SOIL SCIENCE ANNUAL
2021, 72(4), 143892

https://doi.org/10.37501/soilsa/143892

Spatial variability of Brunic Arenosols and associated soils along the slope of the Słupia River valley (middle Pomerania, northern Poland)

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Received: 23.06.2021
Accepted: 11.11.2021
Associated editor: J. Waroszewski

Keywords

Brunic Arenosols
Soil formation
Slope processes
Fluvioglacial landscape
Soil properties

Abstract

This study was aimed at evaluating the spatial heterogeneity of the soil cover along the slope of the Słupia River valley (Middle Pomerania, northern Poland). Various soil properties are discussed in a context of parent material origin and its transformation through post-depositional processes, and the role of relief as a factor influencing the spatial variability of the soils and sediments. A broad spectrum of soil characteristics, including texture, contents of elements and indicators of soil eco-chemical state, weathering and pedogenesis, were determined from 10 soil profiles using standard procedures. Brunic Arenosols were a major component of the studied sequences. However, their morphology varied, reflecting the impact of the post-depositional transformation of their parent materials by water erosion and other processes typical for slopes. The Ti:Zr ratio suggested only a local-scale transformation of the primary deposits. Typically, soils from the upper slope locations and the transitional zone between the valley slope and the supra-flood terrace were characterised by lower solum thicknesses when compared to the slope foot, middle slope and valley bottom. The presence of colluvial horizons in some locations constituted evidence downslope sediment transport. Weathering features in the studied soils were evidenced by the presence of brown or rust coloured B horizons enriched in pedogenic forms of Fe and Al. The distribution of free Fe and Al along the studied slope suggested lateral transport of those elements. The soils strongly varied in terms of total organic C and N contents and stocks, the highest stocks of these being noted in soils from higher locations and the slope foot, and being the lowest in mid-slope locations. The P, K, Ca and Mg contents were typically low in these sandy soils. All the soils were characterised by typical pH and sorptive characteristics, although their spatial variability was considerable.

1. Introduction

Brunic Arenosols constitute one of the major components of soil cover in the temperate climatic zone. Sandy materials of glacial, fluvioglacial and aeolian origin, as well as the products of weathering of some certain rock types are typical substrates in their formation. The most characteristic feature of these soils is their relatively simple structure, with a rust-coloured B horizon (Bv, sideric) enriched in free sesquioxides, resulting from weathering and biogenic accumulation. Although the origin and properties of Brunic Arenosols have been the subject of many studies, there is no consensus among soil scientists on many of their aspects. The role of a periglacial environment in the formation of the Bv horizon and the age of the soils are the issues most discussed. Some authors (e.g. Kowalkowski and Nowak, 1968; Kowalkowski, 1976, 1977a; Manikowska, 1997) have highlighted the importance of frost weathering and the periglacial origin of Brunic Arenosols. However, r Prusinkiewicz (1965), Banaszuk (1977), Bednarek (1991) and Janowska (2001), among other authors, have found evidence of a Holocene origin and a great importance of vegetation in their formation. Degórski (2002) found correlations between parent material age (depositional period), climatic conditions and associated vegetation and certain characteristics of Brunic Arenosols. However, Bednarek (1991) and Janowska (1994, 2001) did not observe any correlation between the chemical properties of the Bv horizon and soil age.

Currently, Brunic Arenosols are mainly forest soils. They are most often covered by coniferous species, although some studies have indicated that they are also associated with deciduous forests (Ferczyńska-Uggla, 1976; Andrzejczyk and Sewerniak, 2016). Biały (1999) reported that, due to the high susceptibility of Brunic Arenosols to podzolisation, the use of coniferous species should be limited in forests. Błońska et al. (2013) demonstrated great variability in these soils in terms of enzymatic activity, which is strongly related to soil sub-type and vegetation richness. Forest Brunic Arenosols have been majorly affected by direct and indirect human activity in both past and modern times. Anthropogenic changes have affected the morphology and chemistry of the soils due to agricultural use (Czubaszek and Banaszuk, 2004; Dłużewski et al., 2019), deforestation and forest site preparation (Sewerniak et al., 2014), forest management practices (Łabęda and Kondras, 2020), military activities (Jankowski, 2019), charcoal production (Hirsch et al., 2018) and wildfires (Gonet, 2010), among many other things. The most commonly observed podsolisation is an effect of the introduction of coniferous monocultures into forests replacing the natural vegetation (Jankowski, 2014a). In this context, the importance of soil model areas, as refuges for close to natural Brunic Arenosols should be highlighted (Chojnicki et al., 2021).

The issue of the position in the landscape of Brunic Arenosols and their spatio-temporal linkage with other components of terrestrial ecosystems, in particular, other soils is of great interest, although still poorly explored. Brunic Arenosols occur in association with Podzols, Cambisols, Luvisols, Phaeozems and other soil units. The transition between Brunic Arenosols and other components of the soil cover is smooth, with sometimes only quantitative criteria allowing distinction between the soil reference groups (Janowska, 2001). Considering the importance of Brunic Arenosols in the temperate climatic zone, the dynamic changes that can be observed over the last few centuries as a result of various aspects of human activity and their stratigraphic position, further studies are highly recommended.

This study aimed to evaluate the spatial variability of Brunic Arenosols and associated soils along the slope of the Słupia River valley located in the landscape of Middle Pomerania (northern Poland). The various soil characteristics are discussed in a context of the origin of the parent material and its transformation through post-depositional processes, and the role of relief as a factor influencing the spatial heterogenity of the soils and sediments. The study covered a broad spectrum of soil characteristics, including texture, elemental content and indicators of soil eco-chemical state, weathering and pedogenesis.

2. Material and methods

The study was performed in northern Poland, south of Słupsk City (Fig. 1). The landscape of the studied area was developed by ice sheet transgression during the Pomeranian Phase of the Vistula Glaciation, followed by geomorphological processes in the periglacial zone during the Gardno Phase of the Vistula glaciation in addition to Holocene processes (Florek, 1991; Kozarski, 1995). The contemporary climate is relatively mild due to the influence of the Baltic Sea. Mean annual temperatures for the period 1950–2007 varied from 6.0 to 9.7°C (mean 7.8°C) whereas the annual sum of precipitation is from 521.7 to 1260.5 mm (mean 793.8 mm) (Kirschenstein and Baranowski, 2008). The study involved 10 soil profiles

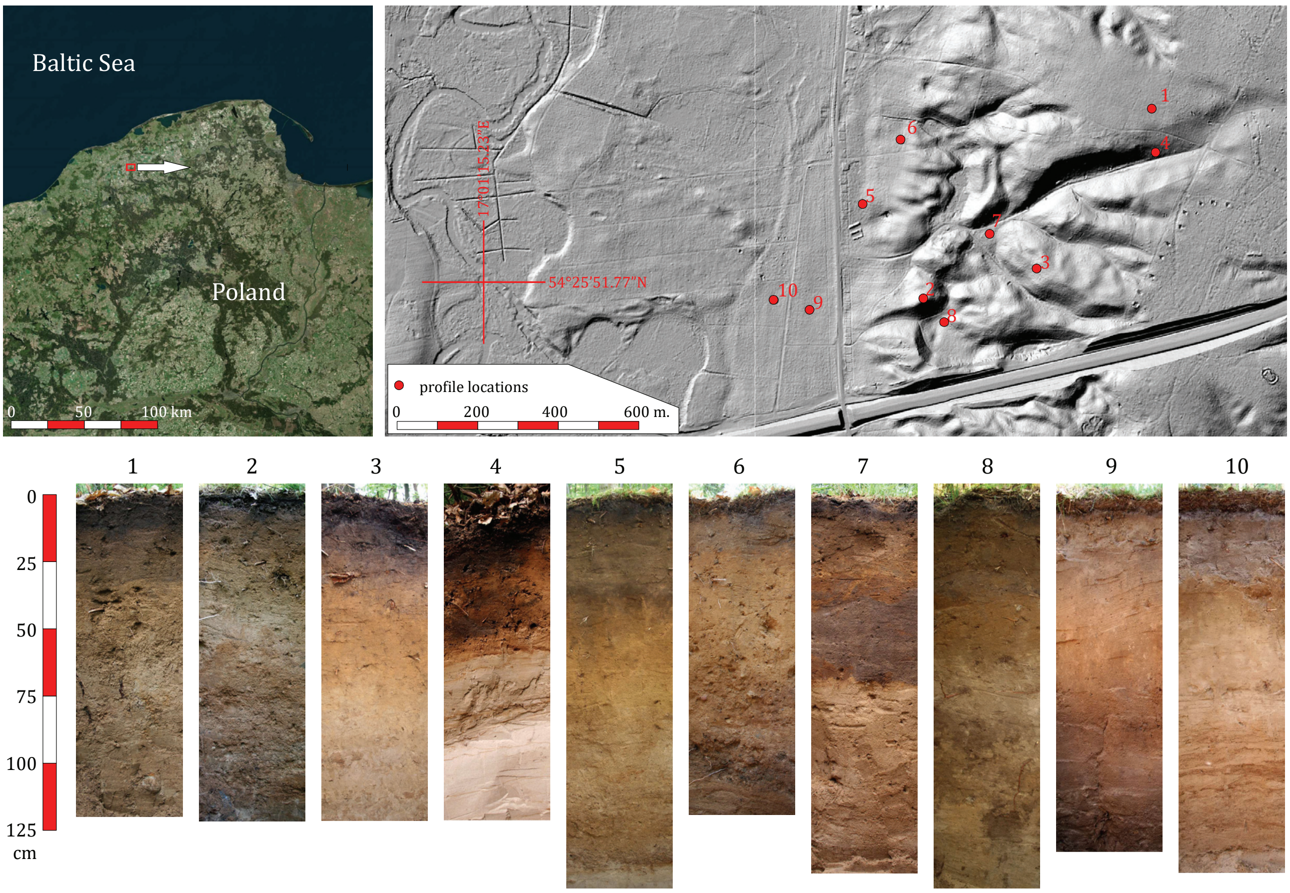

Fig. 1. Locations and morphology of the studied soils

distributed along a toposequence of the west-facing slope of the Słupia River valley. The slope was strongly affected by water erosion, which is reflected in its morphology (Fig. 1). The soil sequence covered the marginal part of the plateau (location 1), built-up of glacial till covered with a thin layer of fluvioglacial sand; dissected land elevations covered with residual deposits over glacial till (location 2); several slope locations within fluvioglacial sandy cover (locations 3–6); the bottom parts of a dry valley partially filled with colluvial deposits over fluvioglacial sand (locations 7 and 8) and the transitional zone between the river valley slope and the supra-flood terrace (locations 9 and 10) (Fig. 1, Table 1). The area is currently afforested, with Scots pine predominating in the tree layer.

One soil pit was done at each location. The soils were described using the Food and Agriculture Organization of the United Nations (FAO, 2006) criteria, classified according to the World Reference Base (WRB) system (IUSS Working Group WRB, 2015) and then sampled. One disturbed sample and two undisturbed 100 cm^3 samples were taken from each soil horizon. Undisturbed samples were dried at 105°C and weighted. The disturbed samples were air-dried and sieved through a 2.0 mm sieve to remove the gravel fraction. Analyse of the earth fraction included:

- Particle-size distribution using the mixed pipette and sieve methods. Polish Soil Science Society (PTG 2009) classification of textural fractions and groups was applied; Bulk density of the undisturbed samples using the gravimetric method;
- pH in a suspension with water and 1 mol dm^{-3} KCl solution at a soil:water/KCl ratio of 1:2.5 for the mineral samples and 1:10 for the organic samples using the potentiometric method;
- Total organic carbon (TOC) and nitrogen (N) contents by dry combustion (Vario MacroCube, Elementar Germany);
- Total contents of P, K, Ca, Mg, Fe, Al, Ti and Zr by inductively coupled plasma atomic emission spectrometry (ICP-OES, Avio 200, Perkin Elmer) after samples digestion in a mixture of 40% HF, 65% HNO_3 and 38% HCl in the proportion 5:3:2 by volume;
- The contents of free Fe (Fe_d) using the Mehra and Jackson (1960) extraction procedure, and amorphous Fe (Fe_o) and Al (Al_o) following extraction using the Schwertmann method (Van Reeuvijk, 1995). The elemental contents of the extracts were determined by ICP-OES;
- Exchangeable acidity (H_w) and the exchangeable Al (Al_w) content using the Sokolov method, and the content of exchangeable bases (Ca^{2+}, Mg^{2+}, K^+ and Na^+) using ICP-OES, after sample extraction in a 1 mol dm^{-3} solution of ammonium acetate, pH = 7.0. Based on the results, the sum of exchangeable bases (TEB) ($Ca^{2+} + Mg^{2+} + K^+ + Na^+$), the cation exchange capacity (CEC) (H_w + TEB) and the effective saturation of the soil sorption complex with basic cations ((TEB · 100%)/($Ca^{2+} + Mg^{2+} + K^+ + Na^+ + Al_w$)) were calculated.

The statistical analysis included obtaining the correlation coefficients and performing a cluster analysis. The analysis was performed using Past 3.0 software. Quantum GIS 2.18 was used for spatial visualisation of the results.

3. Results

3.1. Soil classification, morphology and basic physical characteristics

Eutric Umbric Planosols, developed from a thin cover of fluvioglacial sand over glacial till, were typical of the marginal zone of the plateau (Profile 1). Dystric Brunic Arenosols (Profiles 2, 3, 4, 6 and 9) and Dystric Albic Brunic Arenosols (Profile 10) constituted major components of eroded land elevations and slopes built from fluvioglacial and residual sands, whereas Brunic Umbrisols (Profile 5), Brunic Umbrisols (Colluvic) (Profile 8) and Dystric Arenosols (Colluvic) (Profile 7) occured at lower locations. The morphology of the soils varied along the slope, reflecting soil-forming processes, the predominant role of

Table 1
Basic characteristics of the studied profile locations

Profile number	Location in relief	Dominant (admixtures) species in tree layer*	Origin of parent material
1	Plateau	B (O)	Fluvioglacial sand over glacial till
2	Plateau	O	Residual sand over glacial till
3	Upper slope	P, B	Fluvioglacial sand
4	Middle slope	B (O,S)	Fluvioglacial sand
5	Foot slope	S,P (B)	Fluvioglacial sand
6	Foot slope	P (B)	Fluvioglacial sand
7	Dry valley bottom	O	Colluvium over fluvioglacial sand
8	Dry valley botton	O (M)	Colluvium over fluvioglacial sand
9	Fluvioglacial plain	P (O,H)	Fluvioglacial sand
10	Fluvioglacial plain	P (SB,O)	Fluvioglacial sand

P – Scots pine, SB – Siver birch, O – Pedunculated oak, H – European hornbeam, B – European beech, S – Norway spruce, M – Common maple various factors of soil formation and the spatial linkage between the components of the soil cover (Fig. 1). The solum depth varied from 44 to 120 cm, including transitional zones to the parent material and buried horizons. The thickness of the A horizons in the studied soils varied from 7 to 37 cm. This depth was the shallowest in the upper and mid-slope locations and the deepest at the slope foot and in the dry valley bottom. The A horizons in profiles 1, 5, 7 and 10 were characterised by a vertical heterogeneity. Weathering features occured in the soils as rust-coloured horizons (Bw), or a brownish-coloured upper part of the luvic horizon (EtBw) in profile 1. The morphology of the Bw horizons varied greatly, including the thickness, colour and transition into the C horizon (Table 2). In profiles 3, 4, 6, 7 and 9 the there was an initial podsolisation and/or there were lithological

Table 2
Particle-size distribution and basic physical characteristics of the studied soils

Horizon	Depth [cm]	Gravel %	Sand %	Silt %	Clay %	Texture*	Soil colour	Bulk density g cm^{-3}
Profile 1 – Eutric Umbric Planosol								
A	0–10	1.8	80.6	14.2	5.3	ls	10YR 2/2	0.88
A(p)	10–28	3.6	87.3	11.3	1.4	ls	10YR 2.5/3	1.45
EtBw	28–48	3.2	80.3	17.0	2.7	ls	10YR 4/5	1.56
2Btg	48–75	3.1	68.5	19.9	11.6	sl	10YR 4/4	1.68
2Cg	75–150	6.5	64.9	19.9	15.1	sl	10YR 4/6	1.71
Profile 2 – Dystric Brunic Arenosol								
A	0–20	7.2	86.3	12.8	0.9	s	7.5YR 3.5/4	1.40
Bw	20–54	10.0	85.0	13.8	1.1	ls	7.5YR 4/4	1.54
C	54–111	13.1	84.0	9.8	6.1	ls	7.5YR 4/5	1.65
2Cg	111–150	11.3	78.3	11.0	10.7	sl	10YR 5/3.5	1.82
Profile 3 – Dystric Brunic Arenosol								
AEs	0–8	2.9	91.2	6.8	1.9	s	10YR 3/1	1.35
Bwhs	8–39	2.2	91.5	6.7	1.8	s	10YR 2.5/3	1.41
Bw	39–63	1.7	94.7	5.2	0.1	s	10YR 4/6	1.36
BwC	63–78	2.2	93.6	6.4	0.1	s	10YR 5.5/6	1.44
C	78–150	1.6	91.1	8.4	0.5	s	10YR 5/4	1.61
Profile 4 – Dystric Brunic Arenosol								
AEs	0–7	3.0	91.2	5.9	2.9	s	7.5YR 2/2	1.21
Bwhs	7–21	1.7	97.5	2.4	0.0	s	10YR 4/5	1.41
Bw1	21–43	1.3	89.6	8.7	1.7	s	10YR 4/6	1.41
Bw2	43–53	9.9	93.7	4.7	1.6	s	7.5YR 4/6	1.54
C1	53–78	0.0	95.4	4.2	0.4	s	10YR 5/4	1.49
C2	78–150	0.0	95.1	4.9	0.0	s	10YR 6/3	1.45
Profile 5 – Brunic Umbrisol								
A1	0–7	1.2	89.3	5.1	5.7	s	7.5YR 2/1	1.26
A2	7–30	0.4	93.3	6.0	0.7	s	7.5YR 3/3	1.42
2A	30–37	0.5	93.0	5.8	1.2	s	7.5YR 3/2	1.40
2Bw	37–60	1.0	96.9	3.0	0.0	s	7.5YR 4/6	1.37
2BwC	60–77	1.5	99.2	0.8	0.0	s	7.5YR 4.5/6	1.48
2C1	77–140	6.1	99.4	0.6	0.0	s	10YR 5/4	1.58
2C2	140–150	0.3	93.9	6.1	0.0	s	10YR 6/4	1.49
Profile 6 – Dystric Brunic Arenosol								
A	0–18	2.4	95.4	4.0	0.6	s	7.5YR 4/4	1.41
Bw1	18–38	4.6	94.8	5.2	0.0	s	7.5YR 4/5	1.36
Bw2	38–70	15.8	96.5	3.2	0.2	s	7.5YR 5/7	1.46
C1	70–100	34.3	93.6	4.5	1.9	s	7.5YR 4/4	1.47
C2	100–150	8.5	91.1	3.2	5.6	s	10YR 5/4	1.60

Table 2, continue

Horizon	Depth [cm]	Gravel %	Sand %	Silt %	Clay %	Texture*	Soil colour	Bulk density g cm^{-3}
Profile 7 – Dystric Arenosol (Colluvic)								
A1	0–8	2.0	91.0	5.1	3.8	s	10YR 2/2	1.26
A2	8–28	5.6	95.9	4.1	0.0	s	10YR 4/4	1.61
Bw1	28–38	2.7	96.3	3.6	0.1	s	7.5 YR 4/4	1.48
A3	38–56	2.2	92.9	6.5	0.6	s	10YR 3/3.5	1.40
Bw2	56–63	4.3	98.5	1.4	0.1	s	7.5YR 4/4	1.39
2C	63–150	5.5	99.7	0.2	0.1	s	10YR 5/4	1.51
Profile 8 – Brunic Umbrisol (Colluvic)								
A	0–30	2.0	91.3	7.1	1.6	s	10YR 3/3	1.33
Bw	30–46	2.0	94.7	5.0	0.3	s	10YR 3/4	1.41
BwC	46–70	3.4	95.5	4.4	0.1	s	10YR 4/3	1.54
2Ab	70–97	3.5	96.1	3.9	0.0	s	10YR 4/3	1.48
2A/Cb	97–120	4.3	98.5	1.5	0.0	s	2.5Y 5/4	1.47
2Cb	120–150	3.5	98.3	1.8	0.0	s	2.5Y 5/4	1.55
Profile 9 – Dystric Brunic Arenosol								
A(p)	0–14	0.5	93.8	5.5	0.7	s	10YR 3/3	1.44
ABw	14–31	0.0	95.1	4.7	0.2	s	10YR 4/4	1.41
Bw	31–58	0.2	98.8	1.2	0.0	s	7.5YR 4/4	1.64
C1	58–90	0.9	99.1	0.9	0.0	s	10YR 4/6	1.59
C2	90–150	0.0	98.8	1.1	0.0	s	10YR 5/4	1.54
Profile 10 – Dystric Albic Brunic Arenosol								
AEs	0–3	0.0	98.2	1.8	0.0	s	10YR 4/1	1.48
AEs(p)	3–22	0.2	95.0	4.4	0.6	s	10YR 3/4	1.48
Bwhs	22–44	0.0	95.6	4.4	0.0	s	10YR 4/4	1.37
C1	44–70	1.0	98.3	1.7	0.0	s	10YR 5/4	1.45
C2	70–150	2.0	99.5	0.4	0.0	s	10YR 5/4	1.54

* s – sand; sl – sandy loam; ls – loamy sand

discontinuities. The bulk density ranged from 0.88 to 1.82 g cm^{-3}, showing a general increasing tendency with depth.

The soils were sandy in texture, except for the 2Btg and 2Cg horizons in profile 1 and the 2Cg horizon in profile 2, which were classed as sandy loam (Table 2). The clay content varied from 0.0 to 15.1%.

3.2. Chemical composition of the soils

The TOC content in the O horizons ranged from 212.3 to 572.0 g kg^{-1}, being the highest in the Oi horizons and the lowest in horizons Oe, or Oa. The A horizons contained 1.3–40.1 g kg^{-1} of TOC, whereas the B horizons had 1.3–12.6 g kg^{-1} (Table 3). The N content varied from 7.8 to 17.4 g kg^{-1} in the O horizons, from 0.13 to 2.13 g kg^{-1} in the A horizons and from 0.08 to 0.56 g kg^{-1} in the B horizons. The content of both elements generally decreased with depth. The C:N ratio varied from 22.4 to 60.0 in the ectohumus, reflecting the tree species composition of the stand and/or the site conditions. In the mineral horizons, the ratio varied from 7.0 to 22.6. The P content was from 0.55–1.54 g kg^{-1} in O horizons, 0.19–0.52 g kg^{-1} in the A horizons, 0.20–0.75 g kg^{-1} in the B horizons and 0.14–0.41 g kg^{-1} in the C horizons (Table 3). This element showed a general decreasing tendency with depth in most of the profiles.

Potassium occurred in amounts of 1.00–5.45 g kg^{-1} in the O horizons, 6.37–9.24 g kg^{-1} in the A horizons, 7.09–11.65 g kg^{-1} in the B horizons and 7.21–12.72 g kg^{-1} in the C-horizons, showing a general increasing tendency with depth (Table 3). The richer horizons were those developed from glacial till or residual materials as compared to fluvioglacial sand or colluvial deposits. The Ca content ranged from 1.31 to 3.84 g kg^{-1} in the O horizons, from 0.66 to 1.96 g kg^{-1} in the solum and from 0.84 to 2.27 g kg^{-1} in the parent materials. Similarly, the Mg content was 0.44–1.21 g kg^{-1}; 0.16–1.18 g kg^{-1} and 0.20–1.61 g kg^{-1}, respectively.

The Ti and Zr contents were determined and the Ti:Zr ratio was used as indicator of lithological heterogeneity. The O horizons contained 22.9–989.0 mg kg^{-1} of Ti, whereas the mineral horizons, including the solum and parent materials, had 346.9–2521.2 mg kg^{-1}. This element was characterised by variable depth tendencies. Generally comparable tendencies were observed for Zr, although that element occurred at several

Table 3
pH and total content of organic carbon and major nutrients in the studied soils

Horizon	Depth [cm]	pH-H_2O	pH-KCl	TOC g kg^{-1}	N g kg^{-1}	P g kg^{-1}	K g kg^{-1}	Ca g kg^{-1}	Mg g kg^{-1}	C:N
Profile 1 – Eutric Umbric Planosol										
Oi	4–1	4.6	4.0	479.7	12.89	0.88	2.85	2.66	1.21	37.2
Oe	1–0	4.8	4.2	489.9	16.73	0.97	2.26	3.84	1.20	29.3
A	0–10	3.4	2.8	39.0	2.13	0.45	9.24	1.26	0.76	18.3
A(p)	10–28	4.3	3.6	11.0	0.65	0.33	9.24	1.28	0.61	16.9
EtBw	28–48	4.5	3.8	3.2	0.41	0.24	10.74	1.53	1.16	7.8
2Btg	48–75	4.9	3.5	1.7	0.24	0.22	11.65	1.27	0.92	7.0
2Cg	75–150	4.9	3.2			0.30	12.72	1.44	1.37	
Profile 2 – Dystric Brunic Arenosol										
Oi	1–0	4.1	3.5	512.2	15.09	1.12	2.41	1.85	0.65	33.9
A	0–20	4.1	3.5	11.7	0.67	0.27	8.12	1.57	0.61	17.6
Bw	20–54	4.7	3.8	4.7	0.36	0.22	9.39	1.96	0.91	13.1
C	54–111	5.1	3.1			0.22	9.68	1.56	1.61	
2Cg	111–150	5.6	3.2			0.24	9.96	1.40	1.04	
Profile 3 – Dystric Brunic Arenosol										
Oi	12–7	4.5	3.7	572.0	10.71	0.61	1.00	1.54	0.55	53.4
Oe	7–0	3.3	2.3	438.4	13.43	0.57	2.59	2.65	0.54	32.6
AEs	0–8	3.5	2.7	14.8	0.78	0.19	7.00	0.95	0.40	19.0
Bwhs	8–39	3.8	3.1	12.6	0.56	0.20	7.49	0.96	0.43	22.6
Bw	39–63	4.5	4.0	4.1	0.28	0.20	7.88	1.07	0.50	14.8
BwC	63–78	4.5	4.1	3.3	0.18	0.21	9.34	1.41	0.97	18.2
C	78–150	4.5	4.1			0.20	10.37	1.39	1.09	
Profile 4 – Dystric Brunic Arenosol										
Oi	11–6	4.4	3.7	518.7	10.67	0.75	1.66	2.01	0.63	48.6
Oe	6–0	3.5	2.6	267.4	7.87	0.60	5.45	1.50	0.61	34.0
AEs	0–7	3.9	3.1	23.8	1.48	0.28	8.21	1.22	0.37	16.2
Bwhs	7–21	4.5	3.8	7.0	0.53	0.24	9.02	1.20	0.51	13.2
Bw1	21–43	4.6	3.9	3.0	0.27	0.21	10.37	1.33	1.18	11.2
Bw2	43–53	4.7	4.1	1.4	0.16	0.24	10.08	1.48	0.74	8.6
C1	53–78	5.4	4.1			0.21	10.45	1.45	1.03	
C2	78–150	5.0	4.0			0.14	12.03	0.84	0.75	
Profile 5 – Brunic Umbrisol										
Oi	5–3	4.3	3.6	536.4	8.94	0.74	1.28	1.35	0.49	60.0
Oe	3–0	4.4	3.6	483.2	12.06	0.93	2.16	2.30	0.69	40.1
A1	0–7	3.7	2.9	40.1	1.91	0.34	7.70	1.26	0.34	20.9
A2	7–30	4.5	3.9	9.1	0.49	0.38	8.08	1.24	0.59	18.5
2A	30–37	4.7	4.1	10.6	0.55	0.42	7.57	1.15	0.40	19.2
2Bw	37–60	4.8	4.4	3.0	0.20	0.34	8.24	1.28	0.46	14.9
2BwC	60–77	4.8	4.5	1.3	0.08	0.24	7.95	1.18	0.52	16.6
2C1	77–140	4.9	4.6			0.21	8.51	1.65	0.50	
2C2	140–150	5.8	4.4			0.17	9.10	1.29	0.61	
Profile 6 – Dystric Brunic Arenosol										
Oi	6–4	4.2	3.5	551.0	10.32	0.82	1.32	1.57	0.55	53.4
Oe	4–0	4.5	3.9	531.4	15.66	1.10	1.41	2.65	0.79	33.9
A	0–18	4.4	3.9	7.6	0.48	0.24	7.05	1.15	0.34	15.8
Bw1	18–38	5.0	4.2	7.1	0.49	0.32	7.09	1.27	0.32	14.4
Bw2	38–70	5.4	4.3	1.5	0.15	0.28	7.95	1.60	0.84	9.7
C1	70–100	5.1	3.9			0.25	8.80	1.69	1.23	
C2	100–150	7.2	5.6			0.29	9.92	2.27	1.34	

Table 3, continue

Horizon	Depth [cm]	$pH\text{-}H_2O$	pH-KCl	TOC g kg^{-1}	N g kg^{-1}	P g kg^{-1}	K g kg^{-1}	Ca g kg^{-1}	Mg g kg^{-1}	C:N
Profile 7 – Dystric Arenosol (Colluvic)										
A1	0–8	4.5	3.6	28.9	1.75	0.46	7.52	1.31	0.27	16.5
A2	8–28	4.8	4.1	5.7	0.48	0.49	8.24	1.19	0.39	11.9
Bw1	28–38	4.9	4.1	5.6	0.41	0.61	7.90	1.06	0.20	13.5
A3	38–56	4.5	3.8	6.9	0.48	0.37	7.98	0.96	0.16	14.5
Bw2	56–63	5.0	4.3	3.0	0.33	0.53	7.68	1.13	0.20	9.1
2C	63–150	5.0	4.4			0.28	8.01	1.28	0.44	
Profile 8 – Brunic Umbrisol (Colluvic)										
Oi	3–0	4.7	4.1	543.0	17.38	1.54	2.15	2.34	0.78	31.2
A	0–30	4.3	3.8	9.4	0.75	0.35	8.30	1.13	0.45	12.7
Bw	30–46	4.5	3.8	5.7	0.43	0.45	7.47	1.00	0.32	13.5
BwC	46–70	4.7	4.0	2.4	0.32	0.37	7.77	1.10	0.33	7.3
2Ab	70–97	4.8	3.9	1.9	0.23	0.25	7.70	1.09	0.36	8.1
2A/Cb	97–120	5.1	4.1	1.3	0.13	0.26	8.41	1.38	0.69	10.2
2Cb	120–150	5.1	4.2			0.19	8.68	1.50	0.76	
Profile 9 – Dystric Brunic Arenosol										
Oi	6–4	4.6	4.2	456.1	10.92	1.14	3.55	1.31	0.56	41.8
Oe	4–2	4.0	3.0	248.3	11.10	0.74	4.40	1.92	0.52	22.4
Oa	2–0	3.7	2.6	368.3	13.87	0.82	2.83	1.61	0.48	26.5
A(p)	0–14	4.7	4.0	8.5	0.45	0.47	7.50	1.08	0.44	19.0
ABw	14–31	4.8	4.3	8.8	0.51	0.52	7.71	1.11	0.41	17.1
Bw	31–58	5.0	4.5	1.6	0.13	0.31	8.33	1.29	0.43	12.3
C1	58–90	5.0	4.7			0.18	7.21	1.13	0.20	
C2	90–150	5.0	4.7			0.15	7.42	1.15	0.27	
Profile 10 – Dystric Albic Brunic Arenosol										
Oi	6–4	4.4	3.8	479.8	10.75	1.09	1.94	1.42	0.48	44.6
Oe	4–2	4.2	3.0	360.2	13.01	0.88	2.15	2.81	0.62	27.7
Oa	2–0	3.8	2.7	212.3	7.84	0.55	3.60	1.38	0.44	27.1
AEs	0–3	4.2	3.2	15.7	0.81	0.20	6.37	0.66	0.27	19.3
AEs(p)	3–22	4.5	3.7	5.1	0.29	0.34	6.66	0.74	0.18	17.6
Bwhs	22–44	4.9	4.4	5.5	0.37	0.75	7.10	1.01	0.30	14.6
C1	44–70	5.2	4.4			0.41	8.07	1.54	0.49	
C2	70–150	5.5	4.5			0.27	7.69	1.55	0.58	

times lower concentrations the Ti, at 0.7–99.9 mg kg^{-1} in the O horizons, 40.4–230.7 mg kg^{-1} in the solum and 25.2–323.9 mg kg^{-1} in the C horizons.

3.3. Forms of iron and aluminium

The total Fe content (Fe_t) varied from 0.21 to 4.95 g kg^{-1} in the O horizons and from 2.26 to 19.54 g kg^{-1} in the mineral horizons, including the parent materials. The richest were those horizons developed from glacial till (12.56–19.54 g kg^{-1}), whereas the poorest horizons were of colluvial origin (2.68–5.88 g kg^{-1}). The vertical distribution of the element varied among the studied profiles (Table 4). Free Fe (Fe_d) occurred in amounts of 0.30–5.96 g kg^{-1}. Its content usually decreased with depth, except in profiles 1 and 6. The Fe_o content ranged from 0.10 to 1.03 g kg^{-1}, showing a general decreasing tendency with depth. The Fe_d/Fe_t ratio varied from 0.04 to 0.58, indicating variable rates of weathering of the mineral substrates. The wide spectrum of Fe_o/Fe_d ratio indicated strongly variable degree of crystallisation of free iron oxides. This generally increased with depth.

The total Al (Al_t) content was higher than the Fe_t content. The O horizons contained 0.37–9.79 g kg^{-1} of that element, whereas the mineral horizons had 10.37–23.09 g kg^{-1} (Table 4). Based on the mean values, differences between the soil horizons developed from various substrates were not great. Amorphous Al (Al_o) occurred in amounts of 0.24–3.07 g kg^{-1}, with the highest values being in the A or Bw horizons and the lowest in the parent materials. Typically, higher Al_o contents occured in lower locations compared to the plateau or upper slopes. The Al_o/Al_t ratio ranged from 0.01 to 0.22, except the O horizons.

Table 4
Iron and aluminum forms in the studied soils

Horizon	Depth [cm]	Fe_t g kg⁻¹	Fe_d g kg⁻¹	Fe_o g kg⁻¹	Fe_d/Fe_t	Fe_o/Fe_d	Al_t g kg⁻¹	Al_o g kg⁻¹	Al_o/Al_t
Profile 1 – Eutric Umbric Planosol									
Oi	4–1	1.72					2.35		
Oe	1–0	1.65					2.34		
A	0–10	7.52	3.49	1.92	0.46	0.55	17.79	1.05	0.06
A(p)	10–28	8.29	3.71	1.93	0.45	0.52	17.60	1.41	0.08
EtBw	28–48	10.12	3.52	1.58	0.35	0.45	23.09	1.18	0.05
2Btg	48–75	16.12	4.84	1.29	0.30	0.27	18.89	0.65	0.03
2Cg	75–150	19.54	5.96	1.11	0.30	0.19	20.77	0.57	0.03
Profile 2 – Dystric Brunic Arenosol									
Oi	1–0	0.30					0.45		
A	0–20	7.93	4.20	1.47	0.53	0.35	16.21	1.17	0.07
Bw	20–54	9.84	3.50	0.55	0.36	0.16	13.52	0.87	0.06
C	54–111	10.17	2.86	0.78	0.28	0.27	21.63	0.45	0.02
2Cg	111–150	12.56	0.47	0.43	0.04	0.91	13.89	0.44	0.03
Profile 3 – Dystric Brunic Arenosol									
Oi	12–7	0.21					0.37		
Oe	7–0	3.11					6.32		
AEs	0–8	4.64	2.55	1.50	0.55	0.59	12.45	0.52	0.04
Bwhs	8–39	4.90	2.76	1.89	0.56	0.68	13.63	0.92	0.07
Bw	39–63	5.14	2.47	1.35	0.48	0.55	15.32	1.73	0.11
BwC	63–78	6.33	2.12	1.04	0.34	0.49	18.27	1.66	0.09
C	78–150	6.56	1.76	0.65	0.27	0.37	18.35	0.92	0.05
Profile 4 – Dystric Brunic Arenosol									
Oi	11–6	0.85					1.24		
Oe	6–0	4.95					9.79		
AEs	0–7	5.80	2.34	1.18	0.40	0.50	14.03	0.77	0.05
Bwhs	7–21	7.37	2.45	1.10	0.33	0.45	14.58	1.52	0.10
Bw1	21–43	8.14	2.28	0.63	0.28	0.28	19.51	1.11	0.06
Bw2	43–53	9.02	2.88	0.53	0.32	0.19	17.15	1.00	0.06
C1	53–78	7.94	1.79	0.54	0.23	0.30	15.04	0.64	0.04
C2	78–150	5.37	0.68	0.22	0.13	0.32	15.04	0.35	0.02
Profile 5 – Brunic Umbrisol									
Oi	5–3	0.27					0.55		
Oe	3–0	1.57					2.17		
A1	0–7	4.97	2.66	1.35	0.54	0.51	13.79	0.77	0.06
A2	7–30	5.44	2.83	1.36	0.52	0.48	15.38	1.32	0.09
2A	30–37	4.91	2.84	1.39	0.58	0.49	15.14	1.81	0.12
2Bw	37–60	4.54	2.11	0.81	0.46	0.38	16.14	2.21	0.14
2BwC	60–77	3.44	1.54	0.47	0.45	0.30	14.27	1.18	0.08
2C1	77–140	2.99	0.84	0.30	0.28	0.35	15.75	0.50	0.03
2C2	140–150	3.56	0.60	0.25	0.17	0.42	14.45	0.51	0.04
Profile 6 – Dystric Brunic Arenosol									
Oi	6–4	0.30					0.63		
Oe	4–0	0.73					1.21		
A	0–18	4.74	2.24	1.20	0.47	0.53	12.96	1.11	0.09
Bw1	18–38	5.69	2.76	1.31	0.48	0.47	14.92	2.21	0.15
Bw2	38–70	8.13	2.00	0.45	0.25	0.22	15.91	1.33	0.08
C1	70–100	10.41	3.00	0.54	0.29	0.18	16.89	0.75	0.04
C2	100–150	8.51	2.18	0.36	0.26	0.16	19.27	0.24	0.01

Table 4, continue

Horizon	Depth [cm]	Fe_t g kg⁻¹	Fe_d g kg⁻¹	Fe_o g kg⁻¹	Fe_d/Fe_t	Fe_o/Fe_d	Al_t g kg⁻¹	Al_o g kg⁻¹	Al_o/Al_t
Profile 7 – Dystric Arenosol (Colluvic)									
A1	0–8	4.43	2.00	1.08	0.45	0.54	13.56	0.83	0.06
A2	8–28	5.88	2.43	1.22	0.41	0.50	15.42	1.75	0.11
Bw1	28–38	4.98	2.61	1.79	0.52	0.68	15.01	2.12	0.14
A3	38–56	4.31	2.20	1.10	0.51	0.50	13.83	0.75	0.05
Bw2	56–63	4.63	2.12	1.22	0.46	0.57	14.36	2.04	0.14
2C	63–150	4.01	1.17	0.36	0.29	0.30	14.40	0.74	0.05
Profile 8 – Brunic Umbrisol (Colluvic)									
Oi	3–0	0.60					0.99		
A	0–30	5.02	2.52	1.43	0.50	0.57	15.27	0.99	0.07
Bw	30–46	3.84	1.85	1.28	0.48	0.69	13.30	1.01	0.08
BwC	46–70	2.68	0.83	0.48	0.31	0.58	13.80	0.68	0.05
2Ab	70–97	2.45	0.42	0.26	0.17	0.62	13.47	0.65	0.05
2A/Cb	97–120	3.40	0.58	0.25	0.17	0.42	15.40	0.92	0.06
2Cb	120–150	3.39	0.38	0.10	0.11	0.28	15.50	0.67	0.04
Profile 9 – Dystric Brunic Arenosol									
Oi	6–4	0.21					0.46		
Oe	4–2	2.82					7.79		
Oa	2–0	3.00					6.46		
A(p)	0–14	4.86	2.36	1.54	0.49	0.65	13.93	1.33	0.10
ABw	14–31	4.54	2.22	1.54	0.49	0.69	15.63	2.82	0.18
Bw	31–58	3.93	1.21	0.74	0.31	0.61	14.76	1.37	0.09
C1	58–90	2.47	0.80	0.43	0.32	0.53	11.81	0.59	0.05
C2	90–150	2.26	0.49	0.23	0.22	0.47	12.52	0.52	0.04
Profile 10 – Dystric Albic Brunic Arenosol									
Oi	6–4	0.31					0.50		
Oe	4–2	1.89					3.72		
Oa	2–0	2.67					6.15		
AEs	0–3	2.39	0.85	0.42	0.35	0.49	10.37	0.25	0.02
AEs(p)	3–22	3.42	1.50	0.90	0.44	0.60	10.52	0.57	0.05
Bwhs	22–44	4.00	1.67	1.49	0.42	0.89	13.76	3.07	0.22
C1	44–70	4.30	0.31	0.29	0.07	0.93	13.49	1.63	0.12
C2	70–150	2.54	0.30	0.12	0.12	0.38	14.71	0.84	0.06

3.4. Sorptive properties and pH

The reaction of the soils varied from strongly acidic to close to neutral (pH-H_2O 3.3–7.2; pH-KCl 2.3–5.6). The lowest pH was typically noted in the Oe and Oa ectohumus sub-horizons or the A horizons (Table 3). There the pH increased with depth and was the highest in the parent material. The acidic nature of the soils was confirmed by the ionic composition of the soil sorption complex. In most cases H^+ and Al^{3+} predominated over basic cations, except in the Btg and Cg horizons in profile 1, the Cg horizon in profile 2 and the C2 horizon in profile 6 (Table 5). The H_w varied from 0.05 to 4.77 $cmol_{(+)}$ kg^{-1}, whereas TEB ranged from 0.03 to 3.79 $cmol_{(+)}$ kg^{-1}. In all the soils, Ca^{2+} was the major basic cation. The CEC varied from 0.08 to 5.84 $cmol_{(+)}$ kg^{-1}, and was positively correlated with clay (r = 0.721) and TOC (r = 0.746). It was the highest in the A horizons, decreasing with depth. There was also a clear spatial tendency, with higher CEC values noted in the plateau soils developed from glacial till or residual materials as compared to fluvioglacial sands or colluvic materials.

Table 5
Sorptive characteristics of the studied soils

Horizon	Depth [cm]	Na^+	K^+	Ca^{2+}	Mg^{2+}	H_w	Al_w	CEC	BS*
				$cmol_{(+)}\ kg^{-1}$					%
Profile 1 – Eutric Umbric Planosol									
A	0–10	0.03	0.07	0.18	0.12	4.77	2.13	5.17	15.8
A(p)	10–28	0.02	0.04	0.14	0.05	2.51	1.41	2.75	14.5
EtBw	28–48	0.03	0.06	0.29	0.09	1.66	0.94	2.13	33.1
2Btg	48–75	0.03	0.12	2.01	0.40	2.16	1.22	4.72	66.8
2Cg	75–150	0.04	0.16	2.48	0.89	2.26	1.25	5.84	74.1
Profile 2 – Dystric Brunic Arenosol									
A	0–20	0.04	0.03	0.11	0.08	2.57	1.44	2.83	15.4
Bw	20–54	0.02	0.03	0.14	0.06	1.81	1.04	2.07	19.8
C	54–111	0.03	0.06	0.89	0.68	1.75	0.98	3.41	62.8
2Cg	111–150	0.05	0.10	2.55	1.09	1.17	0.66	4.96	85.2
Profile 3 – Dystric Brunic Arenosol									
AEs	0–8	0.02	0.02	0.09	0.06	3.08	1.46	3.27	11.5
Bwhs	8–39	0.02	0.02	0.04	0.05	3.10	1.59	3.24	7.8
Bw	39–63	0.01	0.01	0.04	0.01	0.78	0.43	0.86	15.0
BwC	63–78	0.01	0.02	0.04	0.02	0.54	0.31	0.63	22.1
C	78–150	0.02	0.03	0.03	0.03	0.68	0.39	0.78	20.2
Profile 4 – Dystric Brunic Arenosol									
AEs	0–7	0.02	0.05	0.31	0.15	3.01	1.37	3.54	28.0
Bwhs	7–21	0.02	0.03	0.03	0.03	1.85	1.03	1.95	8.9
Bw1	21–43	0.01	0.03	0.02	0.03	1.99	1.12	2.09	7.6
Bw2	43–53	0.01	0.02	0.02	0.02	1.13	0.64	1.20	10.7
C1	53–78	0.01	0.02	0.27	0.08	0.79	0.45	1.17	45.8
C2	78–150	0.01	0.03	0.02	0.04	1.20	0.69	1.30	12.5
Profile 5 – Brunic Umbrisol									
A1	0–7	0.06	0.07	0.87	0.20	3.26	1.37	4.46	46.6
A2	7–30	0.02	0.02	0.08	0.02	1.18	0.65	1.32	17.9
2A	30–37	0.02	0.01	0.07	0.01	0.67	0.37	0.78	22.8
2Bw	37–60	0.01	0.01	0.02	0.01	0.26	0.15	0.31	22.6
2BwC	60–77	0.01	0.01	0.01	0.01	0.16	0.09	0.19	28.5
2C1	77–140	0.01	0.01	0.01	0.01	0.11	0.06	0.15	40.6
2C2	140–150	0.01	0.02	0.05	0.04	0.15	0.09	0.27	56.9
Profile 6 – Dystric Brunic Arenosol									
A	0–18	0.02	0.02	0.09	0.02	0.83	0.42	0.98	26.4
Bw1	18–38	0.02	0.01	0.10	0.02	0.56	0.32	0.70	31.2
Bw2	38–70	0.01	0.02	0.10	0.03	0.30	0.17	0.46	47.5
C1	70–100	0.02	0.04	0.35	0.12	0.89	0.48	1.43	52.5
C2	100–150	0.03	0.06	2.65	0.19	0.10	0.04	3.03	98.5

Table 5, continue

Profile 7 – Dystric Arenosol (Colluvic)									
A1	0–8	0.02	0.10	1.53	0.33	2.39	0.98	4.37	66.9
A2	8–28	0.01	0.03	0.04	0.01	1.39	0.69	1.47	11.0
Bw1	28–38	0.01	0.03	0.04	0.01	0.84	0.43	0.93	17.1
A3	38–56	0.01	0.02	0.06	0.01	1.40	0.70	1.51	12.8
Bw2	56–63	0.03	0.02	0.03	0.01	0.51	0.25	0.60	26.5
2C	63–150	0.00	0.01	0.02	0.01	0.35	0.15	0.40	24.6
Profile 8 – Brunic Umbrisol (Colluvic)									
A	0–30	0.01	0.03	0.07	0.02	1.78	0.86	1.92	13.9
Bw	30–46	0.01	0.01	0.04	0.01	1.24	0.58	1.31	11.3
BwC	46–70	0.01	0.01	0.03	0.01	0.84	0.39	0.91	13.4
2Ab	70–97	0.02	0.01	0.03	0.01	1.10	0.52	1.18	13.0
2A/Cb	97–120	0.01	0.01	0.03	0.01	0.73	0.34	0.80	16.1
2Cb	120–150	0.01	0.02	0.03	0.03	0.54	0.27	0.63	23.3
Profile 9 – Dystric Brunic Arenosol									
A(p)	0–14	0.01	0.03	0.04	0.02	0.93	0.50	1.03	16.2
ABw	14–31	0.01	0.01	0.04	0.01	0.47	0.25	0.54	21.5
Bw	31–58	0.01	0.01	0.01	0.01	0.15	0.09	0.19	27.3
C1	58–90	0.01	0.01	0.01	0.01	0.05	0.03	0.08	53.6
C2	90–150	0.01	0.01	0.01	0.01	0.10	0.06	0.13	37.4
Profile 10 – Dystric Albic Brunic Arenosol									
AEs	0–3	0.02	0.05	0.09	0.05	1.40	0.56	1.61	27.1
AEs(p)	3–22	0.01	0.02	0.03	0.02	0.96	0.47	1.03	13.9
Bwhs	22–44	0.01	0.01	0.04	0.01	0.47	0.25	0.54	21.3
C1	44–70	0.01	0.01	0.02	0.01	0.36	0.21	0.42	20.6
C2	70–150	0.01	0.01	0.02	0.01	0.14	0.08	0.18	32.8

*effective saturation with bases

4. Discussion

Parent material origin and relief are considered to be highly important factors influencing the spatio-temporal variability of soil cover at various scales (Jenny, 1941; Konecka-Betley et al., 1994; Janowska, 2001; Jonczak et al., 2013). These factors directly influence soil-forming processes and many soil characteristics. Moreover, indirect effects can impact the water regime (Moeslund et al., 2013), vegetation (Florinsky and Kuryakova, 1996) and microclimatic conditions (Macyk et al., 1978) among other things. The role of the parent material is mainly as a substrate for soil-forming processes. It has certain properties that determine, within a certain range, the direction of soil development. Meanwhile, relief is considered to be factor in internally differentiating sediments from various depositional environments and determining slope processes. The strong linkage between these two factors, and the linkage between them and the other factors involved in soil formation determine large heterogeneity in the soil cover over post-glacial landscapes. Brunic Arenosols are common components of such landscapes.

The studied profiles covered soils with a wide spectrum of morphological, physical and chemical characteristics. Eutric Umbric Planosols from the plateau (profile 1) were characterised by their bipartite texture. According to current understanding, the vertical variability of textural parameters in that soil reference group (and related groups, according to the WRB classification) can result from lessivage and/or lithological discontinuity (Świtoniak, 2006). Contrasting differences between the upper (A, A(p) and EtBw) and underlying (2Btg and 2Cg) horizons, in terms of texture and a sharp transition from the EtBw into the 2Btg horizon, indicate a greater importance of lithology over lessivage in the studied case. Considering the low vertical variability in the Ti:Zr ratio (Fig. 2), it can be stated that glacial till (present in the 2Btg and 2Cg horizons) was also the primary source of

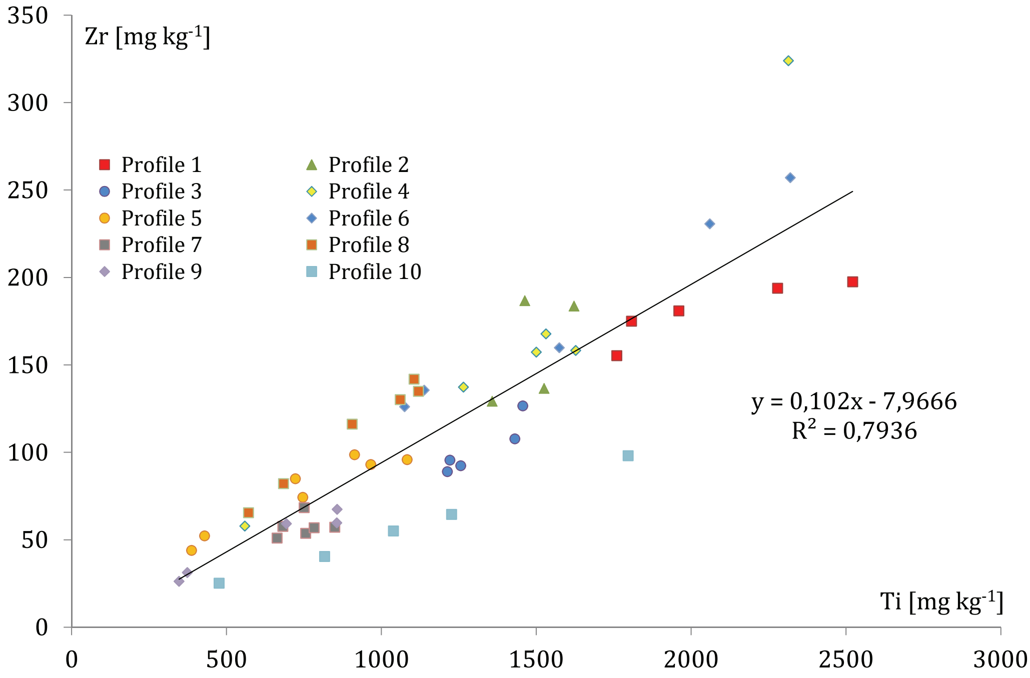

Fig. 2. Correlation between total contents of Ti and Zr in the studied soils excluding O-horizons

the mineral substrates for the upper horizons. The top layer of till was transformed by fluvial processes, although redeposition of these sediments occurred only on local scale. The Ti and Zr contents were strongly positively correlated, and the Ti:Zr ratio was characterised by relatively low variability (7.1–14.9 in the mineral horizons of profiles 1–9). The ratio was slightly higher in profile 10, which was located in a transitional zone between the valley slope and the supra-flood terrace. The land elevations dissected by dry valleys are covered by coarse-textured, gravel-enriched (Table 2) residual materials overlying glacial till (profile 2). Typically, Dystric Brunic Arenosols occur in such locations. These soils are also typical in slope locations. However, their morphology and certain characteristics varied along the slope, with soils from an upper location (profile 3) and the transitional zone between the valley slope and the supra-flood terrace (profile 10) being characterised by thinner sola compared to the lower and middle slopes or valley bottom (profiles 4, 6, 9). The presence of colluvial horizons in some profiles constituted evidence of downslope sediment transport. Deep A horizons (Umbric) in profile 8 represented an effect of that process, with the soil being classed as a Brunic Umbrisol (Colluvic). Erosion intensification probably resulted in denudation of the primary soil in profile 7, followed by covering by stratified colluvium (Fig. 1).

The Bw horizons varied greatly in the profiles, including in terms of thickness and colour. The transition into the C horizon was usually gradual, which is typical for this soil reference group (Konecka-Betley et al., 1994; Degórski, 2002; Brożek and Zwydak, 2010). In profile 4, located on the slope, the transition was sharp. This might suggest relocation of only the developed Bw horizon, constituting evidence of strong erosion in the post-glacial landscape, with advanced pedogenesis. The observed spatial variability in the advancement of the soil-forming processes in the Brunic Arenosols, based on morphological features, was confirmed by the chemical indicators. The Fe_t and Al_t contents were relatively low (Table 5), although typical of soils developed from sandy materials (Janowska, 2001; Brożek and Zwydak, 2010; Jonczak et al., 2013). The Fe_d content varied among the profile locations and horizons, showing a general downslope decreasing tendency. The vertical distribution of Fe_d in profile 1 also suggests a considerable intensity of weathering in the upper parts of the parent material. This observation requires more detailed study. In the Brunic Arenosols, the highest Fe_d contents were noted in the B or A horizons. The Fe_d/Fe_t ratio showed great vertical variability in the profiles and low spatial variability in the studied sequence. The spatial differences between the soils are more evident when comparing the stocks of Fe_d in soil pedons (1 x 1 m wide and 1.5 m deep) (Table 6). A clear downslope decreasing tendency, from 12.23 kg m^{-2} in profile 1 to 1.45 kg m^{-2} in profile 10, was recorded. Malczyk (1988) reported a different distribution pattern for Fe_t in an aeolian landscape, with the lowest content occurring in the dune top and the highest on the slope foot.

The Fe_o/Fe_d ratio, as a measure of free iron amorphism (Konecka-Betley, 1968; Pokojska, 1979), showed great variability in the studied soils (Table 4). Typically, the highest values were recorded in the A horizons, indicating the poor crystallisation of sesquioxides, and the values then decreased with depth. This is a common tendency in Brunic Arenosols. Poor crystallisation in the A horizon can be explained as an inhibitory effect caused by humic substances (Cornell and Schwertmann, 1979). Generally, soil profiles in lower relief locations are characterised by lower sesquioxide crystallinity than in higher locations. This is probably result of a higher moisture content and the downslope transport of Fe_o following its accumulation in depressions in the landscape. This process "lateral podsolization" is common in hilly landscapes, resulting in the formation of reddish horizons enriched in sesquioxides (Sommer et al., 2000; Jankowski, 2014b). Soils containing such horizons were noted in locations

Table 6
Stocks of selected components in the studied soils up to 150 cm excluding O-horizons

Component	Unit	Profile number									
		1	2	3	4	5	6	7	8	9	10
TOC	kg m^{-2}	8.08	5.76	9.19	4.57	8.81	4.55	7.62	7.14	4.51	3.78
N	kg m^{-2}	0.59	0.38	0.46	0.34	0.47	0.33	0.54	0.65	0.27	0.23
P	kg m^{-2}	0.69	0.58	0.45	0.40	0.59	0.62	0.81	0.66	0.59	0.81
Fe_d	kg m^{-2}	12.23	6.04	4.79	3.21	3.41	5.33	3.67	2.27	2.40	1.45
H_w	$mol_{(+)}$ m^{-2}	54.82	41.48	28.55	29.66	9.90	9.83	16.76	22.46	4.88	7.86
TEB	$mol_{(+)}$ m^{-2}	59.98	44.54	2.38	3.50	2.43	27.32	3.40	1.86	1.00	1.21
CEC	$mol_{(+)}$ m^{-2}	114.80	86.02	30.93	33.16	12.33	37.15	20.17	24.32	5.88	9.07

around the studied area. The downslope transport of sesquioxides was also confirmed by the distribution of Al_o, with higher concentrations being typical of lower, rather than higher, locations. The vertical transport of Al_o, constituting evidence of podsolization was seen in the majority of the studied profiles. The displacement of labile Al fractions is an indicator of the early stages of podsolisation, before any visual effects have developed (Bednarek, 1991). Moreover, Kuźnicki and Skłodowski (1974) stated that podsolization intensity in Brunic Arenosols is strongly controlled by the origin of the parent material, whereas Konecka-Betley (1977) highlighted the importance of the presence of humic substances, particularly fulvic acids.

The accumulation of organic matter is an inherent process in soil formation. Sandy soils, including Brunic Arenosols, are usually poor in that component. The studied soils varied greatly in terms of TOC content (Table 3) and stocks (Table 6). The highest stocks were generally noted in the soils from higher locations and from the slope foot. A limited impact of water erosion on the soils from the upper locations and the deposition of organic matter rich colluvic materials at the slope foot locations are likely the major factors influencing the large accumulations of TOC in those soils. There were comparable tendencies in the spatial distributions of TOC and N, which were strongly positively correlated, particularly in the mineral horizons (r = 0.983). The spatial variability of the C:N ratio indicates heterogeneity in the studied environment, in terms of trophic conditions. Typically, P occurred in its highest amounts in the O horizons and in its lowest amounts in the parent material. The observed general downslope increasing tendency in the P contents and stocks in the mineral horizons suggests lateral transport of that element and its accumulation in depressions in the landscape. Irrespective of the observed spatial variability, the P contents in the studied soils is considered to be low, and comparable to observations by other authors on Brunic Arenosols (Okołowicz et al., 2003; Brożek and Zwydak, 2010). Sandy substrates are also usually poor in K, Ca and Mg (Kuźnicki et al., 1974), and this is confirmed here (Table 3). These elements are usually more enriched in Brunic Arenosols influenced by high groundwater levels (Kowalkowski, 1977b).

Brunic Arenosols are typically acidic soils (Janowska, 2001; Brożek and Zwydak, 2010). All the studied soils showed increasing pH with depth in their mineral horizons. This can be explained by the percolative water regime and the influence of forest vegetation as a source of the acidity (Augusto et al., 2002). Spatial variability was unexpectedly low in this regard. Considering the soil pH, a predominance of acidic ions in the soil sorption complex would be expected. This was confirmed here for the majority of horizons. More than 50% of basic cations were recorded only in the parent materials of profiles 1, 2, 3, 5 and 6. There was an interesting spatial distribution of acidic ion stocks in the soil pedons of up to 150 cm. Much higher stocks were observed in the upper locations, followed by the mid-slopes and the lowest stocks in the foot slope locations, suggesting a significant role of relief as a factor influencing soil sorption. This tendency is clearer from the sum of the acidic and basic cations (Table 6). The importance of relief as a factor in soil sorptive properties is still poorly understood. Its role can be viewed in the context of erosion and downslope sediment transport. A high positive correlation between CEC and TOC content highlights the significant role of humic substances.

5. Conclusions

Our findings confirm the significant roles of lithology, relief and slope processes as factors influencing the formation and spatial variability of soil cover in young glacial landscapes. The soil cover of the studied toposequence was dominated by Dystric Brunic Arenosols, Dystric Albic Brunic Arenosols and Brunic Umbrisols. The origin of the parent material, and its transformation by water erosion and other processes typical of slopes, strongly influenced the soil morphology and various other characteristics along the studied slope. Although the spatial and vertical variability of the textural parameters suggested varied origins for the soil mineral substrates, the low variability of the Ti:Zr ratio confirmed only a local-scale transformation of soil mineral substrates. Typically, the soils from the upper slope locations and the transitional zone between the valley slope and supra-flood terrace were characterised by thinner sola compared to the soils from the slope foot, the middle slope or the valley bottom. The presence of colluvial horizons in some locations constituted evidence of downslope sediment transport. The brown or rust coloured B horizons enriched in pedogenic forms of Fe and Al constituted evidence of strong weathering. The spatial distribution of sesquioxides suggested their lateral transport. The soils varied greatly in terms of TOC content and stock. The highest stocks were noted in the soils from higher locations and from the slope foot, and were lowest in the mid-slope locations, highlighting the importance of erosion as a factor influencing soil organic matter accumulation. A comparable tendency was seen for N, and both N and TOC were strongly positively correlated. The contents of P, K, Ca and Mg were low, as is typical of sandy soils developed from fluvioglacial substrates. All of the soils had pH values and sorptive characteristics typical of Brunic Arenosols, although their spatial variability was large. Higher CEC values were recorded in the higher locations, followed by the upper and mid-slopes, with the lowest found at the slope foot.

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Przestrzenne zróżnicowanie gleb rdzawych i gleb towarzyszących wzdłuż stoku doliny Słupi (Pomorze Środkowe, północna Polska)

Słowa kluczowe

Gleby rdzawe
Geneza gleb
Procesy stokowe
Krajobraz fluwioglacjalny
Właściwości gleb

Streszczenie

Badania miały na celu ocenę przestrzennego zróżnicowania pokrywy glebowej w obrębie fluwioglacjalnej toposekwencji na stoku doliny Słupi w okolicach Słupska. Procesy glebotwórcze i właściwości gleb dyskutowano w kontekście pochodzenia materiałów macierzystych i ich transformacji w procesach post-sedymentacyjnych, a także roli rzeźby terenu jako czynnika determinującego przestrzenną zmienność gleb i osadów. W 10 profilach glebowych oznaczono szerokie spektrum właściwości stosując standardowe metody, m.in. uziarnienie, zawartość pierwiastków ogółem, wskaźniki stanu eko-chemicznego oraz wskaźniki zwietrzenia i zaawansowania procesów glebotwórczych. Uzyskane wyniki potwierdziły duże znaczenie litologii i rzeźby terenu jako czynników w rozwoju gleb i kształtowaniu ich przestrzennej zmienności. Głównym składnikiem pokrywy glebowej w badanej sekwencji były gleby rdzawe, które wykazywały zróżnicowanie morfologiczne odzwierciedlające wpływ przekształceń post-depozycyjnych osadów wskutek erozji wodnej, a także innych procesów typowych dla stoków. Wartości stosunku Ti:Zr sugerują jednak jedynie lokalne przekształcenia pierwotnych osadów. Mniejszą miąższością solum w obrębie badanego stoku charakteryzowały się gleby przykrawędziowej części wysoczyzny, górnych części stoków oraz strefy przejściowej pomiędzy stokami a dnem doliny Słupi w porównaniu z glebami dolnych części stoków i den dolinek erozyjnych. Obecność poziomów pochodzenia deluwialnego w niektórych lokalizacjach stanowi zapis procesów erozji w minionych czasach. Katenalne rozmieszczenie wolnych i amorficznych form Fe i Al wskazuje na śródglebowe przemieszczenie tych substancji wraz z wodami. Badane gleby silnie różnią się pod względem zawartości oraz zasobów węgla organicznego i azotu. Największe zasoby tych składników notowano w glebach wysoczyzny i podnóży stoków, zaś najmniejsze w obrębie środkowych partii stoków. Zawartości P, K, Ca i Mg były typowe dla gleb piaszczystych. Wszystkie gleby wykazywały typowe wartości pH i właściwości sorpcyjne, jednakże zmienność katenalna była w tym zakresie znacząca.