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Occurrence of podzolization in soils developed from flysch regolith in the Wieliczka Foothills (Outer Western Carpathians, southern Poland)

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Abstract

Podzolization process play a key role in the conditioning of forest habitats and the storage of organic carbon in soils. In the Carpathian Foothills development of Podzols is hampered either by the properties of the loess cover or the major part of the flysch parent material. However, soils subjected to podzolization occur sporadically in this area. The aim of this study was to determine the threshold of podzolization occurrence in the flysch parent material occurring locally in the Wieliczka Foothills and to determine the spatial variability of soils on a hillslope. The results showed that shift into podzolization is primarily related to the occurrence of sand-textured parent materials with low contents of clay and iron. Secondly, differences in organic matter decomposition rates may also affect podzolization. Soils in the investigated slope transect showed catenary increase of clay and pedogenic oxides contents. The formation of accumulative soils in the lower slope positions may be related with higher pH of the parent material that affects precipitation of soil constituents from laterally translocated solution. Furthermore, the effects of lateral soil solution flux limits the area where intensive vertical podzolization occur. Thus, considering lateral podzolization is crucial for correct determination of forest habitat conditions, estimation of soil organic carbon sequestration potential as well as in soil cartography.

1. Introduction

Podzolization process is considered as mobilization of Al, Fe and other products of minerals weathering by organic acids in a surface part of soil and its immobilization in a subsurface part (e.g. Lundström et al., 2000). From the ecological point of view soils subjected to podzolization play a significant role in: (1) conditioning forests habitats due to the depletion of nutrients in the root zone (e.g. Lasota, 2004a, 2004b), and (2) serving as a crucial organic carbon sink (Brock et al., 2020).

In the soil cover of the Carpathian Foothills podzolized soils occur very sporadically (Skiba and Drewnik, 2003). The majority of soils of this area is developed from carbonate-free loess sediments covering flysch deposits. The loess cover is a parent material for soils classified according to the WRB (IUSS Working Group WRB, 2015) as Luvisols and Retisols, and according to Polish Soil Classification (PSC) (Systematyka gleb Polski, 2019; Kabała et al., 2019) to clay-illuvial soils covering about 80% of the area (Uziak, 1962; Zasoński, 1981, 1983; Skiba, 1995; Szymański et al., 2011). The other soils are: (1) Cambisols either developed from loess colluvic material (PSC: brown soils or ordinary delluvial soils) or formed in a result of substantial erosion of lessivaged soils (PSC: brown soils or eroded clay-illuvial soils), (2) Fluvisols (PSC: alluvial soils) and (3) Gleysols (Skiba et al., 1998). Locally occur Calcaric Leptosols (PSC: rendzinas) (Zasoński and Skiba, 1988). Soil podzolization is restricted to the small areas where the regolith of sandstones or conglomerates layers that build some flysch deposits occur at the surface (usually associated with rock outcrops) and is not covered with loess materials (Adamczyk et al., 1989). Moreover, the regolith of more fine-grained flysch rocks, i.e. mudstones, claystones or shales, due to high concentrations of clay and iron also suppress development of Podzols (Gruba, 2001). Thus, there is a need for detailed studies on conditions that determine Podzol formation and the thresholds of its occurrence.

Podzolization is also one of the soil-forming processes showing very distinct differentiation of the effects at the landscape level (Sommer et al., 2000, 2001). Due to lateral soil solution fluxes at hillslopes podzolization may operate either in vertical and in lateral direction leading to formation of relatively depleted soils in upper slope positions and enriched

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ones at footslopes. This phenomenon was described in different mountainous and upland areas where environmental conditions favored podzolization of soils (Schlichting, 1963; Glazovskaya, 1968; Karavayeva, 1968; Lucas and Chauvel, 1992; Sommer et al., 1997, 2000, 2001; Jankowski, 2001, 2014; Bourgault et al., 2015, 2017; Waroszewski et al., 2016). The effects of lateral soil solution fluxes may also coincide with differences in soil moisture along a hillslope and its influence on podzolization development (Dzięciołowski, 1976; Seibert et al., 2007; Migoń and Kacprzak, 2014) or with variation of soil properties originating from differences of a bedrock in a catena (Musielok et al., 2021). A soil pattern formed as a result of this process – with depletion and accumulation zones located alternately in a landscape – may substantially differentiate habitat conditions within a small area.

The main aim of this study was to determine the threshold of podzolization occurrence in the flysch parent material occurring locally in the Wieliczka Foothills. Furthermore, an attempt was made to determine the spatial variability of soils on a forested hillslope in the environmental conditions of the Carpathian Foothills.

2. Study area, materials and methods

The study was carried out in the Wieliczka Foothills in southern Poland (Fig. 1a) at the slopes of Mount Dziurak (424 m a.s.l.) (Fig. 1b). The uppermost part of Mt. Dziurak is built of the flysch rock layers of Silesian Formations (Burtan and Wójcik, 2017) that consist of coarse-grained sandstones and conglomerates described in the literature as the Istebna layers (Ślączka et al., 2006). These flysch rock layers in this area have the dip direction to SW. In lower slope positions the loess sediments covers or are mixed with the regolith of flysch rocks (Adamczyk et al., 1989). The area is covered with mixed fir-beech forest (Fig. 1c). The native vegetation in the study area were most probably deciduous forests (*Tilio-Carpinetum*) with hornbeam (*Carpinus betulus* L.), lime (*Tilia cordata* Mill.), oak (*Quercus* sp.), and beech (*Fagus sylvatica* L.) (Towpasz and Zemanek, 1995); however, it is likely that fir (*Abies alba* Mill.) forests predominated at higher elevations with poorer soils. The climate of the studied area is moderately humid with mean annual precipitation between 700 and 900 mm and mean annual temperature ranging from 6°C to 8°C (Hess, 1965; Wypych et al, 2018).

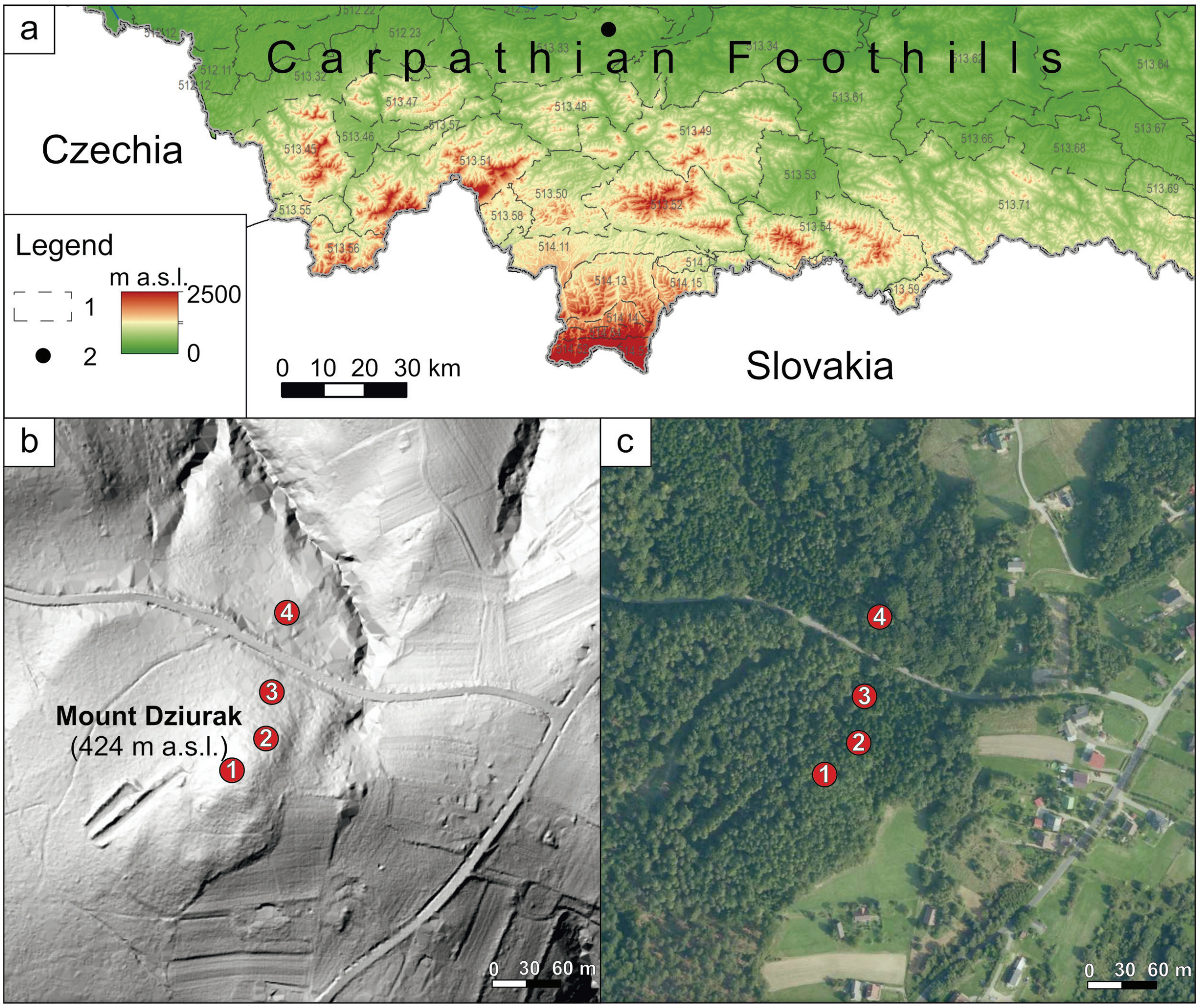
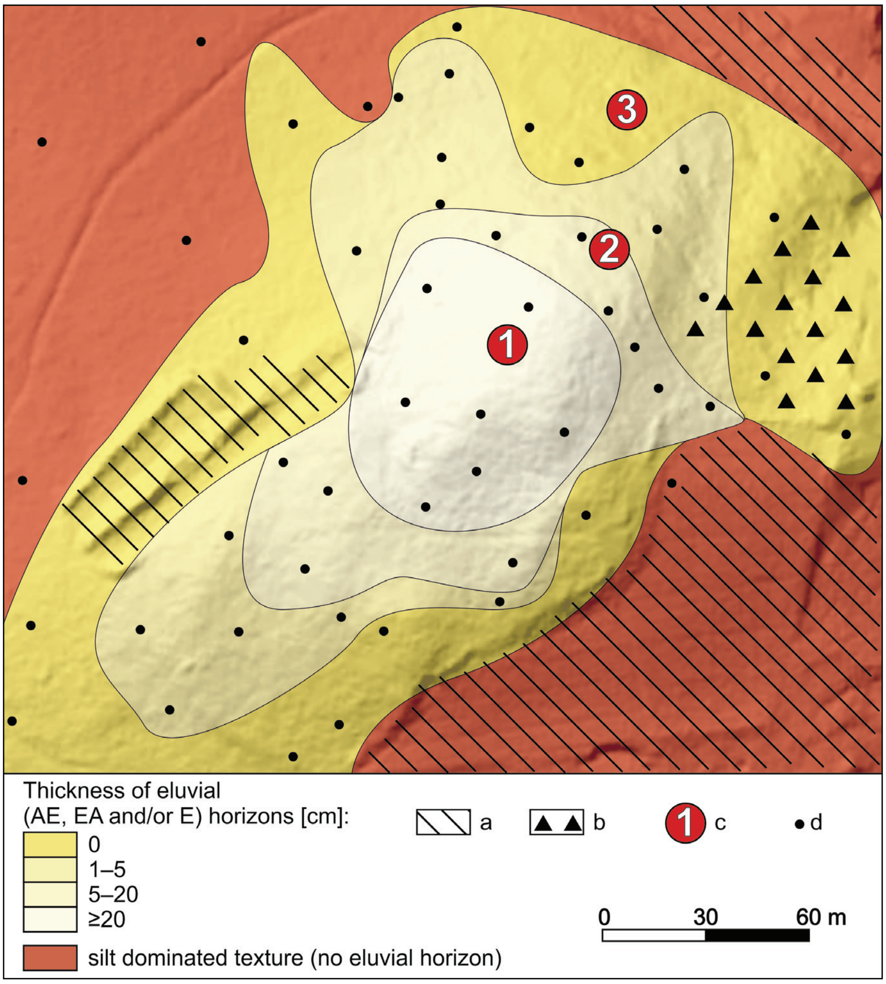


Fig. 1. Location of the study area (a – study area within the area of the Carpathian Foothills, 1 – mesoregions according to Solon et al. (2018), 2 – study area; b – location of the investigated sites on the Digital Elevation Model; c – location of the investigated sites on the ortophoto)

Fig. 2. Occurrence and thickness of the eluvial horizons in soils of Dziurak Mt (a – areas with soils disturbed by human activity, b – occurrence of pit-mound microtopography associated with old windthrows, c – location of study sites with investigated soil profiles, d – location of shallow soil pits or boreholes)



The selection of the study sites was preceded by the detailed mapping of the soil cover and geomorphic forms (Fig. 2). In total 59 pits or boreholes were excavated. Then four study sites representative for the slope positions were selected for further investigations (Table 1). The study sites were located along the 140 m long slope transect on the northeastern slopes of Dziurak Mt (Fig. 1b). Site 1 represented the summit flattening, site 2 – upper slopes, site 3 – upper middle slopes, and site 4 – lower middle slopes. Soils at the sites 1–3 were developed from the flysch rocks of the Istebna layers, while soil at the site 4 was developed from cover bed including regolith of flysch and significant loess admixture (Table 1). The sites 2–4 were located on straight and convex slope of constant inclination between 15 and 20° (Fig. 1b). The soil profiles at the study sites were described according to the Guidelines for Soil Description (Jahn et al. 2006). The soil color was described for samples in the moist and dry states using Munsell soil color charts. Soil samples (ca. 0.5–1 kg) were collected from all genetic horizons. Moreover, a core sampler (63.5 cm^3) was used to collect undisturbed soil samples from the mineral soil. The samples were air-dried, then gently crushed, and sieved through a 2 mm mesh stainless steel sieve. All the living roots were removed from the samples.

Table 1
Location and site characteristic

Site No	Coordinates	Geomorphic position	Elevation [m a.s.l.]	Parent material
1	49°50’52.92’’N, 20°02’23.03’’E	Summit flattening	424	Flysch regolith (Istebna layers)
2	49°50’53.90’’N, 20°02’24.96’’E	Upper slope	415	Flysch regolith (Istebna layers)
3	49°50’55.32’’N, 20°02’23.85’’E	Upper middle slope	397	Flysch regolith (Istebna layers)
4	49°50’58.21’’N, 20°02’26.51’’E	Lower middle slope	375	Loess mixed with flysch regolith

The soil pH was measured in deionized water and in 1M KCl solution at a 1:2.5 ratio (Thomas, 1996). The pH values were below 6.2 in all the samples, hence it was assumed that the investigated soils were carbonate-free. The concentration of total carbon (TC) was determined by dry combustion gas chromatography using a CHN analyzer (vario MICRO cube elemental analyzer, Elementar, Germany). Due to the lack of carbonates in the soils, it was assumed that TC content corresponds to soil organic carbon (SOC) content (Egli et al., 2010). The particle-size distribution was determined using combined sieving and hydrometer method (Gee and Bauder, 1986; Van Reeuwijk, 2002). The bulk density (BD) was determined using oven-drying and weighing method. The base saturation (BS) was calculated as a ratio of base cations (BC – Ca2+, Mg2+, Na+, K+) measured in the ammonium acetate (pH 7) extract (Burt 2004) using AAS to the sum of BC and exchangeable aluminium (IUSS Working Group WRB 2015). Exchangeable Al was determined by titrating 1M KCl, unbuffered extract with 0.1M NaOH in presence of 3.5% NaF. The concentration of free Fe-oxides in bicarbonate–citrate–sodium dithionite (BCD) extract (Fe_d) and amorphous Fe- and Al-oxides in ammonium oxalate extracts (Fe_o and Al_o) (Van Reeuwijk, 2002) were determined using AAS (240FS AA, Agilent Technologies). The soil chemical composition was determined via ICP-ES after digestion of the samples using lithium metaborate/tetraborate and dilute nitric acid at Bureau Veritas (Vancouver, BC, Canada). On the basis of the chemical composition mass balance calculations for selected elements (Al, Fe, Mg and Na) concentrations were obtained using the open-system mass transport function $\tau_{j,w}$ (Chadwick et al., 1990):

$$\tau_{j,w} = \frac{C_{j,w} \cdot C_{i,p}}{C_{i,w} \cdot C_{j,p}} - 1,$$

where: i denotes the immobile element, $C_{j,p}$ is the concentration of element j in unweathered parent material, and $C_{j,w}$ is the concentration of element j in weathered soil. Zr was used as the immobile element. The quantification of gains or losses of soil elements was calculated in the relation to the content of elements in the lowermost CB horizons. In the case of profile 1 the CB horizon of profile 2 served as the reference unweathered horizon. Fe_d/Fe_t ratio that serve as the weathering index (Schwertmann, 1964) was also calculated.

Moreover, to compare the soils in the investigated transect mass densities of pedogenic oxides and clay were calculated on a volume basis down to the upper boundary of the CB horizons (according to Sommer et al., (2001):

$$M_x = \sum_{i=1}^{n} \left(x_i BD_i y_i \frac{100 - cf_i}{10{,}000} \right),$$

where: M_x denotes mass of element x in soil fine-earth expressed in kg m^{-2} profile depth^{-1}, x_i is the concentration of element x in horizon i [g kg^{-1} fine earth], n is the number of horizons to the upper boundary of CB horizon, BD is the bulk density [Mg m^{-3}], y is the thickness of the horizon i [cm], and cf_i is concentration of coarse fragments in the horizon i [vol. %].

For podzolized soils 'illuviation-eluviation ratio of podzolization' (IER_{podzol}) was calculated (Sommer et al., 2001). IER_{podzol} is a dimensionless ratio between the sum of the illuvial horizon thicknesses and the sum of the eluvial horizons thicknesses in a soil profile. Sommer et al. (2001) named soils with IER_{podzol} values below 0.5 as 'E-Podzols', while with values greater than 2.0 as 'Bs-Podzols'.

Soil profiles were classified according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015) and Polish Soil Classification (Systematyka gleb Polski, 2019; Kabała et al., 2019).

3. Results

The thickness of the investigated soils was between 70 cm and 90 cm and the soils contained from 3% up to 50% of coarse fragments – usually from the gravel fraction (Table 2, Fig. 3). The color of soil material in studied soils was usually 10YR or 7.5YR, while the structure was granular jointly with subangular in the upper part of soils and angular blocky in the lower parts (Table 2, Fig. 3). SOC content varied from 0.3% in the lowermost CB horizons up to 35% in organic (O) horizons (Table 3). All soils showed very high content of SOC in A horizons. Furthermore, in soil at site 1 SOC distribution in the profile showed relative increase in Bhs horizon, while in the other profiles gradually decreased down the soil profiles. C/N ranged from 9 to 31 with the highest values in Ah horizon of profile 1 and EA horizon of profile 2 (Table 3). The reaction in all investigated soils was acidic with the pH (in water) in the range from 3.4 in Ah horizon of profile 2 to 5.5 in CB horizon of profile 3 (Table 3). pH values showed also a catenary trend (particularly clear in the lowermost horizons) with the lowest values in profile 1 and the highest in profiles 3 and 4. The BS ranged from 3% to 79% with the minimum value in Bw1 horizon of profile 4 and maximum in CB horizon of profile 3 (Table 3). The lowest BS was found usually in the middle part of the profile (Bhs or Bw horizons), while the highest BS was typical for Ah and CB horizons. The texture in profiles 1 and 2 was usually loamy sand, in profile 3 – sandy loam, while in profile 4 it was loam changing into silt loam in the lowermost horizon (Table 4). The BD varied from 0.3 g cm^{-3} in Ah horizons to 1.5 g cm^{-3} in CB horizons gradually increasing with the soil depth (Table 4).

The chemical composition was homogenous for the profiles 1–3 with content of SiO_2 usually above 90% (Table 5, values used in the text consider the share of loss on ignition). However, the content of this component was slightly lower in profile 3 in comparison with profiles 1 and 2. In contrast to profiles 1–3, profile 4 showed more differentiated chemical composition with substantially lower content of SiO_2 (between 83% and 86%) and relatively higher content of Al_2O_3, Fe_2O_3, MgO and CaO (Table 5).

The content and distribution of pedogenic Al and Fe oxides indicated podzolization in profiles 1 and 2 with depleted EA and E horizons and enriched subsurface Bhs and Bs horizons (Table 6). The values of Al_o+1/2Fe_o in illuvial horizons of profiles 1 and 2 showed relative increase in comparison with horizons

Table 2
Morphology of the analyzed soils

Depth	Horizon	CF[a]		Color		Structure[d]	Roots	Consistence[e]
		Content [% vol.]	Fraction [USDA][b]	Moist	Dry			
Site 1. Albic Podzol (WRB 2015), Typical podzolic soil (PSC 2019)								
1–0	Oie	0	-	n.d.[c]	n.d.	n.d.	many	VFR
0–6	Ah	0	-	10YR 1.7/1	10YR 3/1	SB, GR	common	FR
6–20	E1	0	-	10YR 4/1	10YR 6/1	SB, GR	common	FR
20–35	E2	10	g, cb	10YR 5/2	10YR 7/2	SB, GR	common	FI
35–50	Bhs	30	g, cb	7.5YR 5/4	7.5YR 7/4	AB, SB, GR	common	FI
50–75	BsC	50	g, cb, st	7.5YR 5/4	7.5YR 7/4	AB, SB, GR	few	VFI
Site 2. Albic Podzol (WRB 2015), Typical podzolic soil (PSC 2019)								
3–0	Oie	0	-	n.d.	n.d.	n.d.	many	VFR
0–5	Ah	0	-	10YR 1.7/1	10YR 2/2	GR	many	VFR
5–10	EA	0	-	10YR 4/1	10YR 6/1	SB, GR	many	VFR
10–15	E	0	-	10YR 5/2	10YR 8/1	AB, SB	common	FR
15–22	Bhs	5	g, cb	7.5YR 5/4	7.5YR 7/3	AB, PL	common	FI
22–40	Bs	40	g, cb	7.5YR 6/4	7.5YR 7/4	AB, SB, GR	common	FR
40–70	BC	20	g, cb	7.5YR 6/4	7.5YR 7/4	AB, SB, GR	few	FR
70–90	CB	20	g, cb	10YR 6/4	10YR 8/2	AB, SB, GR	few	FI
Site 3. Epidystric Endoeutric Cambisol (WRB 2015), Leached brown soil (PSC 2019)								
2–0	Oie	0	-	n.d.	n.d.	n.d.	many	VFR
0–2	Ah	0	-	10YR 2/2	10YR 2/2	GR	many	VFR
2–6	A	3	g	10YR 5/1	10YR 5/1	GR	common	FR
6–18	Bw(s)1	3	g	7.5YR 7/4	7.5YR 7/4	SB, AB	few	FI
18–33	Bw(s)2	10	g, cb	10YR 8/2	10YR 8/2	SB, AB, GR	few	FI
33–60	BC	10	g, cb	10YR 8/2	10YR 8/2	AB	few	FI
60–70	CB	30	g, cb	10YR 8/2	10YR 8/2	AB, SB, GR	-	VFI
Site 4. Dystric Cambisol (WRB 2015), Leached brown soil (PSC 2019)								
1–0	Oie	0	-	n.d.	n.d.	n.d.	common	VFR
0–5	Ah	3	g	10YR 2/1	10YR 4/1	SB, GR	common	FR
5–25	Bw1	3	g	10YR 5/3	10YR 7/3	AB	few	FI
25–45	Bw2	5	g	10YR 5/4	10YR 7/3	AB	few	FI
45–70	CBg	10	g	10YR 5/4 + 10YR 6/3	10YR 7/3 + 10YR 8/1	AB	few	FI

[a] Coarse fragments
[b] Fraction of coarse fragments according to the United States Department of Agriculture: g – gravel, cb – cobbles, st - stones
[c] Not determined
[d] Structure type: SB – subangular blocky, AB – angular blocky, GR – granular, PL – platy
[e] Consistence: VFR- very friable, FR – friable, FI – firm, VFI – very firm

lying above; however, they did not fulfill the requirements for spodic horizons (IUSS Working Group WRB, 2015). In profiles 3 and 4 distribution of Fe_d, Fe_o and Al_o did not indicate any evidence of profile translocation and subsurface enrichment. The Fe_o/Fe_d values showed bimodal distribution in profiles 1 and 2 (with peaks in Ah and Bhs horizons), while in soils at sites 3 and 4 values of Fe_o/Fe_d ratio decreased down the profiles (Table 6). The degree of weathering expressed by Fe_d/Fe_t ratio was the highest in profile 1 with the values between 0.8 and 1.0, while the lowest was in profiles 3 and 4 (0.3–0.6 and 0.3–0.5, respectively; Table 6).

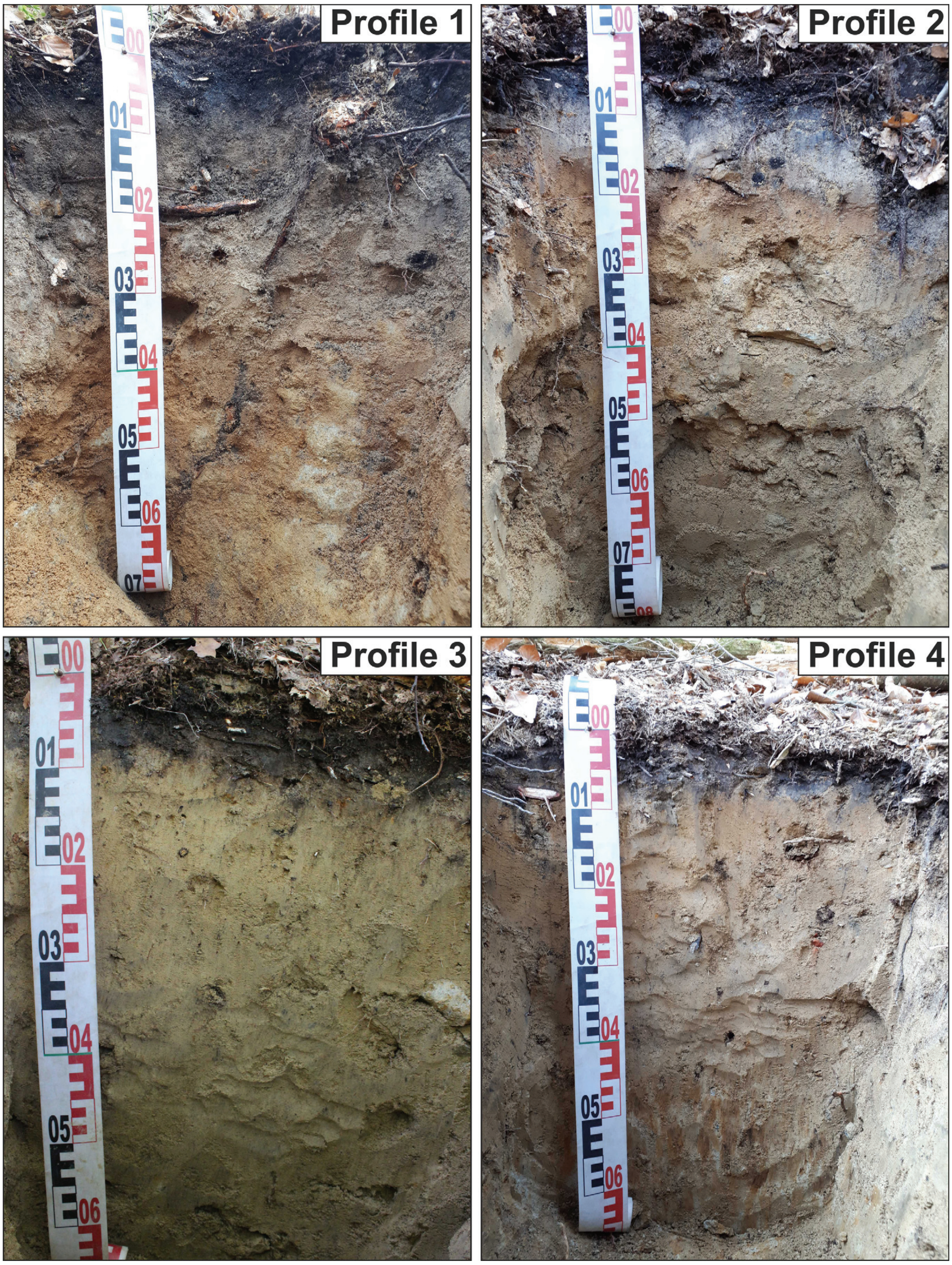


Fig. 3. Morphology of the analyzed soils at sites 1–4

The open-system mass balance calculations for Al, Fe, Mg and Na showed depletion of all soils with these components in relation to its concentration in the CB horizons (Fig. 4). Relatively more depleted were podzolized soils at sites 1 and 2 (up to 90% Fe and Mg in E and EA horizons), while non-podzolized soils at sites 3 and 4 were clearly less depleted. Moreover, occurrence of podzolization in profiles 1 and 2 was reflected in relatively lower τ values obtained for Bhs and Bs horizons in comparison with E horizons (Fig. 4).

The topofunctions of mass densities obtained for Fe_d, and Fe_o along the investigated transect showed a gradual catenary increase (Fig. 4a). Pedogenic Fe showed threefold higher mass densities in soil located at the lower middle slope in comparison with soil at the summit flattening. Al_o mass increased only slightly in soils located along in the investigated transect (Fig. 4a). The clay mass densities showed the lowest value in soil at the upper slope and twofold higher value in soil in the lower middle slope position (Fig. 4b). The IER_{podzol} value for

Table 3
Chemical properties of the analyzed soils

Depth	Horizon	SOC[a]	C/N	pH		BS[c]
		[%]		[H_2O]	[KCl]	[%]
Site 1. Albic Podzol (WRB 2015), Typical podzolic soil (PSC 2019)						
1–0	Oie	35.7	25	3.9	2.9	n.d.
0–6	Ah	7.8	31	3.6	2.8	11
6–20	E1	0.9	17	3.9	3.2	12
20–35	E2	0.4	18	4.0	3.3	9
35–50	Bhs	0.6	18	4.4	3.9	4
50–75	BsC	0.6	n.d.[b]	4.5	4.0	8
Site 2. Albic Podzol (WRB 2015), Typical podzolic soil (PSC 2019)						
3–0	Oie	34.8	24	4.3	3.6	n.d.
0–5	Ah	13.1	23	3.4	2.9	21
5–10	EA	3.1	30	3.8	3.0	11
10–15	E	1.1	17	4.1	3.3	6
15–22	Bhs	1.0	17	4.3	3.7	4
22–40	Bs	0.7	11	4.7	4.1	9
40–70	BC	0.7	n.d.	4.8	4.1	7
70–90	CB	0.3	n.d.	4.8	4.1	10
Site 3. Epidystric Endoeutric Cambisol (WRB 2015), Leached brown soil (PSC 2019)						
2–0	Oie	32.2	22	4.5	4.1	n.d.
0–2	Ah	17.3	22	3.5	2.9	22
2–6	A	2.6	23	3.8	3.1	5
6–18	Bw(s)1	0.7	16	4.4	3.7	4
18–33	Bw(s)2	0.4	9	4.6	3.9	7
33–60	BC	0.2	n.d.	5.2	4.0	36
60–70	CB	0.3	n.d.	5.5	4.1	79
Site 4. Dystric Cambisol (WRB 2015), Leached brown soil (PSC 2019)						
1–0	Oie	22.1	18	3.6	3.0	n.d.
0–5	Ah	13.2	23	3.5	2.9	8
5–25	Bw1	1.7	20	4.3	3.6	3
25–45	Bw2	0.5	11	4.5	3.7	7
45–70	CBg	0.4	n.d.	4.9	3.7	26

[a] Soil organic carbon
[b] Not determined
[c] Base saturation

profile 1 was 1.4 – much higher than the upper limit for 'E-Podzol' – while for profile 2 it was 2.5 qualifying this soil as 'Bs-Podzol' (Table 6).

Based on the set of obtained properties soils at sites 1 and 2 were classified according to WRB (IUSS Working Group WRB, 2015) as Albic Podzols. Although the soils did not meet the chemical requirements for the spodic horizon (too low Al_o and Fe_o contents), the color of the illuvial horizons and the presence of albic materials in E horizons enabled classifying these soils as Podzols. Soil at site 3 was classified as Epidystric Endoeutric Cambisol and soil at site 4 as Dystric Cambisols. According to Polish Soil Classification (Systematyka gleb Polski, 2019; Kabała et al., 2019) profiles 1 and 2 were classified as typical podzolic soils, while profiles 3 and 4 as leached brown soils.

Table 4
Texture and bulk density of the analyzed soils

Depth	Horizon	Particle size distribution [%]								Textural class [a] [USDA]	BD[b]
		V. coarse sand (2.0–1.0 mm)	Coarse sand (1.0–0.5 mm)	Med. sand (0.5–0.25 mm)	Fine sand (0.25–0.10 mm)	V. fine sand (0.10–0.05 mm)	Coarse silt (0.05–0.02 mm)	Fine silt (0.02–0.002 mm)	Clay (< 0.002 mm)		[g cm^{-3}]
Site 1. Albic Podzol (WRB 2015), Typical podzolic soil (PSC 2019)											
0–6	Ah	7	23	27	22	5	5	4	7	LS	1.04
6–20	E1	6	17	27	28	8	1	4	9	LS	1.12
20–35	E2	4	12	28	34	9	3	7	3	S	1.41
35–50	Bhs	7	14	25	29	8	3	4	10	LS	1.07
50–75	BsC	10	18	27	26	6	2	6	5	LS	1.48
Site 2. Albic Podzol (WRB 2015), Typical podzolic soil (PSC 2019)											
0–5	Ah	4	26	24	21	6	8	6	5	LS	0.28
5–10	EA	4	15	24	29	8	7	9	4	LS	0.64
10–15	E	7	14	21	27	9	7	10	5	LS	1.27
15–22	Bhs	6	15	22	26	8	3	15	5	LS	1.25
22–40	Bs	6	15	22	26	8	5	8	10	SL	1.15
40–70	BC	9	16	23	26	8	3	12	3	LS	1.35
70–90	CB	7	20	24	26	8	2	8	5	LS	1.46
Site 3. Epidystric Endoeutric Cambisol (WRB 2015), Leached brown soil (PSC 2019)											
0–2	Ah	4	24	23	23	6	7	10	3	LS	0.32
2–6	A	5	14	19	24	8	7	12	11	SL	0.62
6–18	Bw(s)1	5	13	19	23	9	9	13	9	SL	1.29
18–33	Bw(s)2	4	13	19	24	9	8	15	8	SL	1.37
33–60	BC	4	12	20	25	9	7	18	5	SL	1.43
60–70	CB	12	13	19	23	8	12	7	6	SL	1.44
Site 4. Dystric Cambisol (WRB 2015), Leached brown soil (PSC 2019)											
0–5	Ah	2	13	12	15	7	14	23	14	L	0.73
5–25	Bw1	3	7	8	13	7	14	31	17	L	1.03
25–45	Bw2	3	6	8	12	7	20	29	15	L	1.24
45–70	CBg	2	5	8	11	6	24	26	18	SiL	1.23

[a] Textural class according to the United States Department of Agriculture: LS – loamy sand, S – sand, SL – sandy loam, L – loam, SiL – silt loam
[b] Bulk density

Table 5
Chemical composition of the analyzed soils

Depth	Horizon	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Zr	LOI[a]
		[%]										ppm	[%]
Site 1. Albic Podzol (WRB 2015), Typical podzolic soil (PSC 2019)													
0–6	Ah	89.07	2.01	0.28	0.03	0.03	0.15	1.11	0.12	0.03	0.01	117	7.1
6–20	E1	94.95	2.48	0.09	0.01	0.02	0.13	1.12	0.11	0.04	0.01	208	1.0
20–35	E2	93.94	2.68	0.18	0.03	0.02	0.21	1.56	0.19	0.01	0.01	223	1.1
35–50	Bhs	93.78	2.73	0.26	0.04	0.01	0.18	1.45	0.15	0.03	0.01	152	1.3
50–75	BsC	93.17	3.05	0.41	0.05	0.02	0.22	1.59	0.16	0.02	0.01	196	1.3
Site 2. Albic Podzol (WRB 2015), Typical podzolic soil (PSC 2019)													
0–5	Ah	72.25	3.25	1.01	0.08	0.08	0.24	1.36	0.21	0.07	0.01	175	21.4
5–10	EA	90.33	2.95	0.45	0.04	0.03	0.28	1.58	0.20	0.03	0.01	183	4.0
10–15	E	95.19	2.06	0.30	0.02	0.01	0.18	1.30	0.11	0.01	0.01	167	0.8
15–22	Bhs	92.26	3.32	0.55	0.05	0.03	0.29	1.66	0.18	0.02	0.01	150	1.6
22–40	Bs	90.78	4.04	0.64	0.06	0.04	0.35	1.86	0.25	0.03	0.01	188	1.9
40–70	BC	88.33	5.62	1.01	0.15	0.04	0.48	2.16	0.31	0.04	0.01	203	1.8
70–90	CB	89.72	5.08	0.76	0.12	0.03	0.45	2.08	0.23	0.03	0.01	152	1.4
Site 3. Epidystric Endoeutric Cambisol (WRB 2015), Leached brown soil (PSC 2019)													
0–2	Ah	65.59	4.52	1.37	0.14	0.11	0.35	1.43	0.32	0.10	0.01	182	26.0
2–6	A	85.90	4.79	0.81	0.10	0.06	0.46	1.90	0.36	0.04	0.01	239	5.5
6–18	Bw(s)1	87.97	5.10	1.01	0.13	0.06	0.46	1.89	0.36	0.03	0.01	243	2.9
18–33	Bw(s)2	89.16	4.95	0.81	0.13	0.06	0.45	1.88	0.33	0.03	0.02	245	2.1
33–60	BC	89.15	5.05	0.87	0.14	0.08	0.48	1.95	0.34	0.03	0.02	231	1.8
60–70	CB	88.55	5.41	0.92	0.17	0.10	0.51	2.05	0.33	0.03	0.02	206	1.8
Site 4. Dystric Cambisol (WRB 2015), Leached brown soil (PSC 2019)													
0–5	Ah	64.50	6.14	1.97	0.28	0.15	0.42	1.45	0.52	0.12	0.02	275	24.3
5–25	Bw1	81.91	7.46	2.13	0.38	0.13	0.61	1.97	0.63	0.04	0.03	365	4.6
25–45	Bw2	82.42	7.67	2.03	0.41	0.14	0.64	2.09	0.64	0.06	0.05	356	3.7
45–70	CBg	79.75	8.79	2.99	0.58	0.19	0.65	2.29	0.62	0.06	0.06	352	3.9

[a] Loss on ignition

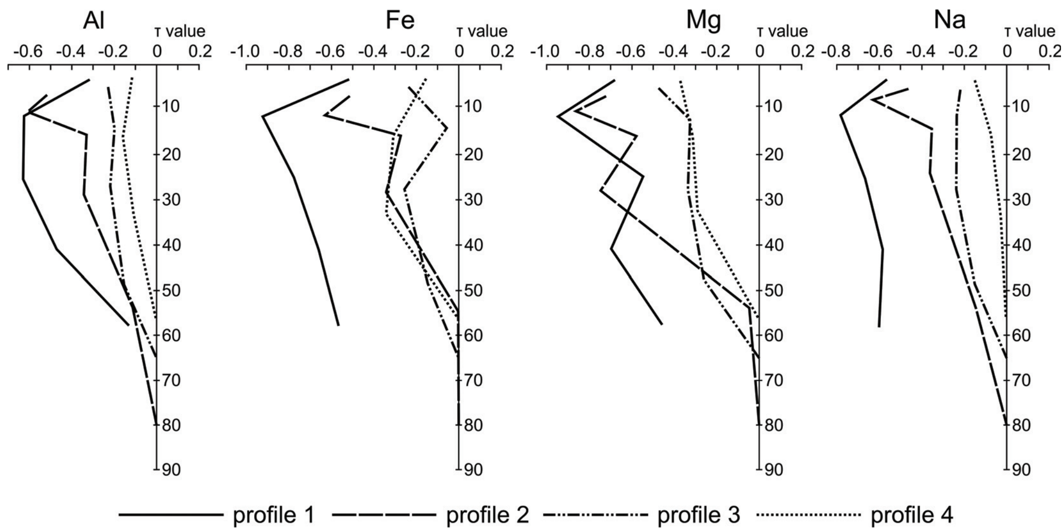


Fig. 4. Open-system mass balance calculations for soils at sites 1–4

Table 6
Concentration of pedogenic oxides in the analyzed soils and related indices of podzolization process

Depth	Horizon	Fe_d[a]	Fe_o[b]	Al_o[b]	$Al_o + 1/2\ Fe_o$	Fe_o/Fe_d[c]	Fe_d/Fe_t[d]	IER_{podzol}[e]
		[%]						
Site 1. Albic Podzol (WRB 2015), Typical podzolic soil (PSC 2019)								
0–6	Ah	0.16	0.06	0.19	0.22	0.40	0.76	1.43
7–20	E1	0.06	0.01	0.15	0.16	0.08	0.94	
20–35	E2	0.12	0.02	0.15	0.16	0.12	0.95	
35–50	Bhs	0.18	0.10	0.34	0.39	0.47	0.98	
50–75	BsC	0.23	0.10	0.38	0.43	0.45	0.79	
Site 2. Albic Podzol (WRB 2015), Typical podzolic soil (PSC 2019)								
0–5	Ah	0.25	0.09	0.32	0.36	0.36	0.28	2.50
5–10	EA	0.14	0.02	0.16	0.17	0.13	0.42	
10–15	E	0.13	0.02	0.14	0.15	0.16	0.63	
15–22	Bhs	0.23	0.12	0.30	0.36	0.50	0.59	
22–40	Bs	0.17	0.09	0.34	0.39	0.55	0.37	
40–70	BC	0.17	0.05	0.29	0.32	0.31	0.23	
70–90	CB	0.53	0.04	0.20	0.22	0.06	0.98	
Site 3. Epidystric Endoeutric Cambisol (WRB 2015), Leached brown soil (PSC 2019)								
0–2	Ah	0.37	0.15	0.41	0.48	0.40	0.28	n.d.[f]
2–6	A	0.25	0.14	0.28	0.35	0.58	0.42	
6–18	Bw(s)1	0.31	0.10	0.29	0.34	0.33	0.42	
18–33	Bw(s)2	0.35	0.08	0.21	0.25	0.24	0.60	
33–60	BC	0.26	0.05	0.17	0.20	0.20	0.42	
60–70	CB	0.26	0.06	0.15	0.18	0.24	0.40	
Site 4. Dystric Cambisol (WRB 2015), Leached brown soil (PSC 2019)								
0–5	Ah	0.56	0.29	0.50	0.65	0.52	0.31	n.d.
5–25	Bw1	0.61	0.34	0.44	0.61	0.57	0.39	
25–45	Bw2	0.70	0.30	0.42	0.57	0.44	0.47	
45–70	CBg	1.14	0.37	0.48	0.67	0.33	0.52	

[a] Content of Na-bicarbonate/citrate/dithionite extracted iron
[b] Content of ammonium oxalate extracted iron and aluminum
[c] Iron activity ratio (Schwertmann, 1964)
[d] Weathering index (Schwertmann, 1964)
[e] Illuviation-eluviation ratio of podzolization (Sommer et al., 2001)
[f] Not determined

4. Discussion

4.1. Podzolization threshold

The main factors that trigger podzolization in soil are: (1) humid climatic conditions (Schaetzl and Rothstein, 2016), (2) presence of forest or heath vegetation that is a source of organic matter to form O horizons (Buurman, 1984), and (3) coarse-textured and leached parent material (Augusto et al., 1998; Stützer, 1998). The climate of the studied area is characterized with often precipitation deficit during late summer and early autumn (Obrębska-Starklowa et al., 1995); however, for most of the year the evapotranspiration does not exceed precipitation. Mokma and Buurman (1982) considered this as the indispensable condition of podzolization occurrence. Furthermore, in all soils O horizons supplying humic acids into mineral soil were present (Table 2, Fig. 3).

Podzols (profiles 1 and 2) showed higher SOC content in O horizons in comparison with the non-podzolized soils (profiles 3 and 4), while the latter contained substantially more SOC in A horizons. Relatively higher C/N values in profiles 1 and 2 may be attributed to slower turnover of organic matter in Podzols due to its slightly lower pH (Brock et al., 2020) in comparison with adjacent non-podzolized soils (Table 3). On the other hand, higher microbial degradation of organic matter, reflected in lower C/N values in soils at sites 3 and 4 (Table 3), may lead to formation of stable organo-mineral compounds in A horizons (Kalbitz et al., 2005) and, thus, suppress podzolization.

Another condition that varied along the investigated transect was related with the properties of the parent material. Both Podzols (profiles 1 and 2) were developed from material of loamy sand texture with minimum 77% sand and maximum 10% clay (Table 4). Such texture, particularly the low content of clay, is considered as favorable for podzolization occurrence (Jersak et al., 1995; Sauer et al., 2007). Studies on formation of Podzols in unfavorable parent materials, e.g. rich in carbonates (Protz et al., 1984; Schaetzl, 1991) or iron and magnesium (D'Amico et al., 2008) reported that translocation of metal-organic compounds down the soil profile is possible if parent material has less than 10% clay. In this study parent materials of soils in profiles 1 and 2 contained 5% clay and the maximum 10% clay was noticed in the illuvial horizons (Table 2), suggesting that translocation of soil constituents down the profile in this case involved also the clay fraction. The content of clay in profile 3 was slightly higher than in profiles 1 and 2; however, similarly to Podzols it was usually below 10% (Table 4). In contrast, the whole soil in profile 4 contained between 14% and 18% clay (Table 4). Such amount of clay fraction already hamper the development of Podzols due to high potential to immobilize metal-organic complexes (Mokma and Buurman, 1982; Buurman, 1984). Moreover, it should be noticed that profiles 1–3 contained relatively high amount of coarse fragments (Table 1) that may enhance downward solution flux (Schaetzl, 1991).

Another factor related to the parent material that was responsible for triggering podzolization was the content of iron (Duchaufour and Souchier, 1978; Buurman, 1984). The CB horizon of Podzol in this study contained 0.7% Fe_2O_3 (Table 5, profile 2) which was clearly below the limit of 2% Fe_2O_3, determined by Duchaufour and Souchier (1978) in soils developed from granites in Vosges in France. Above this Fe_2O_3 content podzolization was strongly inhibited. Also in profile 3 the content of Fe_2O_3 did not exceed 2%; however, it was substantially higher than in adjacent Podzols (Table 5). On the other hand, non-podzolized profile 4 throughout the whole thickness contained more than 2% Fe_2O_3 (Table 5).

The role of pH in triggering podzolization in studied soils was unclear. Surface A horizons showed very similar pH values measured in water (between 3.4 and 3.8, Table 3) indicating that the chemical properties of organic matter input were not the main factor driving podzolization in this case. On the other hand, pH values in the lowermost horizons (at similar depth below the ground) were much higher in non-podzolized profile 3 (pH in water 5.5) in comparison with profiles 1 and 2 (pH in water 4.5 and 4.8, respectively). This suggested that the parent material properties play the main role in triggering podzolization.

4.2. Tendencies for lateral podzolization

Despite exhibiting a very similar properties to Podzols (profiles 1 and 2) as well as having similar environmental background (i.e. parent material, vegetation, slope inclination, etc.), soil at site 3 did not show any evidence of translocation of metal-organic complexes down the profile and thus was classified as Cambisol (PSC: brown soil). Considering spatial relations between the soils in the investigated transect profile 3 may be considered as accumulative soil showing relative enrichment in comparison with substantially more depleted soils at sites 1 and 2. Open-system mass balance for Al, Fe, Mg and Na (Fig. 4) as well as the topofunctions of mass densities obtained for pedogenic oxides and clay (Fig. 5) indicated relatively smaller depletion of profile 3 in relation to soils in upper slope positions. Such soil pattern along a slope may be attributed to the effects of lateral subsurface soil solution flux (Sommer et al., 2000, 2001) although this process was not fully justified by the differences in the soil morphology (Fig. 3, Table 2) and the values of illuviation-eluviation ratio of podzolization (Table 6).

Due to its coarse texture soils at sites 1–3 may be considered as well drained (Table 4). Furthermore, no significant differences in the soil moisture within this part of transect were noticed. Hence, the possible influence of the oxidation-reduction processes on the soil development pathway, as it was described by Seibert et al. (2007) in soils of Swedish National Forest Inventory, in this study may be rejected. The only features related to reduction processes were observed in the lowermost part of profile 4, which was silt loam (Fig. 3, Tables 2 and 4). Moreover,

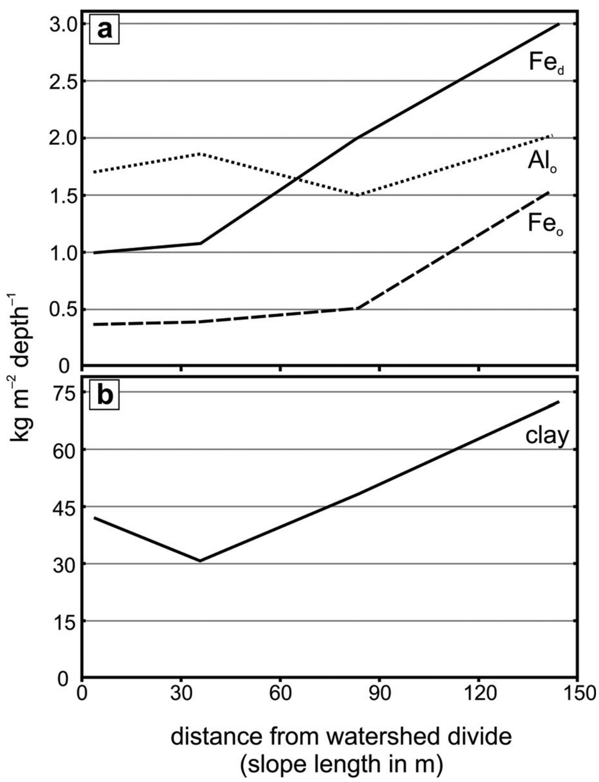


Fig. 5. Topofunctions of mass densities along the investigated transect (a – Fed, Feo and Alo, b – clay)

this soil was not affected by direct lateral soil solution flux along the investigated slope due to location on a slope below the road embankment (Fig. 1b).

Lateral soil solution flux can move downslope when encountering a less permeable layer within a soil profile. Due to location of the studied soils in a transect on the obsequent slope there was no possibility that genuine diversity of flysch deposits (e.g. sandstone regolith lying over more clayey mudstones) provide occurrence of less permeable layer in a subsoil parallel to the slope surface, as it was described by Musielok et al. (2021) in soils developed from flysch in the Bieszczady Mts. However, Jankowski (2014) noticed that in sandy soils of the northern Poland illuvial Bhs horizons as being clogged up with metal-organic compounds and humus pellets may serve as a barrier for infiltrating water. The slight relative increase of the BD in the lower parts of E and in Bhs horizons of profiles 1 and 2 in comparison with upper and lower horizons as well as higher content of clay found in Bhs horizons (Table 4) may support this hypothesis.

Another factor that may have conditioned the soil pattern along the studied slope and affected formation of less depleted soil at site 3 was the differentiation of the soil pH. Gustaffson et al. (1995) in soils developed from glacial tills and glaciofluvial sediments of the northern Scandinavia showed that higher pH is one factor that force the metal-organic complexes to precipitate and form illuvial horizon. Similar results in relation to lateral soil solution flux were obtained by Jankowski (2014) who described higher pH in the accumulative soils located in depressions between inland dunes and glaciofluvial terraces than in the soils on elevated areas.

Relatively lower depletion of soils at lower slope positions caused by accumulation of the translocated soil compounds affected pedogenic threshold of podzolization in the studied area. Vertical translocation of soil elements in profile 3 was inhibited due to relatively high content of clay (Table 4) and iron (Table 5) occurring already in A and Bw(s)1 horizons. Moreover, soil color of Bw(s)1 horizon of profile 3 with the hue 7.5YR (Table 1) in tandem with relatively high content of Fe_d, Fe_o and Al_o (Table 6) suggest the enrichment in pedogenic seqioxides already at the depth of 6–18 cm from the surface of mineral soil. The relatively high content of these soil components at shallow depth may be result of either incipient vertical and lateral translocation.

In this study some evidence of lateral podzolization were determined at a distance less than 30 m long – between profiles 2 and 3 (Fig. 1b, 2). Similar effects of lateral podzolization on a large scale were described by Jankowski (2001, 2014), Bourgault et al. (2015, 2017), and Musielok et al. (2021). In all abovementioned studies effects of lateral podzolization were found already at the distance smaller than 10 m. It should be emphasized that the effects of lateral podzolization, which were reflected i.a. in the different thicknesses of eluvial horizons, could be found only on some of the investigated slopes (Fig. 2). Firstly, the occurrence of the lateral podzolization in soils was dependant on the presence of favorable (sandy) parent material. This type of parent material was absent in upper middle slope positions in southeastern part of the studied area, therefore soils did not show any evidence of podzolization. Secondly, uppermost soil horizons could have been disturbed by the human activity (e.g. construction of earthen embankments in western slopes of Dziurak Mt) or the effects of geomorphic processes (e.g. old windthrows in northeastern part of the studied area).

5. Conclusions

1. The pedogenic threshold of podzolization occurrence in the flysch parent material occurring locally in the Wieliczka Foothills was primarily related to relative differences in the parent material properties. Soils with sand dominated texture and with very low content of clay fraction as well as low content of iron showed podzolization evidence, while adjacent soils with higher content of clay and iron did not show any evidence of vertical translocation of metal-organic compounds. The slightly lower decomposition rate of organic matter may have also affected initiation of podzolization process.
2. Soil in upper middle slope position developed from the same parent material and having similar environmental background as soils in higher slope positions was enriched with clay, pedogenic oxides and less depleted in Al, Fe, Mg, and Na. Possible influence of differences in soil moisture affecting podzolization development was excluded in this study. Despite having no clear impermeable layer in a subsoil, that could serve as barrier, downslope soil solutions flux may occur over illuvial horizons showing relatively higher BD and higher clay content.
3 The immobilization of soil constituents translocated laterally at the hillslope may be related with the higher pH of the parent material that affects precipitation of soil solutions.
4. The effects of lateral soil solution flux limited the area where intensive vertical podzolization occured. Thus, considering the effects of possible lateral podzolization as one of the factors responsible for the differentiation of soil properties at hillslopes is crucial for correct determination of forest habitat conditions, estimation of SOC sequestration potential as well as in soil cartography.

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References

Adamczyk, B., Niemyska-Łukaszuk, J., Drożdż-Hara, M., 1989. The part of soil in ensuring the purity of water in the dam reservoir in Dobczyce. Part I. Typology of soils and their all-over characteristic in watersheads of Ratanica and Dębnik. Acta Agraria et Silvestria – Series Silvestris 28, 125–146. (in Polish with English abstract)

Augusto, L., Bonnaud, P., Ranger, J., 1998. Impact of tree species on forest soil acidification. Forest Ecology and Management 105, 67–78. https://doi.org/10.1016/S0378-1127(97)00270-3

Bourgault, R.R., Ross, D.S., Bailey, S.W., 2015. Chemical and morphological distinctions between vertical and lateral podzolization at Hubbard Brook. Soil Science Society of America Journal 79(2), 428–439. https://doi.org/10.2136/sssaj2014.05.0190

Bourgault, R.R., Ross, D.S., Bailey, S.W., Bullen, T.D., McGuire, K.J., Gannon, J.P., 2017. Redistribution of soil metals and organic carbon via lateral flowpaths at the catchment scale in a glaciated upland setting. Geoderma 307, 238–252. https://doi.org/10.1016/j.geoderma.2017.05.039

Brock, O., Kalbitz, K., Absalah, S., Jansen, B., 2020. Effects of development stage on organic matter transformation in Podzols. Geoderma 378, 114625. https://doi.org/10.1016/j.geoderma.2020.114625

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

Burtan, J., Wójcik, A., 2017. Objaśnienia do szczegółowej mapy geologicznej Polski 1:50 000. 997, Arkusz Wieliczka. Państwowy Instytut Geologiczny, Warszawa.

Buurman, P., 1984. Podzols. Van-Nostand Reinhold Soil Science Series, New York.

Chadwick, O.A., Brimhall, G.H., Hendricks, D.M., 1990. From a black to a grey box — a mass balance interpretation of pedogenensis. Geomorphology 3, 369–390. https://doi.org/10.1016/0169-555X(90)90012-F

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

Duchaufour, P., Souchier, B., 1978. Roles of iron and clay in genesis of acid soils under a humid, temperate climate. Geoderma 20, 15–26. https://doi.org/10.1016/0016-7061(78)90046-0

Dzięciołowski, W., 1976. Proces bielicowania w świetle analizy stosunków morfologicznych sekwencji gleb w rezerwacie Bielice Gackie. Proces bielicowania. Materiały 2 Krajowej Konferencji, 1976 May 4–5. Polish Society of Soil Science, Toruń, Poland, 59–74. (in Polish)

Egli, M., Sartori, G., Mirabella, A., Giaccai, D., 2010. The effects of exposure and climate on the weathering of late Pleistocene and Holocene Alpine soils. Geomorphology 114, 466–482. https://doi.org/10.1016/j.geomorph.2009.08.008.

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, 427–445.

Glazovskaya, M.A., 1968. Geochemical landscapes and types of geochemical soil sequences. Transactions 9th International Congress of Soil Science 1968, August 6–16, Adelaide, Australia, 303–312.

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 with English abstract)

Gustafsson, J.P., Battacharya, P., Bain, D.C., Fraser, A.R., McHardy, W.J., 1995. Podzolisation mechanisms and the synthesis of imogolite in northern Scandinavia. Geoderma 66, 167–184. https://doi.org/10.1016/0016-7061(95)00005-9

Hess, M., 1965. Altitudinal climatic zones in the Polish Western Carpathians. Zeszyty Naukowe UJ: Prace Geograficzne 11. (in Polish)

IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014, update 2015: International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports, 106, FAO, Rome.

Jahn, R., Blume, H.-P., Asio, V.B., Spaargaren, O., Schad, P., 2006. Guidelines for soil description, 4th ed. FAO, Rome, Italy.

Jankowski, M., 2001. Conditions of occurrence, properties and genesis of intra-dune iron enriched soils. Roczniki Gleboznawcze – Soil Science Annual 52, Suppl. 49–63. (in Polish with English abstract)

Jankowski, M., 2014. The evidence of lateral podzolization in sandy soils of Northern Poland. Catena 112, 139–147. https://doi.org/10.1016/j.catena.2013.03.013

Jersak, J., Amundson, R., Brimhall Jr., G., 1995. A mass balance analysis of podzolization: Examples from northeastern United States. Geoderma 66, 15–42. https://doi.org/10.1016/0016-7061(94)00064-H

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

Kalbitz, K., Schwesig, D., Rethemeyer, J., Matzner, E., 2005. Stabilization of dissolved organic matter by sorption to the mineral soil. Soil Biology and Biochemistry 37, 1319–1331. https://doi.org/10.1016/j.soilbio.2004.11.028

Karavayeva, N.A., 1968. Formation and evolution of cemented Ortstein horizons (iron pans) in the Taiga zone. Transactions 9th International Congress of Soil Science, 1968, August 6–16, Adelaide, Australia, 451–458.

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)

Lucas, Y., Chauvel, A., 1992. Soil formation in tropically weathered terrains. [In:] Butt, C.R.M., Zeegers, H. (Eds.), Handbook of exploration geochemistry – in tropical and subtropical terrains. Elsevier, Amsterdam, 57–77.

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

Migoń, P., Kacprzak, A., 2014. Lateral diversity of regolith and soils under a mountain slope — implications for interpretation of hillslope materials and processes, Central Sudetes, SW Poland. Geomorphology 221, 69–82. https://doi.org/10.1016/j.geomorph.2014.06.003

Mokma, D.L., Buurman, P., 1982. Podzols and podzolization in temperate regions. ISM Monograph 1. International Soil Museum, Wageningen, The Netherlands.

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

Obrębska-Starklowa, B., Hess, M., Olecki, Z., Trepińska, J., Kowanetz, L., 1995. Climate. [In:] Warszyńska, J. (Ed.), The Polish Carpathians — Environment, human, and his activity, Wydawnictwo Uniwersytetu Jagiellońskiego, Kraków, 31–47 (in Polish).

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/cjss84004

Sauer, D., Sponagel, H., Sommer, M., Giani, L., Jahn, R., Stahr, K., 2007. Podzol: Soil of the Year 2007. A review on its genesis, occurrence, and functions. Journal of Plant Nutrition and Soil Science 170, 581–597. https://doi.org/10.1002/jpln.200700135

Schaetzl, R.J., 1991a. 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., 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

Schlichting, E., 1963. Interpretation of "Ortstein" soils in a subarctic-alpine region (in German). Zeitschrift für Pflanzenernährung, Düngung, Bodenkunde 100, 121–126.

Schwertmann, U., 1964. Differenzierung der Eisenoxide des Bodens durch Extraktion mit Ammoniumoxalat-Lösung. Zeitschrift für Pflanzenernährung, Düngung, Bodenkunde 105, 194–202. https://doi.org/10.1002/jpln.3591050303

Seibert, J., Stendahl, J., Sørensen, R., 2007. Topographical influences on soil properties in boreal forests. Geoderma 141, 139–148. https://doi.org/10.1016/j.geoderma.2007.05.013

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

Skiba, S., Drewnik, M., Klimek, M., Szmuc, R., 1998. Soil cover in the marginal zone of the Carpathian Foothills between the Raba and Uszwica Rivers. Prace Geograficzne 103, 125–135.

Skiba S., Drewnik M., 2003. Soil Map of the Polish Carpathian Mountains. Roczniki Bieszczadzkie 11, 15–20. (in Polish with English abstract)

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

Sommer, M., Thies, H., Kolb, E., Bachle, H., Stahr, K., 1997. Bio-geochemistry of a cirque-lake landscape – An interdisciplinary study in a catchment of the northern Black Forest, Germany. Water Resources Research 33, 2129–2142. https://doi.org/10.1029/97WR01501

Sommer, M., Halm, D., Weller, U., Zarei, M., Stahr, K., 2000. Lateral podzolization in a granite landscape. Soil Science Society of America Journal 64, 1434–1442. https://doi.org/10.2136/sssaj2000.6441434x

Sommer, M., Halm, D., Geisinger, C., Andruschkewitsch, I., Zarei, M., Stahr, K., 2001. Lateral podzolization in a sandstone catchment. Geoderma 103, 231–247. https://doi.org/10.1016/S0016-7061(01)00018-0

Stützer, A., 1998. Early stages of podzolisation in young aeolian sediments, western Jutland. Catena 32, 115–129. https://doi.org/10.1016/S0341-8162(98)00039-3

Szymański, W., Skiba, M., Skiba, S., 2011. Fragipan horizon degradation and bleached tongues formation in Albeluvisols of the Carpathian Foothills, Poland. Geoderma 167–168, 340–350. https://doi.org/10.1016/j.geoderma.2011.07.007

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

Ślączka, A., Kruglow, S., Golonka, J., Oszczypko, N., Popadyuk, I., 2006. The General Geology of the Outer Carpathians, Poland, Slovakia, and Ukraine. [In:] Golonka, J., Picha, F., (Eds.), The Carpathians and their foreland: Geology and hydrocarbon resources, AAPG Memoir 84, 221–258.

Towpasz, K., Zemanek, B., 1995. Vegetation. [In:] Warszyńska, J. (Ed.), The Polish Carpathians – Environment, human, and his activity. Wydawnictwo Uniwersytetu Jagiellońskiego, Kraków, 77–94. (in Polish)

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, pp. 475–490.

Uziak, S., 1962. Typology of some silty soils of the Carpathian Foothills. Annales UMCS, Sec. B., XXX, 1–60. (in Polish)

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

Waroszewski, J., Egli, M., Kabała, C., Kierczak, J., Brandova, D., 2016. Mass fluxes and clay mineral formation in soils developed on slope deposits of the Kowarski Grzbiet (Karkonosze Mountains, Czech Republic/Poland). Geoderma 264, 363–378. https://doi.org/10.1016/j.geoderma.2015.08.044

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.

Zasoński, S., 1981. Chief soil-forming processes on very fine sand rocks of the Wieliczka Foothills. Part I. General description of soils and some of their chemical properties. Roczniki Gleboznawcze – Soil Science Annual 32(2), 115–143. (in Polish with English abstract)

Zasoński, S., 1983. Main soil-forming processes in silty deposits of the Wielickie Foothills. Part II. Micromorphological properties. Roczniki Gleboznawcze – Soil Science Annual 34(4), 123–159. (in Polish with English abstract)

Zasoński, S., Skiba, S., 1988. Chemical and micromorphological properties of calcareous soils in the environs of Cieszyn. Roczniki Gleboznawcze – Soil Science Annual 39(3), 71–90. (in Polish with English abstract)

Występowanie bielicowania w glebach wytworzonych z fliszu na Pogórzu Wielickim (Zewnętrzne Karpaty Zachodnie, południowa Polska)

Słowa kluczowe

Bielicowanie
Progi pedogeniczne
Geneza gleb
Flisz
Pogórze Karpackie

Streszczenie

Proces bielicowania odgrywa kluczową rolę w kształtowaniu siedlisk leśnych i magazynowaniu węgla organicznego w glebach. Na Pogórzu Karpackim rozwój gleb bielicowych jest utrudniony przez właściwości materiału macierzystego – przede wszystkim bezwęglanowych utworów lessowych lub zwietrzeliny skał fliszowych. Sporadycznie na tym obszarze występują jednak gleby objęte procesem bielicowania. Celem pracy było określenie progu występowania bielicowania w glebach wytworzonych z fliszowego materiału macierzystego występującego lokalnie na Pogórzu Wielickim oraz określenie przestrzennego zróżnicowania gleb na badanych stokach. Wyniki wykazały, że przekroczenie progu bielicowania jest związane przede wszystkim z występowaniem materiału macierzystego o piaszczystym uziarnieniu i o niskiej zawartości frakcji iłowej oraz o niskiej zawartości żelaza. Ponadto, różnice w tempie rozkładu materii organicznej również mogą mieć wpływ na zainicjowanie w glebach procesu bielicowania. Gleby w badanym transekcie stokowym wykazały wzrost zawartości frakcji iłowej i pedogenicznych półtoratlenków żelaza i glinu w ujęciu katenalnym. Formowanie się akumulacyjnych gleb w niższych położeniach stokowych może być związane z wyższym pH materiału macierzystego, który wpływa na strącanie składników gleby z roztworu przemieszczającego się śródpokrywowo wzdłuż stoku. Ponadto skutki bocznego przepływu roztworów ograniczają obszar występowania intensywnego bielicowania. Dlatego też uwzględnienie efektów bocznego bielicowania ma kluczowe znaczenie dla prawidłowego określenia warunków siedliskowych lasu, oceny potencjału sekwestracji węgla organicznego, a także w kartografii gleb.