SOIL SCIENCE ANNUAL
2026, 77(1), 218341

https://doi.org/10.37501/soilsa/218341

BY-NC-ND

Bioclimatic vs. lithogenic drivers of Podzols developed from flysch: new insights from the Gorce Mountains, southern Poland

Łukasz Musielok[1*], Anna Rudnik[1], Krzysztof Buczek[2], Jarosław Lasota[3], Patrycja Tomala[1], Agnieszka Kafel[1], Katarzyna Wątor[4]

[1] Jagiellonian University, Faculty of Geography and Geology, Institute of Geography and Spatial Management, Department of Pedology and Soil Geography, ul. Gronostajowa 7, 30-387 Kraków, Poland
[2] Institute of Nature Conservation, Polish Academy of Sciences, al. Adama Mickiewicza 33, 31-120 Kraków, Poland
[3] University of Agriculture in Kraków, Faculty of Forestry, Department of Ecology and Silviculture, al. 29 Listopada 46, 31-425 Kraków, Poland
[4] AGH University of Krakow, Faculty of Geology, Geophysics and Environmental Protection, al. Mickiewicza 30, 30-059 Kraków, Poland

* Corresponding author: dr. Łukasz Musielok, e-mail: l.musielok@uj.edu.pl, ORCID iD: https://orcid.org/0000-0002-8241-7429

Received: 2025-09-29
Accepted: 2026-02-19
Published online: 2026-02-19
Associated editor: Cezary Kabała

Keywords:

Podzols
Flysch
Soil moisture
Soil temperature
Soil-forming factors

Abstract

The soils of the Outer Carpathians, including the Gorce Mountains, are developed from flysch regolith or flysch-derived slope sediments, which predominantly form Cambisols. However, Podzols also occur locally in these areas. Their formation was attributed either to the presence of coarse-grained parent material at lower elevations or to bioclimatic factors at higher elevations that promote strong soil acidification and initiate podzolization. This study aimed to determine how soil properties across the Cambisol–Podzol transition in the highest parts of the Gorce Mountains relate to present-day bioclimatic conditions. The results of comprehensive studies, including soil temperature and moisture measurements, vegetation studies, and soil properties analyses, showed that while a generally humid and cool climate is an indispensable condition for podzolization, the properties of the parent material play a decisive role. Podzols are consistently associated with sandstone-derived, coarse-grained parent materials poor in clay and iron. The adjacent soils developed from fine-grained mudstones, although displaying redox features in their upper horizons resembling colours of eluvial horizons, show no clear evidence of illuviation processes and possess properties that support a far richer assemblage of vascular plant species in the forest undergrowth. These findings challenge the view that bioclimatic conditions are the main factor in podzolization in the upper montane zone of the Flysch Carpathians and emphasize the crucial importance of lithological variability in soil development at high elevations.

1. Introduction

The regolith of flysch rocks and slope deposits, reshaped by morphogenetic processes and derived from weathered materials of these different-grained sedimentary rocks, forms the parent material of soils in the Outer (Flysch) Carpathians region (Skiba, 1995), often called the Beskidy Mountains. In Poland, this area covers around 19,000 km^2, which is approximately 6% of the country's total area (Balon and Jodłowski, 2014; Solon et al., 2018), though flysch formations are the widespread parent material of soils within the Alpine-Himalayan mountain belt (Trifonov et al., 2012). Soil parent materials found in the Beskidy Mts. are typically loamy-textured, with a high proportion of the clay fraction (Kacprzak and Skiba, 2000; Kacprzak 2003). This contributes to a relatively high content of alkaline cations, such as Mg^{2+} and Ca^{2+}, that are carried by clay minerals. In many areas, enrichment of soils with aeolian (wind-blown) dust has also been observed, further influencing soil development (Kacprzak et al., 2015; Musielok et al., 2022). Cambisols of varying trophic status (Dystric or Eutric) commonly form in these parent materials, depending on the degree of leaching and carbonates removal from the soil profile, as well as the variation in particle size distribution across different slope positions (Kacprzak, 2003). In the humid mountain climate of the Beskidy Mts., with a mean annual atmospheric precipitation (MAAP) in the range from 1000 mm up to 1450 mm (Obrębska-Starklowa, 2004), Gleysols, Stagnosols, and small patches of Histosols often accompany Cambisols (Nicia and Miechówka, 2004; Kowalska et al., 2019; Skiba, 1995). Low air temperatures, along with higher humidity in the region compared to the adjacent foothills and lowlands, promote the accumulation of soil organic matter (SOM), leading to the acidification of soils's surface horizons. Under favourable environmental conditions, this can result in the development of the podzolization process (Adamczyk, 1983; Skiba, 1995,

© 2026 by the authors. Licensee Soil Science Society of Poland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY NC ND 4.0) license (https://creativecommons.org/licenses/by-nc-nd/4.0/).

Miechówka et al. 2006; 2015; Musielok et al., 2021). However, well-developed Podzols are rare in the Flysch Carpathians and typically occur on highly permeable regoliths and derived slope deposits with relatively coarse textures, and in favourable topographic settings (Gruba, 2001; Skiba and Szymański, 2009; Musielok et al., 2022). Despite their limited extent, these soils significantly influence habitat conditions and may affect sustainable forest management (Lasota, 2004a; 2004b; Musielok, 2022; Labaz et al., 2014; Jankowski, 2010).

In their studies on the differentiation of the soil cover in the Gorce Mountains – one of the highest mountain ranges within the Beskidy Mts. – Adamczyk (1966) and Adamczyk and Komornicki (1970) identified two pedogenic pathways of Podzols formation in the flysch of the Magura Nappe, which constitutes a significant part of the Outer Carpathians (Jankowski and Margielewski, 2021). In the lower montane zone of the Gorce Mts., the authors identified a class of Podzols primarily associated with coarse-textured parent materials derived from sandstone and conglomerate layers. In contrast, on higher elevations (above 1100–1150 m a.s.l.), classified by Medwecka-Kornaś and Kornaś (1968) as the upper montane zone, Podzols development was observed on finer-textured materials (Adamczyk and Komornicki, 1970). In the latter locations, the authors pointed to bioclimatic factors as the primary drivers of the podzolization process. Some of these Podzols profiles were also found outside of forested areas (Adamczyk and Komornicki, 1970). This suggests that in areas situated above 1100–1150 m a.s.l., a combination of climate and vegetation factors may overcome the limitations posed by parent material properties (fine-grained textures and relatively high share of alkaline cations), thereby enabling the podzolization process to take place. Similar cases have been documented worldwide, including the Alps (Buurman et al., 1976; D'Amico et al., 2008), Alaska (Alexander et al., 1994; Spinola et al., 2022), Hudson Bay (Protz et al. 1984), and Michigan (Schaetzl, 1991), highlighting the significant role of climate and vegetation conditions in soil development.

In this study, we consider two key influences: (1) locally variable climatic conditions, particularly in the context of ongoing global warming (Pepin et al., 2022), and (2) the local heterogeneity of parent material derived from flysch formations, which may significantly impact soil-forming processes, especially at higher elevations (Musielok et al. 2021; Kacprzak et al., 2015). Based on earlier findings from the region, we aim to determine how soil properties in the highest parts of the Gorce Mountains correspond to present-day bioclimatic conditions. We hypothesize that Podzols tend to occur in areas with lower temperatures and higher soil moisture, regardless of their parent material properties, while noting that these patterns reflect current conditions rather than the entire process of soil formation.

2. Study area, materials and methods

The research was conducted in the highest parts of the Gorce Mountains in southern Poland (Fig. 1a), focusing on three mountain summit domes of similar elevation, all exceeding 1150 m a.s.l.: Kiczora Mt. (Fig. 1b) in the western part of the study area, and Gorc Mt. and Mraźnica Mt. (Fig. 1c) in the eastern part. All study area is built of flysch deposits of varying textures, formed from the Late Cretaceous to the Early Miocene, and representing the Magura Nappe (Szczęch and Cieszkowski, 2021). The highest ridge parts of the Gorce Mountains are characterized by a mosaic of forests dominated by *Picea abies* or *Fagus sylvatica*, and meadows subject to forest succession (Medwecka-Kornaś and Kornaś, 1968; Buczek and Mulet, 2022; Fig. 1, Fig. 2). The climate of the studied areas is cool with the mean average air temperature (MAT) between 3°C and 5°C, and humid with MAAP between 1000 mm and 1230 mm (Obrębska-Starklowa, 1970; Wypych et al., 2018).

The influence of vegetation and climate on soil development in the study area during the Holocene can be inferred from palaeobotanical studies conducted at sites located on lower slopes and valley floors, as well as in the vicinity of the Gorce Mountains (Bucała et al., 2014; Buczek, 2019; Czerwiński et al., 2020; Kołaczek et al., 2021; Margielewski et al., 2022). During the Boreal phase (10.2–9.6 ka BP), spruce began to replace the pine–birch forests that had dominated since the beginning of the Holocene, forming a dense vegetation cover at higher elevations (Buczek, 2019; Kołaczek et al., 2021; Margielewski et al., 2022). Subsequently, between approximately 4.4 and 4.2 ka BP, fir, beech, and hornbeam expanded, restricting spruce forests to the highest mountain ranges (Czerwiński et al., 2020).

Human activity began to exert a pronounced influence on the environment of the study area at the turn of the 14th and 15th centuries with the arrival of the Vlachs. Their land-use practices involved extensive deforestation of mountain slopes and ridges, followed by the establishment of pastures and meadows characterized by high biodiversity (Bucała et al., 2014; Buczek et al., 2019). The greatest extent of deforestation occurred in the mid-19th century (Buczek and Mulet, 2022). Considering these factors, the present-day diversity of soil types in the study area reflects the combined long-term effects of a cool and humid climate persisting throughout the Holocene, vegetation dynamics dominated by coniferous forests, parent material characteristics, and historical land use.

The study sites were chosen after thorough field mapping, which included digging several soil pits and drilling boreholes, located in areas representing different landform types and evenly distributed across the study areas. Selected representative sites exhibiting variation in the lithology of parent materials, a range of land cover types that have persisted since at least the mid-19th century, and varied topography (Table 1) were then examined through interdisciplinary studies. The research included the monitoring of soil temperature and moisture (4 sites), conducting vegetation inventories (4 sites), and investigating soil profiles (6 sites). At forested sites with contrasting parent material (K1, K2, G1, and M1), soil temperature and moisture were measured using SM150T sensors (Delta-T Devices Ltd., United Kingdom). The sensors were installed in the topsoil mineral horizons at a depth of 0–5 cm. The field measurements at sites K1 and K2 spanned from November 18, 2019, to September 8, 2020, while those at sites G1 and M1 spanned from November 18, 2019, to October 17, 2021. The results of soil moisture measurements were calibrated for the specific soil material in which

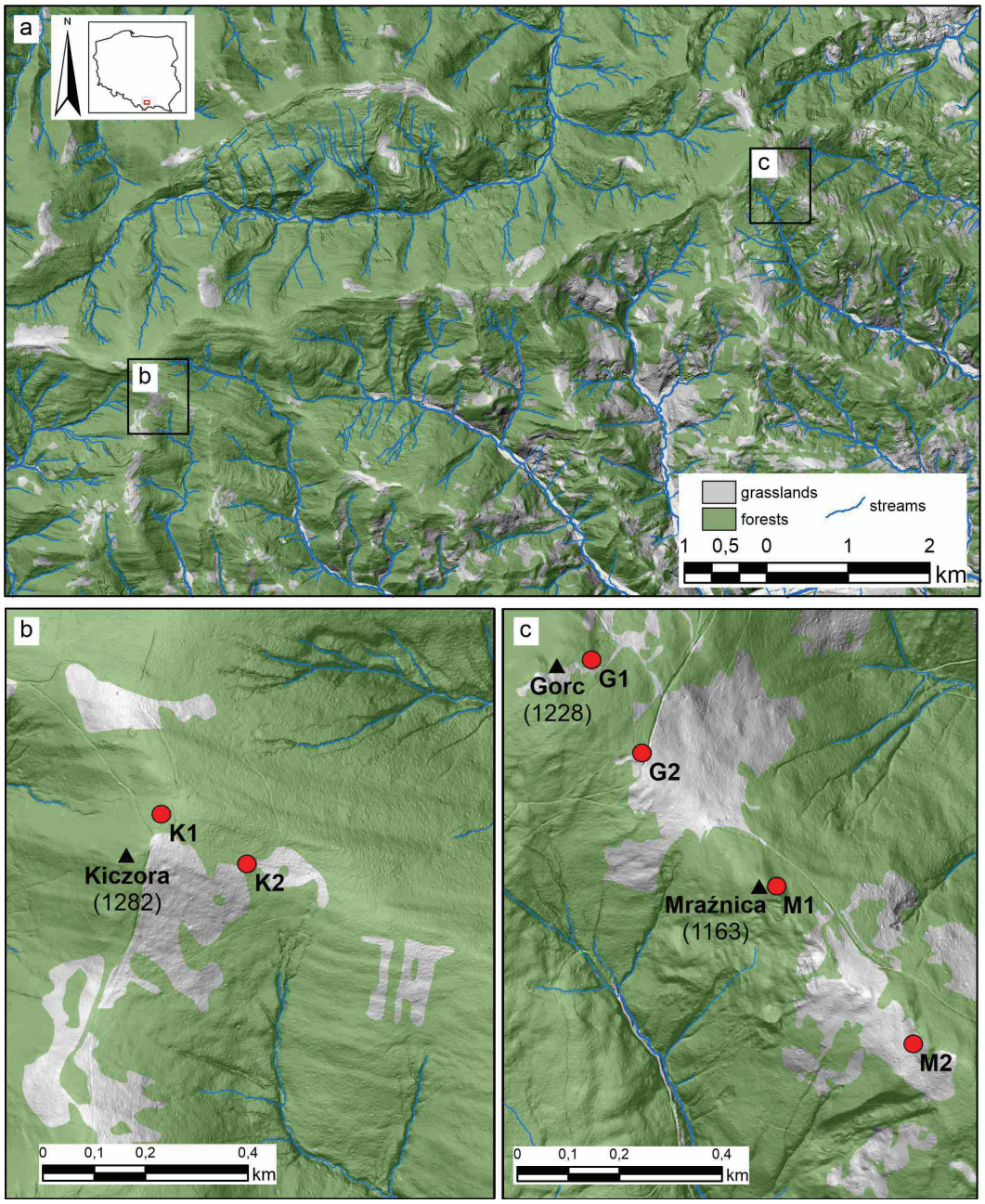

Fig. 1. Location of the study area: (a) the Gorce Mountains range; (b) the summit dome of Kiczora Mount with the locations of study sites; (c) the summit domes of Gorc and Mraźnica mounts with the locations of study sites

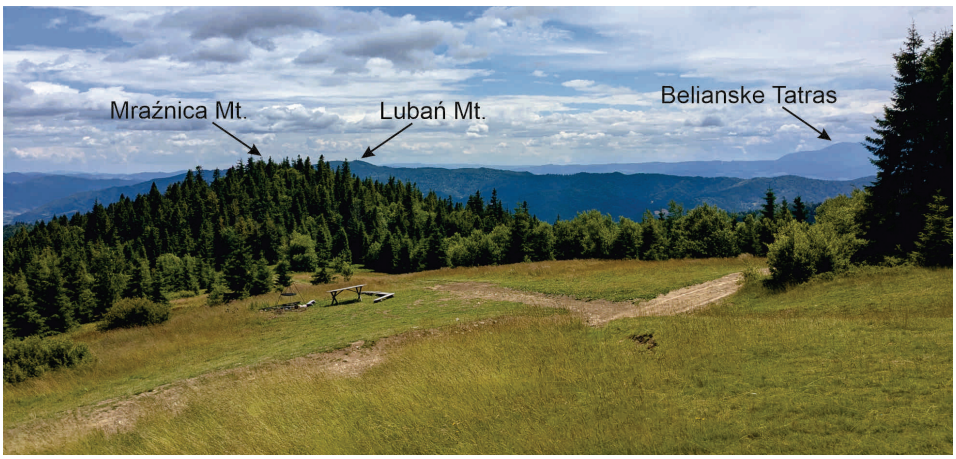

Fig. 2. Landscape of the Gorce Mountains ridge with a mosaic of meadows and forests

Table 1
Location and site characteristics

Site	Coordinates	Elevation [m a.s.l.]	Dominant lithology of parent material	Land cover type	Topography
K1	49°32'25" N; 20°09'01" E	1274	sandstones	forest	summit flat
K2	49°32'21" N; 20°09'10" E	1235	mudstones	forest	upper convex slope
G1	49°33'52" N; 20°15'12" E	1221	mudstones	forest	summit flat
G2	49°33'49" N; 20°15'21" E	1171	mudstones	grassland	upper convex slope
M1	49°33'40" N; 20°15'34" E	1163	sandstones	forest	summit ridge
M2	49°33'32" N; 20°15'47" E	1138	sandstones	grassland	upper linear slope

they were installed, based on formulas provided by the sensor manufacturer (Delta-T Devices Ltd., 2016).

At each site with sensors installed, a vegetation inventory was conducted to characterize the forest ecosystem. This included detailed descriptions of ecosystem features such as species composition across vegetation layers A–D, overall plant cover, and a phytosociological analysis. The vegetation inventory was carried out using the Braun-Blanquet method (Braun-Blanquet, 1932), which involved listing all plant species present within a 400 m^2 plot and assessing their abundance and coverage based on the Braun-Blanquet scale.

Soil characterization was carried out at all sites where soil temperature and moisture were monitored and vegetation inventories conducted. Additionally, two grassland sites with contrasting parent material lithologies were also investigated (Table 1). At the study sites K1 and K2 soil profiles were examined using borehole cores to a depth of ca. 0.5 m. At the remaining sites, soil profiles were studied in pits excavated down to the lower boundary of the B horizon, which ranged from 0.5 m to 0.8 m in depth. The profiles were described following the field guide for soil description included in the Polish Soil Classification (Systematyka gleb Polski, 2019). Soil samples were collected from all genetic horizons, air-dried, gently crushed using a wooden rolling pin, cleared of living roots, and passed through a 2 mm mesh sieve. The fine earth fraction (<2 mm) was subjected to several laboratory analyses. Particle-size distribution was determined using a combination of sieving and the hydrometer method (Gee and Bauder, 1986; Van Reeuwijk, 2002). Total carbon content was determined via dry combustion using a CNH elemental analyzer (vario MICRO cube, Elementar, Germany) and reported as soil organic carbon (SOC), as the absence of carbonates was confirmed by testing the soil material with a 10% HCl solution. Soil pH was measured in deionized water at a 1:2.5 soil-to-water ratio (Thomas, 1996). The soil chemical composition was determined by inductively coupled plasma emission spectrometry (ICP-ES) following digestion with lithium metaborate/tetraborate and dilute nitric acid, conducted at Bureau Veritas (Vancouver, BC, Canada). The total iron (Fe_t) content was calculated based on the oxide form (Fe_2O_3). Contents of pedogenic aluminum and iron forms (Al_{ox} and Fe_{ox}) were determined in ammonium oxalate extracts following a 4-hour extraction in the dark, centrifugation, and 0.45-µm filtration (Van Reeuwijk, 2002; Rennert and Lenhardt, 2022) using atomic absorption spectrometry (AAS; 240FS AA, Agilent Technologies). Base saturation (BS) was calculated as the ratio of base cations (BC: Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}), measured in ammonium acetate extract at pH 7 (Burt, 2004) using AAS, to the sum of base cations and exchangeable aluminum, according to the IUSS Working Group WRB (2022). Exchangeable Al was determined by titration of a 1M KCl extract (unbuffered) with 0.1M NaOH in the presence of 3.5% NaF. Based on the field descriptions and the results of laboratory analyses, the studied soils were classified according to the World Reference Base (IUSS Working Group WRB, 2022) and Polish Soil Classification (Systematyka gleb Polski, 2019; Kabała et al., 2019).

3. Results

3.1. Soil temperature and moisture

Soil temperatures were similar in all study sites (Fig. 3), with mean values during the study period ranging from 5.3°C at the K2 site to 5.9°C at the M1 site (Table 2, Fig. 3). Maximum temperatures, recorded in May, June, and August, ranged from 21.4°C to 24.3°C, while minimum temperatures occurred in November, January, and May, ranging from –4.4°C to 0.2°C. All sites exhibited prolonged periods of stable soil temperature between December and May, during which temperatures remained nearly constant and did not exceed 2°C. These stable periods can be attributed to the insulating effect of the snow cover, which reduces the influence of air temperature fluctuations on the soil surface. In contrast to soil temperature, soil moisture measurements showed clear topographic variation. Sites located on summit flats, whether on sandstones (K1) or mudstones (G1), exhibited much higher mean soil moisture levels of 61.3% and 67.8%, respectively. In comparison, sites on an upper concave mudstone slope (K2) and a sandstone summit ridge (M1) had substantially lower mean values of 44.0% and 35.1%, respectively. The highest soil moisture values, with maximums ranging from 60.4% to 99.7%, were recorded at all sites during two distinct periods: late April to early May, associated with snowmelt, and July to August, driven by intense summer rainfall. The lowest soil moisture values, with minimums ranging from 10.3% to 40.7%, occurred in September.

Table 2
Soil temperature and moisture characteristics on the investigated forest sites

Site	Soil temperature			Soil moisture		
	Minimum	Maximum	Mean	Minimum	Maximum	Mean
	°C			[%]		
K1	0.2	21.4	5.5	40.7	99.7	61.3
K2	–3.8	24.3	5.3	20.8	78.1	44.0
G1	-2.3	23.4	5.6	40.6	93.9	67.8
M1	–4.4	23.7	5.9	10.3	60.4	35.1

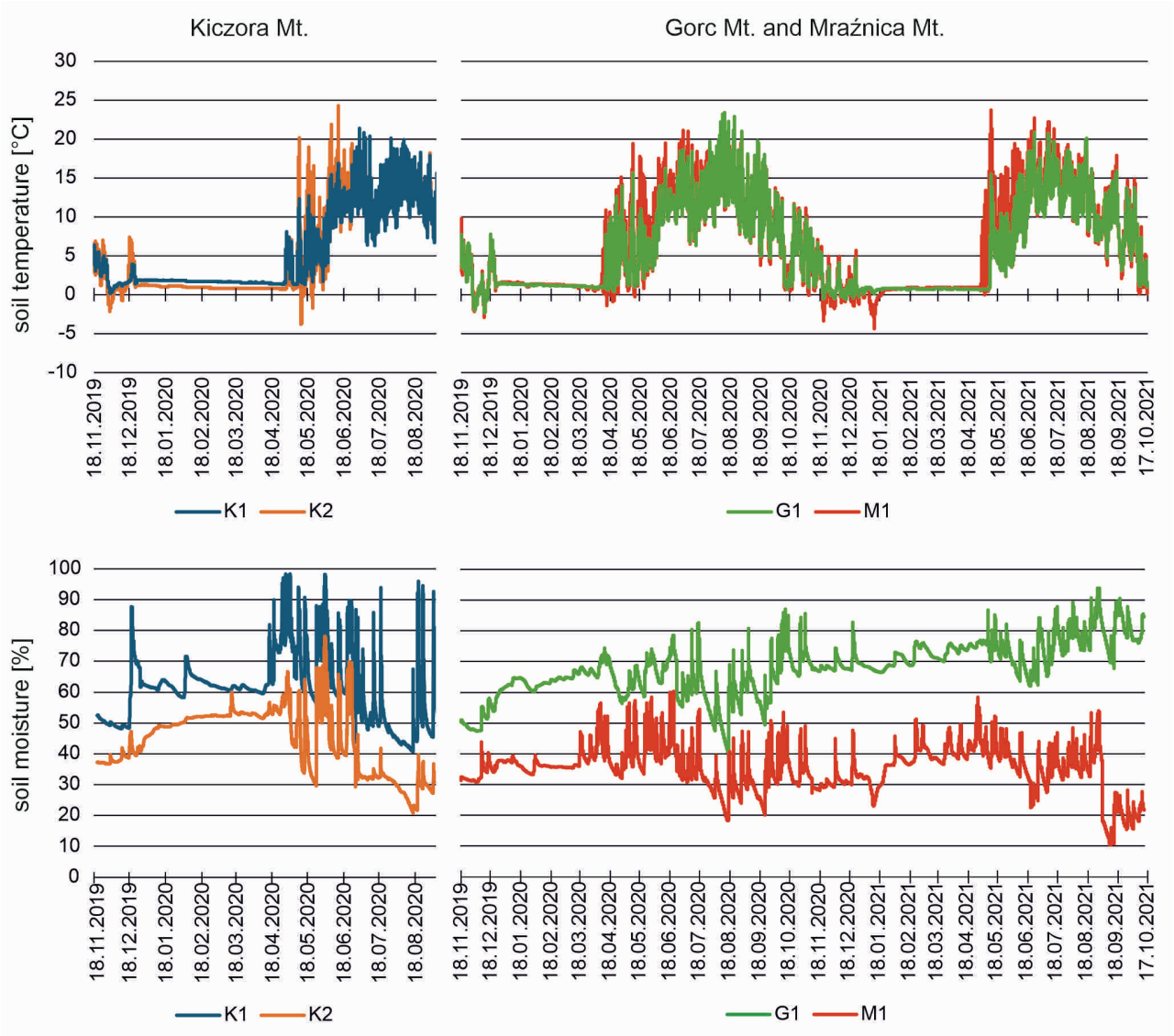

Fig. 3. Soil temperature and moisture values at the investigated sites

3.2. Vegetation

The studied forest sites showed a uniform tree species composition across the investigated sites (Table 3), with *Picea abies* dominating all sites and being the only tree species present at sites K1 and K2. At sites G1 and M1, *Fagus sylvatica* and *Abies alba* were also present, with beech accounting for 10% and 5%, and fir for 5% and 20% of the tree composition, respectively (Table 3). The forest undergrowth at all sites was dominated by *Vaccinium myrtillus* (Table 4). However, the diversity of other

Table 3
Forest canopy composition on the investigated forest sites

Tree species	K1	K2	G1	M1
	Coverage [%]			
Picea abies	100	100	85	75
Fagus sylvatica	0	0	10	5
Abies alba	0	0	5	20

undergrowth plant species appeared to be related to the lithology of the soil parent materials. This relationship was particularly evident in the pair of sites K1 and K2. At K1, only a few additional species were present, such as *Sphagnum*, *Vaccinium vitis-idaea*, and *Calamagrostis arundinacea*, whereas K2 supported a much richer assemblage of vascular plant species, including *Hieracium murorum*, *Hypericum perforatum*, *Epilobium montanum*, *Cruciata glabra*, *Chaerophyllum hirsutum* and among mosses *Plagiomnium cyuspidatum* (Table 4). In the other

Table 4
Forest undergrowth composition and values of biodiversity indices on the investigated forest sites

Plant species	K1	K2	G1	M1
	Degree of coverage on Braun-Blanquet scale			
Betonica officinalis	–	r	–	–
Calamagrostis arundinacea	1	+	–	3
Campanula persicifolia	–	+	–	–
Carex pilulifera	–	+	–	–
Chaerophyllum hirsutum	–	r	–	–
Chamaenerion angustifolium	r	–	–	–
Cruciata glabra	–	r	–	–
Deschampsia flexuosa	+	–	–	–
Dicranum polysetum	+	–	–	–
Dryopteris carthusiana	+	+	+	+
Dryopteris dilatata	+	–	+	+
Eriophorum vaginatum	r	–	–	–
Epilobium montanum	–	r	–	–
Hieracium lachenalii	–	+	–	–
Hieracium murorum	–	1	–	–
Hieracium umbellatum	–	r	–	–
Hypericum perforatum	–	1	–	–
Hypnum cupressiforme	–	+	–	+
Luzula luzuloides	–	+	–	–
Mnium sp.	–	+	–	–
Oxalis acetosella	–	–	2	1
Phyteuma spicatum	–	r	–	–
Picea abies	–	–	–	+
Pimpinella saxifraga	–	+	–	–
Plagiomnium cuspidatum	–	1	–	–
Pleurozium schreberi	–	+	–	–
Polytrichum commune	+	–	–	–
Polytrichum formosum	–	–	+	–
Potentilla anserina	–	+	–	–
Rhytidiadelphus sp.	–	–	+	1
Rubus hirtus	–	–	2	2
Rubus idaeus	+	–	+	1
Rumex acetosa	–	+	–	–
Salix caprea	–	–	r	–
Sambucus racemosa	–	–	+	–
Sorbus aucuparia	–	–	+	–
Sphagnum sp.	3	–	–	–
Vaccinium myrtillus	5	4	4	2
Vaccinium vitis-idaea	2	–	–	–

site pair (G1 and M1), this relationship was less pronounced (Table 4). At M1, *Calamagrostis arundinacea* indicated sandstone-dominated soil parent material, while *Oxalis acetosella* and *Sambucus racemosa* suggested a more fine-grained parent material.

3.3. Soils

The a studied soils showed high variability in the thickness and morphology of organic (O) horizons (Table 5, Fig. 4). The greatest thickness, reaching up to 11 cm, and the most complex tripartite differentiation of the O horizon into a mor-type

Table 5
Physical and chemical properties of the investigated soils

Symbol	Depth [cm]	CF[a] [% vol.]	Particle size distribution [%]			SOC[b] [%]	pH [H_2O]	BS[c] [%]	Fe_t[d] [g kg^{-1}]	$Al_{ox}+1/2Fe_{ox}$ [%]
			2–0.05 mm	0.05–0.002 mm	<0.002 mm					
Profile K1: Albic Podzol (WRB 2022), podzol (PSC 2019)										
Ol	10–6	0	n.d.	n.d.	n.d.	33.8	5.0		n.d.	n.d.
Of	6–2	0				36.8	3.6	n.d.		
Oh	2–0	0				30.0	3.4			
Ah	0–2	0	68	26	6	11.7	3.9		7.1	0.16
Es	2–8	5	66	23	11	1.5	3.2	7	7.6	0.12
Bhs	8–12	10	67	25	8	3.9	3.7	3	19.0	0.79
Bs1	12–17	20	65	24	11	2.0	4.0	2	25.1	0.98
Bs2	17–28	20	67	22	11	1.6	4.4	2	19.6	0.79
BC	28–(50)	30	65	24	11	1.4	4.6	4	18.4	0.79
Profile K2: Eutric Cambisol (WRB 2022), ordinary brown soil (PSC 2019)										
Olf	3–0	0	n.d.	n.d.	n.d.	38.3	4.9	n.d.	n.d.	n.d.
Ah(g)	0–9	0	37	45	18	8.4	3.4	6	34.2	0.60
Bwg	9–22	10	29	54	17	2.4	4.2	40	34.2	0.78
BC	22–(50)	40	23	54	23	1.6	4.8	93	35.5	0.65
Profile G1: Dystric Cambisol (WRB 2022), ordinary brown soil (PSC 2019)										
Olf	5–2	0	n.d.	n.d.	n.d.	45.3	4.8	n.d.	n.d.	n.d.
Oh	2–0	0				25.0	3.8			
Ah(g)	0–6	0	17	61	22	5.0	4.0	3	39.4	0.87
BAg	6–25	0	11	64	25	1.9	4.6	4	40.4	0.87
Bw1	25–45	5	11	60	29	1.9	4.7	5	42.7	0.74
Bw2	45–65	5	10	64	26	2.0	4.8	6	42.5	0.81
BC	65–(80)	60	17	59	24	1.0	5.0	9	38.7	0.61
Profile G2: Endoeutric Cambisol (WRB 2022), ordinary brown soil (PSC 2019)										
Ol	3–1	0	n.d.	n.d.	n.d.	39.7	5.1	n.d.	n.d.	n.d.
Ofh	1–0	0				31.9	4.8			
Ah(g)	0–3	0	41	52	7	8.2	4.3	7	36.1	0.72
ABg	3–10	0	36	55	9	4.7	4.4	4	36.4	0.83
Bw1	10–28	20	22	63	15	2.7	4.8	5	36.6	0.74
Bw2	28–50	60	31	51	18	1.7	5.4	31	39.1	0.63
BC	50–(70)	75	21	59	20	0.8	5.9	70	45.1	0.40

Table 5 – continue

Symbol	Depth [cm]	CF[a] [% vol.]	Particle size distribution [%]			SOC[b] [%]	pH [H_2O]	BS[c] [%]	Fe_t[d] [g kg^{-1}]	Al_{ox}+1/2Fe_{ox} [%]
			2–0.05 mm	0.05–0.002 mm	<0.002 mm					
Profile M1: Skeletic Albic Podzol (WRB 2022), debris podzolic soil (PSC 2019)										
Ol	11–8	0	n.d.	n.d.	n.d.	50.2	5.1	n.d.	n.d.	n.d.
Of	8–5	0				42.6	3.7			
Oh	5–0	0				36.4	3.5			
Ah	0–5	60	51	46	3	14.0	3.4	4	12.0	0.41
AE	5–20	60	58	40	2	7.0	3.7	2	10.6	0.42
Es	20–40	40	52	41	7	4.3	4.1	2	13.4	0.55
Bhs	40–55	50	49	43	8	3.3	4.5	4	26.5	1.41
Bs	55–(70)	75	52	40	8	2.1	4.7	4	21.0	1.02
Profile M2: Protospodic Cambisol (WRB 2022), podzolic brown soil (PSC 2019)										
Olf	3–2	0	n.d.	n.d.	n.d.	34.4	4.1	n.d.	n.d.	n.d.
Oh	2–0	0				23.4	3.8			
Ah	0–5	0	49	47	4	6.7	4.0	4	14.6	0.47
Bhs	5–20	30	51	47	2	3.9	4.3	3	19.3	0.82
Bsw	20–35	50	50	42	8	3.4	4.6	3	17.9	0.91
BC	35–(50)	75	50	42	8	2.2	4.7	4	18.4	0.83

[a] CF – coarse fragments; [b] SOC – soil organic carbon; [c] BS – base saturation; [d] Fe_t – total content of iron

sequence (Ol–Of–Oh) were observed in forest sites underlain by sandstone (K1 and M1). Forest sites with mudstone-derived soils (K2 and G1) were characterized by thinner O horizons, reaching up to 5 cm, usually consisting of a single Ofh layer or a simplified Olf–Oh sequence. Grassland sites were characterized by even thinner O horizons, reaching up to 3 cm, typically exhibiting Ol or Olf features, and at site M2, also an Oh horizon (Table 5, Fig. 4). The content and distribution of coarse fragments within the soil profiles were closely related to the dominant parent material (Table 5). In sandstone-derived soils (K1, M1, M2), the proportion of coarse fragments ranged from 5% to 75%, increasing sharply already from the surface mineral horizons and reaching peak volume share in the BC horizons. In contrast, soils developed from mudstones (K2, G1, G2) contained substantially lower amounts of coarse fragments, especially in the upper parts of the profiles. The texture of soils developed from sandstone was predominantly classified as sandy loam to loam, with sand content ranging from 49% to 68%, silt from 22% to 47%, and clay from 2% to 11%. In contrast, mudstone-derived soils exhibited textures ranging from loam and silt loam to clay loam, with sand content between 10% and 41%, silt between 45% and 64%, and clay between 7% and 29% (Table 5). The chemical composition of soils was dominated by SiO_2, with contents of 82.5–90.6% in sandstone-derived soils and 70.0–75.9% in mudstone-derived soils. Al_2O_3 and Fe_2O_3 were the other major components, present at 5.4–9.4% and 1.0–3.8% in sandstone-derived soils, and at 13.1–15.8% and 4.9–6.4% in mudstone-derived soils, respectively. Among the alkaline components, K_2O had the highest share, ranging from 1.1–1.6% in sandstone-derived soils and 2.2–2.9% in mudstone-derived soils. A pronounced contrast between the two soil groups was also observed for MgO, with its content being only 0.3–0.7% in soils developed from sandstones, but markedly higher, at 1.4–2.0%, in mudstone-derived soils. SOC content in the investigated soils ranged from 23.4% to 45.3% in O horizons and from 0.8% to 14.0% in mineral horizons. The profile distribution of SOC showed a sharp decline with depth; however, at sites M1 and M2, SOC contents remained above 2% even in the lowermost horizons. Soil pH was similar in soils developed from sandstones and mudstones, ranging from pH 3.2 to 5.1 and pH 3.4 to 5.9, respectively. In contrast, BS values varied considerably among the investigated soils. The lowest BS values, ranging from 2% to 9%, were recorded in soils at sites K1, G1, M1, and M2, while significantly higher values, ranging from 4% up to 93%, were observed at sites K2 and G2 (Table 5). The Fe_t content in the investigated soils ranged from 7.1 g kg^{-1} to 26.5 g kg^{-1} in sandstone-derived soils and from 34.3 g kg^{-1} to 45.1 g kg^{-1} in those developed from mudstones. The profile distribution of Fe_t generally showed a gradual increase with depth, in soils at sites K1 and M1, reaching peak contents in the Bs or Bhs (Table 5). Furthermore, the profile distribution of Al_{ox} and Fe_{ox} clearly indicated the development of spodic horizons

Fig. 4. Morphology of investigated soil profiles

(Bhs and Bs) in soils at sites K1 and M1, supporting their classification as Podzols (podzolic soils according to Polish Soil Classification). The soil developed from sandstone under grassland vegetation at site M2 met the criteria for a protospodic horizon. In contrast, soils at the other sites (K2, G1, G2) were classified as Cambisols, although slight reducing conditions were observed in their topsoil mineral horizons (Table 5).

4. Discussion

In mountain regions, the variability of climatic conditions, reflected in increased precipitation and lower temperatures with increasing elevation, significantly influences the processes shaping soil property diversity (Álvarez Arteaga, 2008; Bojko and Kabała, 2016). Among the most important aspects affected by these conditions are the content and composition of SOM (Drewnik, 2006; Prescott et al., 2010), which strongly depends on the rates of dead biomass decomposition and directly influences soil pH (Bojko and Kabała, 2016). In turn, soil pH plays a crucial role in regulating nutrient availability and overall soil fertility, contributing, on a par with climatic conditions, to the natural altitudinal zonation of plant communities in mountainous regions (Mangral et al., 2023). This vegetation zonation, in turn, influences the quantity and composition of biomass input to the soil, thereby causing a dynamic interplay between climate, vegetation, SOM, and soil chemical properties. This bioclimatic factor strongly affects soil properties and may trigger shifts in pedogenic domains (Bockheim et al., 2000, Bojko and Kabała, 2016; Musielok et al., 2024).

In the studied environmental conditions, marked by a clear excess of precipitation over evapotranspiration throughout the year and the accumulation of slowly decomposing dead biomass that promotes acidic soil reaction and intensive chemical weathering in the upper soil layers, there might be a strong tendency toward podzolization (Schaetzl and Rothstein, 2016; Lundström et al., 2000).

The results of this study revealed minor variations in soil temperature patterns and values during the monitoring period, but pronounced topography-dependent differences in soil moisture across the study sites (Fig. 2, Table 2). Observed variations in soil moisture, a factor that potentially triggers or contributes to the intensification of podzolization (Schaetzl et al., 2015, Musielok et al., 2022), were not reflected in the differentiation of soil types across the investigated sites.

Given the short duration of soil temperature and moisture monitoring, no firm conclusions can be drawn regarding the influence of climate over the entire period of soil formation. Nevertheless, considering the persistence of the main controlling factors (the humid climate and the presence of coniferous forest vegetation), the hypothesis that Podzols occur at cooler and wetter sites regardless of parent material properties was not supported by data from the analyzed sites. Furthermore, differences in the undergrowth vegetation did not consistently follow soil moisture patterns and appeared to be more strongly dependent on the type of soil parent material. Soil properties, typically shaped by bioclimatic factors, such as soil SOC content and pH in the O and upper mineral horizons, were consistent across all sites (Table 5). The only noticeable variation was in humus form (mor vs. moder), although this characteristic also may be dependent on the properties of the parent material (Labaz et al., 2014).

In contrast, the mineral soil horizons below the Ah showed distinct variations in their properties, shaped by different soil-forming processes that depended on the dominant lithology of the parent material (sandstone vs mudstone). Soils with higher content of clay, Fe_t, BS, and lower share of SiO_2 exhibited typical features of flysch-derived Cambisols (ordinary brown soils in Polish Soil Classification) with thick, well-developed Bw horizons, while coarser-textured soils with very high share of SiO_2, lower Fe_t content and a smaller proportion of alkaline cations in the soil sorption complex displayed clear morphology and profile differentiation characteristic of Podzols (Fig. 3, Tables 5 and 6).

Furthermore, soils developed from the same parent material but occurring under different land cover types, such as forests and grasslands, exhibited numerous similarities in properties inherited from the parent material and were unaffected by land cover (Fig. 3, Tables 5 and 6).

For instance, soil texture and chemical composition, were properties directly related to the variation of flysch parent material. These two properties are also considered the primary factors conditioning Podzols' development (Spinola et al., 2022). The results, which demonstrated variability in soil texture and Fe_t content along the transition from Podzols to non-podzolic soils, were consistent with the findings of Miechówka et al. (2015) from the western and central parts of the Gorce Mts., Gruba (2001) from the westernmost parts of the Beskidy Mts., as well as Musielok et al. (2021; 2022) and Musielok (2022) from the Bieszczady Mts., the Beskid Mały Mts., the Police Range, and the Carpathian Foothills.

Although our findings clearly indicated that the development of Podzols in the studied area, and likely also in much of the Carpathians, where flysch deposits constitute the parent material of soils, depends on the presence of carbonate-free, coarse-textured substrates with low Fe_t content, this does not contradict the earlier conclusions of Miechówka et al. (2015) and Ciarkowska and Miechówka (2017) regarding the role of undergrowth vegetation in influencing the intensity of podzolization in upper montane and subalpine coniferous forests. However, based on the results of this interdisciplinary study, we would like to emphasize that the inherent variability in the properties of the flysch parent material should be considered as the primary factor conditioning the occurrence of Podzols in the region. The bioclimatic factor undoubtedly plays a key role in maintaining podzolization and, in the long term, certainly contributed to its initiation (Bucała et al., 2014; Buczek, 2019; Czerwiński et al., 2020; Kołaczek et al., 2021; Margielewski et al., 2022). Nevertheless, its influence does not overcome the limitation to this process posed by finer-textured and more nutrient-rich parent materials, as suggested by Adamczyk (1966) and Adamczyk and Komornicki (1970).

Another aspect crucial for understanding the occurrence of Podzols in the uppermost parts of the Gorce Mts. is the presence of a surface layer with reducing conditions, most likely caused by water stagnation in fine-grained, silt-dominated materials. Rozpędowska and Skiba (2006) identified similar horizons with reducing conditions in flysch-derived soils of the Babia Góra Massif and the Bieszczady Mts. under planted spruce monocultures and clearly distinguished them from the morphological features associated with the podzolization process. However, in earlier studies where soil classification was based primarily on morphological features, these layers horizons may have been misidentified due to the similar colour of the E horizons in Podzols and slightly reduced ABg or BAg horizons in Cambisols (Figure 4). Such a situation was observed in many locations in the highest part of the eastern Gorce Mountains, where Adamczyk and Komornicki (1970) distinguished a bioclimatic class of Podzols. Meanwhile, detailed soil mapping conducted during the reconnaissance stage of this study revealed the presence of fine-grained Cambisols with stagnogleic features in the topsoil mineral horizons and no clear evidence of metal or SOM translocation down the soil profiles. Thus, the bioclimatic pathway of Podzols development in flysch-derived materials can be questioned, particularly as it may lead to wrong habitat assessment.

5. Conclusions

In this study, we demonstrate that while a humid and cool climate combined with the dominance of coniferous vegetation is a necessary condition for the initiation and maintenance of the podzolization process in soils developed from flysch, the

Table 6
Chemical composition of the investigated soils

Symbol	Depth [cm]	SiO_2 [%]	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O
Profile K1: Albic Podzol (WRB 2022), podzol (PSC 2019)								
Ah	0–2	90.0	5.8	1.0	0.3	0.1	0.7	1.1
Es	2–8	90.6	5.4	1.1	0.3	0.0	0.6	1.2
Bhs	8–12	84.6	8.6	2.7	0.6	0.0	1.1	1.6
Bs1	12–17	83.8	8.4	3.6	0.7	0.1	1.2	1.6
Bs2	17–28	84.3	8.7	2.8	0.6	0.1	1.3	1.5
BC	28–(50)	84.5	8.7	2.6	0.6	0.1	1.3	1.6
Profile K2: Eutric Cambisol (WRB 2022), ordinary brown soil (PSC 2019)								
Ah(g)	0–9	75.9	13.1	4.9	1.4	0.1	1.1	2.2
Bwg	9–22	75.0	13.5	4.9	1.5	0.2	1.1	2.4
BC	22–(50)	74.2	13.7	5.1	1.6	0.3	1.1	2.6
Profile G1: Dystric Cambisol (WRB 2022), ordinary brown soil (PSC 2019)								
Ah(g)	0–6	73.3	14.2	5.6	1.5	0,2	1.4	2.5
BAg	6–25	72.5	14.4	5.8	1.6	0,2	1.4	2.7
Bw1	25–45	72.0	14.6	6.1	1.7	0,2	1.4	2.8
Bw2	45–65	71.0	15.4	6.1	1.8	0,2	1.3	2.9
BC	65–(80)	74.7	13.1	5.5	1.5	0,2	1.4	2.4
Profile G2: Endoeutric Cambisol (WRB 2022), ordinary brown soil (PSC 2019)								
Ah(g)	0–3	74.2	13.8	5.2	1.4	0,3	1.2	2.4
ABg	3–10	73.6	14.3	5.2	1.5	0,2	1.3	2.5
Bw1	10–28	73.6	14.2	5.2	1.6	0,1	1.2	2.6
Bw2	28–50	72.5	14.7	5.6	1.8	0,2	1.2	2.7
BC	50–(70)	70.0	15.8	6.4	2.0	0,3	1.2	2.9
Profile M1: Skeletic Albic Podzol (WRB 2022), debris podzolic soil (PSC 2019)								
Ah	0–5	86.2	8.0	1.7	0.4	0,2	1.2	1.1
AE	5–20	87.2	7.4	1.5	0.4	0,1	1.2	1.2
Es	20–40	86.8	7.4	1.9	0.3	0,1	1.2	1.3
Bhs	40–55	82.5	9.4	3.8	0.5	0,2	1.4	1.3
Bs	55–(70)	86.2	8.0	1.7	0.4	0,2	1.2	1.1
Profile M2: Protospodic Cambisol (WRB 2022), podzolic brown soil (PSC 2019)								
Ah	0–5	86.3	7.6	2.1	0.4	0,2	1.2	1.2
Bhs	5–20	85.5	7.8	2.8	0.5	0,2	1.2	1.2
Bsw	20–35	85.5	8.0	2.6	0.5	0,1	1.3	1.2
BC	35–(50)	84.3	8.8	2.6	0.6	0,2	1.4	1.3

properties of the parent material are primary conditions that control the spatial occurrence of Podzols in the Gorce Mountains. Previous concepts suggesting that bioclimatic factor alone can lead to crossing the threshold of Podzols development in fine-grained parent materials were not supported by our results. Podzols occur exclusively in areas underlain by a thicker, sandstone-dominated parent material, whereas adjacent mudstones, reflecting the tectonic and lithological structure of the flysch, form parent materials from which Cambisols develop. This pattern is observed regardless of uniform thermal conditions and moisture regimes, which, although locally dependent on topography, do not diminish the decisive role of parent material in soil type differentiation.

Acknowledgments

The research was financed by the National Science Centre, Poland (grant No. 2016/23/N/ST10/01383) and has been supported by grants from the Priority Research Area Anthropocene and the Faculty of Geography and Geology under the Strategic Programme Excellence Initiative at Jagiellonian University. We acknowledge the Gorce National Park for the permission to investigate sites at the Kiczora Mt (No 503–27/2019 and 503–6/25). The authors are also grateful to the anonymous reviewers for their insightful comments, which significantly improved the scientific quality of the paper.

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

Łukasz Musielok – Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft. **Anna Rudnik** – Data curation, Investigation, Methodology, Writing – original draft. **Krzysztof Buczek** – Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing – original draft. **Jarosław Lasota** – Conceptualization, Data curation, Investigation, Methodology, Validation, Writing – review and editing. **Patrycja Tomala** – Data curation, Investigation, Validation, Visualization., **Agnieszka Kafel** – Data curation, Investigation. **Katarzyna Wątor** – Investigation, Methodology.

All authors read and approved the final manuscript.

References

Adamczyk, B., 1966. Studies on relations between rock parent material and soil. Part II. Forests soils developed from flysch materials of the Magura Nappe in Gorce Mts. Acta Agraria et Silvestria 6, 4–48. (in Polish)

Adamczyk, B., 1983. Characteristics of the soils of Babia Góra National Park. [In:] Zabierowski, K., (Ed.), Babia Góra National Park, Nature and Man. Studia Naturae B 29, Warszawa-Kraków, Zakład Ochrony Przyrody i Zasobów Naturalnych PAN, 95–120.

Adamczyk, B., Komornicki, T., 1970. The soils of the valleys of characterization of the Jaszcze and Jamne streams. Studia Naturae, Seria A 3, 102–153. (in Polish with English summary)

Alexander, E.B., Ping, C.L., Krosse, P., 1994. Podzolisation in ultramafic materials in southeast Alaska. Soil Science 157, 46–52.

Álvarez Arteaga, G., García Calderón, N.E., Krasilnikov, P.V., Sedov, S.N., Targulian, V.O., Velázquez, R.N., 2008. Soil altitudinal sequence on base-poor parent material in a 653 montane cloud forest in Sierra Juárez, Southern Mexico. Geoderma 144, 593–612. https://doi.org/10.1016/j.geoderma.2008.01.025

Balon, J., Jodłowski, M., 2014. Physicogeographical regionalization of the Western Carpathians – a methodological study. [In:] Ziaja, W., Jodłowski, M. (Eds.), The structure of the natural environment and the physiognomy of the landscape, Kraków, Institute of Geography and Spatial Management, Jagiellonian University, 85–106.

Bockheim, J.G., Munroe, J.S., Douglass, D., Koerner, D., 2000. Soil development along an elevational gradient in the southeastern Uinta Mountains, Utah, USA. Catena 39, 169–185. https://doi.org/10.1016/S0341-8162(99)00091-0.

Bojko, O., Kabała, C., 2016. Transformation of physicochemical soil properties along a mountain slope due to land management and climate changes – A case study from the Karkonosze Mountains, SW Poland. Catena 140, 43–54. https://doi.org/10.1016/j.catena.2016.01.015.

Braun-Blanquet, J., 1932. Plant sociology (Transl. Fuller GD and Conrad HS). McGraw-Hill, New York.

Bucała, A., Margielewski, W., Starkel, L., Buczek, K., Zernitskaya, V., 2014. The reflection of human activity in the sediments of Iwankowskie Lake from subatlantic phase (Polish Outer Carpathians). Geochronometria 41 (4), 377–391.

Buczek, K., 2019. Dating landslides in the Gorce Mts. (Polish Outer Carpathians) – preliminary results. Geological Quaterly 63 (4), 849–860. http://doi.org/10.7306/gq.1501

Buczek K., Mulet, W., 2022. Mountain pastures and glades. A heritage under threat. Gmina Ochotnica Dolna. (in Polish)

Burt, R., 2004. Soil Survey Laboratory Methods Manual. Soil Survey Investigations Report No. 42. Lincoln, NE, USA: USDA-NRCS.

Buurman, P., Van der Plas, L., Slager, S., 1976. A toposequence of alpine soils on calcareous michaschists, Northern Andula region, Switzerland. Journal of Soil Science 27, 395–410.

Ciarkowska, K., Miechówka, A., 2017. The role of bilberry and Alpine lady-fern in soil formation within the Carpathian subalpine spruce forest stands. Geoderma 305, 162–172. https://doi.org/10.1016/j.geoderma.2017.06.004

Czerwiński, S., Margielewski, W., Gałka, M., Kołaczek, P., 2020. Late Holocene transformations of lower montane forest in the Beskid Wyspowy Mountains (Western Carpathians, Central Europe): a case study from Mount Mogielica. Palynology 44 (2), 355–368. https://doi.org/10.1080/01916122.2019.1617207

D'Amico, M., Jilitta, F., Previtali, F., Cantelli, D., 2008. Podzolization over ophiolitic materials in the western Alps (Natural Park of Mont Avic, Aosta Valley, Italy). Geoderma 146, 129–137. https://doi.org/10.1016/j.geoderma.2008.05.025.

Drewnik, M., 2006. The effect of environmental conditions on the decomposition rate of cellulose in mountain soils. Geoderma 132, 116–130. https://doi.org/10.1016/j.geoderma.2005.04.023.

Gee, G.W., Bauder, J.W., 1986. Particle-Size Analysis. [In:] Klute, A. (Ed.), Methods of Soil Analysis. Part 1, Physical and Mineralogical Methods. ASA-SSSA, Madison, Wisconsin, pp. 427–445.

Gruba, P., 2001. The distribution of iron-humic complexes in brown soils formed of sandstones in Beskidy Mountains (southern Poland). Roczniki Gleboznawcze – Soil Science Annual 52, Suppl. 153–157. (in Polish)

IUSS Working Group WRB, 2022. World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps. 4th edition. International Union of Soil Sciences (IUSS), Vienna, Austria.

Jankowski, M., 2010. Some aspects of site conditions of heathlands in the Toruń Basin. Ecological Questions 12, 145–151. https://doi.org/10.12775/v10090-010-0008-x.

Jankowski, L., Margielewski, W., 2021. Geological control of young orogenic mountain morphology: From geomorphological analysis to reinterpretation of geology of the Outer Western Carpathians. Geomorphology 386, 107749. https://doi.org/10.1016/j.geomorph.2021.107749.

Kabała, C., et al., 2019. Polish Soil Classification, 6th edition – principles, classification scheme and correlations. Soil Science Annual 70(2), 71–97, https://doi.org/10.2478/ssa-2019-0009

Kacprzak, A., 2003. Slope covers as the soil parent material in the Western Bieszczady Mountains. Roczniki Gleboznawcze – Soil Science Annual 54(3), 97–110. (in Polish)

Kacprzak, A., Skiba, M., 2000. Soil texture and mineral composition as indicators of parent material genesis in the catena of Mała Rawka (the Western Bieszczady Mts.). Roczniki Bieszczadzkie 9, 169–181. (in Polish)

Kacprzak, A., Szymański, W., Wójcik-Tabol, P., 2015. The role of flysch sandstones in forming the properties of cover deposits and soils – examples from the Carpathians. Zeitschrift für Geomorphologie 59. Suppl. 1, 227–245. https://doi.org/10.1127/zfg_suppl/2015/S-00182.

Kołaczek, P., Buczek, K., Margielewski, W., Gałka, M., Rycerz, A., Woszczyk, M., Karpińska-Kołaczek, M., Marcisz, K., 2021. Development and degradation of a submontane forest in the Beskid Wyspowy Mountains (Polish Western Carpathians) during the Holocene. The Holocene 31(11/12), 1716–1732. https://doi.org/10.1177/09596836211033200

Kowalska, J.B., Zaleski, T., Józefowska, A., Mazurek, R., 2019. Soil formation on calcium carbonate-rich parent material in the outer Carpathian Mountains – A case study. Catena 174, 436–451. https://doi.org/10.1016/j.catena.2018.11.025

Lasota, J., 2004a. Soils of forest site types in Żywiec region. Part I. Forest sites at low elevations of the lower montane zone. Sylwan 2, 3–10. (in Polish with English abstract)

Lasota, J., 2004b. Soils of forest site types in Żywiec region. Part II. Forest sites at high elevations of the lower montane zone. Sylwan 3, 14–20. (in Polish with English abstract)

Labaz, B., Galka, B., Bogacz, A., Waroszewski, J., Kabala, C., 2014. Factors influencing humus forms and forest litter properties in the mid-mountains under temperate climate of southwestern Poland. Geoderma 230–231, 265–273. https://doi.org/10.1016/j.geoderma.2014.04.021

Lundström, U., et al., 2000. Lundström, U.S., van Breemen, N., Bain, D., 2000. The podzolization process. A review. Geoderma 94, 91–107. https://doi.org/10.1016/S0016-7061(99)00036-1.

Mangral, Z.A., Islam, S.U., Tariq, L., Kaur, S., Ahmad R., Malik, A.H., Goel, S., Baishya, R., Barik S.K., Dar T.U.H., 2023.Altitudinal gradient drives significant changes in soil physico-chemical and eco-physiological properties of *Rhododendron anthopogon*: a case study from Himalaya. Frontiers in Forests and Global Change 6. https://www.frontiersin.org/journals/forests-and-global-change/articles/10.3389/ffgc.2023.1181299

Margielewski, W., Michczyńska, D.J., Buczek, K., Michczyński, A., Korzeń, K., Obidowicz, A., 2022. Towards the understanding of the present-day human impact on peatland deposits formed since the late glacial: a "retrospective" age–depth model of the Grel raised bog (Polish Inner Carpathians). Radiocarbon 64(6), 1525–1543. https://doi.org/10.1017/RDC.2022.62

Medwecka-Kornaś, A., Kornaś, J., 1968. Plant communities in the Jaszcze and Jamne valleys. Studia Naturae, Seria A 2, 49–91. (in Polish with English summary)

Miechówka, A., Zadrożny, P., Kowalczyk, E., 2006. Podzol soils of different climatic and vegetation belts of the Babiogórski National Park. Polish Journal of Soil Science 39(1), 73–79.

Miechówka, A., Zaleski, T., Kowalczyk, E., 2015. Distribution of iron and aluminum forms as an indicator of present-day soil-forming processes in soil profiles under wooded spruce Plagiothecio-Piccetum tatricum in the Gorce Mts (southern Poland). Soil Sci. Ann. 60(3), 125–132. https://doi.org/10.1515/ssa-2015-0028.

Musielok, Ł., 2022. Occurrence of podzolization in soils developed from flysch regolith in the Wieliczka Foothills (Outer Western Carpathians, southern Poland). Soil Science Annual 73(1), 147507. https://doi.org/10.37501/soilsa/147507

Musielok, Ł., Drewnik, M., Szymański, W., Stolarczyk, M., Gus-Stolarczyk, M., Skiba, M., 2021. Conditions favoring local podzolization in soils developed from flysch regolith – A case study from the Bieszczady Mountains in southeastern Poland. Geoderma 381, 114667. https://doi.org/10.1016/j.geoderma.2020.114667

Musielok, Ł., Buczek, K., Karcz, T., 2022. Relief-induced feedback mechanisms controlling local podzolization occurrence on flysch slopes – Examples from Outer Western Carpathians (southern Poland). Catena 213, 106124. https://doi.org/10.1016/j.catena.2022.106124

Musielok, Ł., Vancampenhout, K., Muys, B., Gus-Stolarczyk, M., Grabska-Szwagrzyk, E., Stolarczyk, M., Bartos, A., Gołąb, A., Buczek, K., 2024. Dynamic linkages between human pressure and stability of soil organic matter in mid-latitude mountains – A perspective review. Geoderma Regional 39, e00859. https://doi.org/10.1016/j.geodrs.2024.e00859

Nicia, P., Miechówka, A., 2004. General characteristics of eutrophic fen soil. Polish Journal of Soil Science 37(1), 39–47.

Obrębska-Starklowa, B., 1970. The mesoclimate of the Jaszcze and Jamne drainage areas. Studia Naturae, Seria A 3, 7–100. (in Polish with English summary)

Obrębska-Starklowa, B., 2004. Climate of the Babia Góra Massif. [In:] Wołoszyn, B.W., Jaworski, A., Szwagrzyk, J. (Eds.), Babiogórski Park Narodowy—monografia przyrodnicza. Komitet Ochrony Przyrody PAN, Babiogórski Park Narodowy, 137–151. (in Polish with English summary)

Pepin, N.C., Arnone, E., Gobiet, A., Haslinger, K., Kotlarski, S., Notarnicola, C., Palazzi, E., Seibert, P., Serafin, S., Schöner, W., Terzago, S., Thornton, J.M., Vuille, M., Adler C., 2022. Climate Changes and Their Elevational Patterns in the Mountains of the World. Reviews of Geophysics 60, e2020RG000730. https://doi. org/10.1029/2020RG000730

Prescott, C.E., 2010. Litter decomposition: what controls it and how can we alter it to sequester more carbon in forest soils? Biogeochemistry 101, 133–149. https://doi.org/10.1007/s10533-010-9439-0

Protz, R., Ross, G.J., Martini, I.P., Terasmae, J., 1984. Rate of Podzolic soil formation near Hudson Bay. Ontario. Canadian Journal of Soil Science 64, 31–49. https://doi.org/10.4141/cjss84-004.

Rennert, T., Lenhardt, K.R., 2022. Does phase separation quantitatively affect Al, Fe, and Si extraction from soil using acid oxalate? Geoderma 412, 115728. https://doi.org/10.1016/j.geoderma.2022.115728.

Rozpędowska, E., Skiba, S., 2006. Influence of the habitat incompatible spruce vegetation on soils in the Carpathians. Roczniki Bieszczadzkie 14, 237–245. (in Polish with English abstract)

Schaetzl, R.J., 1991. A lithosequence of soils in extremely gravelly, dolomitic parent materials, Bois Blanc Island, Lake Huron. Geoderma 48, 305–320. https://doi.org/10.1016/0016-7061(91)90050-4.

Schaetzl, R.J., Luehmann, M.D., Rothstein, D., 2015. Pulses of podzolization: The importance of spring snowmelt, summer storms, and fall rains on Spodosol development. Soil Science Society of America Journal 79, 117–131. https://doi.org/10.2136/sssaj2014.06.0239

Schaetzl, R.J., Rothstein, D.E., 2016. Temporal variation in the strength of podzolization as indicated by lysimeter data. Geoderma 282, 26–36. https://doi.org/10.1016/j.geoderma.2016.07.005.

Skiba, S., 1995. Soil cover. [In:] Warszyńska, J. (Ed.) The Polish Carpathians – Environment, human, and their activity. Wydawnictwo Uniwersytetu Jagiellońskiego, Kraków, 69–76. (in Polish)

Skiba, S., Szymański, W., 2009. Soil cover of the alpine zone of the Eastern Carpathians on the example of Bieszczady Mts. (Poland) and Gorgany and Charnokhora Mountains (Ukraine). Visnik Odeskogo Nacionalnogo Uniwersitetu 14(7), 226–231.

Solon, J., et al., 2018. Physico-geographical mesoregions of Poland: verification and adjustment of boundaries on the basis of contemporary spatial data. Geographia Polonica 91(2), 143–170. https://doi.org/10.7163/GPol.0115

Spinola, D., Portes, R., Fedenko, J., Lybrand, R., Dere, A., Biles, F., Trainor, T., Bowden, M.E., D'Amore, D., 2022. Lithological controls on soil geochemistry and clay mineralogy across Spodosols in the coastal temperate rainforest of southeast Alaska. Geoderma 428, 116211. https://doi.org/10.1016/j.geoderma.2022.116211

Systematyka Gleb Polski, 2019. Polskie Towarzystwo Gleboznawcze, Komisja Genezy Klasyfikacji i Kartografii Gleb. Wydawnictwo Uniwersytetu Przyrodniczego we Wrocławiu, Polskie Towarzystwo Gleboznawcze, Wrocław–Warszawa.

Szczęch, M., Cieszkowski, M., 2021. Geology of the Magura Nappe, south-western Gorce Mountains (Outer Carpathians, Poland). Journal of Maps 17, 453–464. https://doi.org/10.1080/17445647.2021.1950579

Thomas, G.W., 1996. Soil pH and Soil Acidity. [In:] Sparks, D.L., et al. (Eds.), Methods of Soil Analysis. Part 3, Chemical Methods. SSSA and ASA, Madison, Wisconsin, 475–490.

Trifonov, V.G., Ivanova, T.P., Bachmanov, D.M., 2012. Recent mountain building of the central Alpine-Himalayan Belt. Geotectonics 46, 315–332. https://doi.org/10.1134/S0016852112050068

Van Reeuwijk, L.P., 2002. Procedures for Soil Analysis. International Soil Reference and Information Centre Technical Paper 9. Wageningen.

Wypych, A., Ustrnul, Z., Schmatz, D.R., 2018. Long-term variability of air temperature and precipitation conditions in the Polish Carpathians. Journal of Mountain Science 15, 237–253. https://doi.org 10.1007/s11629-017-4374-3

Czynniki bioklimatyczne i litogeniczne wpływające na występowanie gleb bielicowych na fliszu: nowe spostrzeżenia z Gorców

Słowa kluczowe

Gleby bielicowe
Flisz
Wilgotność gleby
Temperatura gleby
Czynniki glebotwórcze

Streszczenie

Gleby Karpat Zewnętrznych, w tym Gorców, rozwijają się ze zwietrzeliny fliszu lub pokryw stokowych pochodzenia fliszowego, które w przeważającej mierze tworzą gleby brunatne. Jednak w tych obszarach występują również lokalnie gleby bielicowe. Ich powstawanie przypisywano dotąd albo obecności gruboziarnistego materiału macierzystego na niższych wysokościach, albo czynnikom bioklimatycznym na wyższych wysokościach, które sprzyjają silnemu zakwaszeniu gleby i inicjują bielicowanie. Celem niniejszego badania było określenie, w jaki sposób właściwości gleb brunatnych i bielicowych odnoszą się do współczesnych warunków bioklimatycznych w najwyższych partiach Gorców. Wyniki kompleksowych badań, obejmujących pomiary temperatury i wilgotności gleby, badania roślinności i analizy właściwości gleby, wykazały, że chociaż ogólnie wilgotny i chłodny klimat jest niezbędnym warunkiem bielicowania, właściwości materiału macierzystego odgrywają decydującą rolę w występowaniu gleb bielicowych. Gleby bielicowe są konsekwentnie związane z gruboziarnistymi materiałami macierzystymi pochodzenia piaskowcowego, ubogimi we frakcję iłową i żelazo. Sąsiednie gleby rozwinięte na drobnoziarnistych mułowcach, mimo że wykazują słabe cechy odgórnego oglejenia, przypominajace efekty procesu eluwiacji w górnych poziomach, nie wykazują wyraźnych śladów procesów iluwiacyjnych, i posiadają właściwości, które wspierają funkcjonowanie znacznie bogatszych zespołów gatunków roślin naczyniowych w piętrze runa leśnego. Uzyskane wyniki podważają pogląd, że czynniki bioklimatyczne są głównym czynnikiem powodującym bielicowanie w górnoreglowej strefie Karpat fliszowych, i podkreślają kluczowe znaczenie zmienności litologicznej materiału macierzystego w rozwoju gleb na dużych wysokościach.