (Tables 3 and 6) suggesting very similar conditions for soil organic matter accumulation and transformation in soils of both vegetation zones studied here. The lack of clear differences in SOC accumulation between the studied vegetation zones are consistent with observations from alpine environments where microclimatic factors and slope exposure affected organic matter stocks but did not lead to substantial differences in podzol development (Egli et al., 2009).

A characteristic feature of podzolic soils is intensive leaching, resulting in mobilization of weathering products such as Al, Fe, and Si compounds together with organic acids in the upper part of soil profile (Lundström et al., 2000; Sauer et al., 2007; Kuligiewicz et al., 2024). After mobilization of these compounds in the eluvial horizons, organo-metal complexes are translocated and accumulate in spodic (Bs/Bhs) horizons (Lundström et al., 2000; Kabała et al., 2012; Drewnik et al., 2021). Consistently, concentration of ammonium oxalate-extractable iron (Fe_o), aluminium (Al_o) and silicon (Si_o) as well as the podzolization index and values of ODOE, are the highest in illuvial (B) horizons of the studied soils (Tables 3, 5 and 6). Mean concentration of Fe_o, Al_o, Si_o as well as mean values of the podzolization index and ODOE are slightly higher in the upper montane forest zone than in the subalpine zone when entire soil profiles are considered (Table 3). In the spodic horizons however, mean concentration of Al_o, Si_o, and ODOE values are slightly higher in subalpine zone. However, it should be stressed that none of these differences are significant (Tables 3 and 6), indicating no clear trend toward stronger podzolization in either vegetation zone. Similar findings were reported from mountainous podzols in Norway and the Italian Alps, where differences in vegetation cover did not always correspond to differences in the accumulation of Fe and Al compounds in spodic horizons (Stützer, 1999; D'Amico et al., 2008).

This study shows that advancement of podzolization in soils developed from granitoid parent material and occurring in the upper montane forest zone as well as in the subalpine zone is very similar despite differences in type and character of vegetation as well as climatic conditions. Therefore, the results obtained in this study evidence that our hypothesis that advancement of podzolization is higher in soils from subalpine zone than in upper montane forest zone was incorrect.

6. Conclusions

The podzolic soils developed under upper montane coniferous forests (*Plagiothecio-Piceetum tatricum*) and subalpine dwarf pine communities (*Pinetum mugo*) in the Tatra Mountains display features typical of mountainous Podzols formed from granitoid parent material. Their morphology, acidic reaction, and accumulation of Fe, Al and Si compounds in spodic horizons indicate well-expressed podzolization.

Chemical properties of the podzolic soils as well as intensity of podzolization are very similar in the upper montane forest zone and subalpine zone. This shows that environmental conditions in these two vegetation zones in the Tatras are generally similar in relation to podzolization. The only significant difference between these two groups of soils is texture and this may be related to differences in genesis of the parent material (granitoid moraine in forest zone *vs. in situ* residues in subalpine zone) or it may relate to differences in weathering between the zones (i.e. more intensive weathering in forest zone *vs.* subalpine zone).

The findings suggest that, within the studied area, the influence of vegetation type and climatic conditions on the morphology and chemical properties of Podzols is limited in comparison to the impact of dominant soil-forming factors such as parent material. It should be noted, however, that additional (not considered in this study) environmental factors such as microtopography, slope gradient, exposure, and local climatic variability may also affect soil development. Therefore, further detailed studies considering abovementioned factors and including more soil profiles should be conducted in the future.

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Conflict of interest

The authors declare no conflict of interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This research did not involve human or animal subjects.

Author Contributions

Zachary Motyl – Conceptualization, Data curation, Investigation, Methodology, Visualization Writing – original draft. **Wojciech Szymański** – Conceptualization, Data curation, Investigation, Methodology, Supervision, Validation, Writing – review & editing. All authors read and approved the final manuscript.

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Wpływ roślinności szpilkowej na właściwości gleb bielicowych w Tatrach

Słowa kluczowe

Gleby bielicowe
Roślinność szpilkowa
Tatry
Regiel górny
Piętro subalpejskie
Bielicowanie

Streszczenie

Celem pracy było określenie wpływu boru górnoreglowego oraz kosodrzewiny na właściwości fizyczne i chemiczne gleb bielicowych w Tatrach. Opisano dziesięć profili glebowych, w tym pięć spod boru górnoreglowego i pięć spod kosodrzewiny. Wyniki wskazują na ogólne podobieństwo właściwości badanych gleb. Wszystkie badane gleby wykazywały cechy charakterystyczne dla górskich gleb bielicowych. Skład mineralny gleb był podobny w obu piętrach roślinnych i odzwierciedlał granitoidowy materiał macierzysty badanych gleb. Jedyna istotna statystycznie różnica pomiędzy obiema grupami gleb dotyczyła uziarnienia (zawartość frakcji piasku, pyłu i iłu). Gleby spod boru górnoreglowego cechowały się drobniejszym uziarnieniem w porównaniu do tych spod kosodrzewiny. Może to wskazywać na różnice w intensywności procesów wietrzenia lub innej genezy materiału macierzystego w obu piętrach. Średnie wartości pH, zawartości węgla organicznego (SOC), azotu całkowitego (TN), stosunku C/N, węgla rozpuszczalnego (WEOC), azotu rozpuszczalnego (WETN), form amorficznych Fe, Al, oraz Si, współczynnika bielicowania oraz gęstości optycznej ekstraktu szczawianowego (ODOE) były podobne i nie wykazały istotnych statystycznie różnic pomiędzy badanymi grupami gleb. Wyniki badań wskazują na podobieństwo warunków środowiskowych wpływających na rozwój gleb bielicowych w piętrze boru górnoreglowego oraz w piętrze subalpejskim Tatr.