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Evolution of Sandy Soils within Deflation Hollows in Shifting Areas of Sand – a Case Study from the Błędów Desert (Poland)

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Abstract

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Areas of shifting sand are important places for testing the effects of abiotic and biotic factors on soil morphology and evolution, where aeolian processes cause dynamic changes in the natural environment. The main aim of the study was to determine the evolution of soils within deflation hollows in shifting sands. In the context of this purpose, representative study areas were selected: (1) a reference surface in a plantation forest with soils undisturbed by aeolian processes – one pedon, (2) an active deflation hollow – two pedons, (3) a deflation hollow stabilized by reforestation (forest planting ca. 30 and ca. 100 years ago – two pedons). Soil morphology and micromorphology as well as several physical and chemical properties were analyzed. In a deflation hollow, the studied soils are found at various stages of development, mostly characterized by a relatively rapid accumulation of soil organic matter. A well-developed buried illuvial B horizon as an 'ortstein' material can limit aeolian erosion to a certain depth, while above these horizons aeolian erosion and accumulation remain active. History of changes in the environment is to a substantial degree reflected in morphology and micromorphology of the studied soils.

Keywords: aeolian processes; drift sand; ortstein; podzolization; reforestation; soil development

Areas of shifting sand under conditions of humid temperate climate are important places for testing the effects of abiotic and biotic processes on soil morphology, because in such zones the relatively dynamic changes in the natural environment caused by aeolian processes are easily observable (Maddelein & Lust 1992; Lichter 1998; Sparrius *et al.* 2013). A series of events has induced a drift of sands or the creation of a shifting sand area. In West and Central Europe, intensive land use connected with sheep grazing, deforestation, and gathering of sod, which began in the Middle Ages and lasted until the 1850s, resulted in the activation of shifting sands (Maddelein & Lust 1992; Sparrius *et al.* 2013). The development of mining and metallurgy increased the demand for wood, which caused further deforestation and activation of shifting sands in industrial areas (Rahmonov *et al.* 2006). Large-scale planting of pine, which fixed shifting sands in place, was introduced in the 20th century in many areas. Small areas were left without vegetation and were supposed to protect valuable psammophilous habitats or meant to be used for military purposes (Sparrius *et al.* 2013). In Poland, the history of shifting sands is well-represented by the area of the Błędów Desert (Rahmonov & Oleś 2010) and by a large number of smaller areas (currently military training areas) (Jankowski & Sewerniak 2013). Such terrain is highly appropriate for a study of the early stages of soil formation and further development of the soil profile (Sparrius *et al.* 2013).

Most research studies concerning the evolution and functioning of soils in areas of shifting sand are focused on the inland dunes of Belgium (Maddelein

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& Lust 1992), Denmark (Stützer 1998; Mikkelsen *et al.* 2007), the Netherlands (Elgersma 1998), Poland (Jankowski & Sewerniak 2013), and also the United States (Lichter 1998). Some studies focus on coastal dunes (e.g. studies by Jones *et al.* 2008 in Great Britain). However, only a few studies deal with the problem of soil formation within deflation hollows (Maddelein & Lust 1992; Stützer 1998), where both erosion (deflation) and accumulation produce observable effects.

The main aim of the paper was to describe the evolution of soils identified in deflation hollows in areas of shifting sand. A secondary aim was to assess using the soil and its morphologic and micromorphologic properties as an indirect tool for reading the changes in the natural environment.

MATERIAL AND METHODS

Study area. The study area is located in the northern and eastern parts of the Błędów Desert, in southern Poland (Figure 1a, b). The mean annual air temperature in the study area is 7°C and the annual precipitation is 650 to 750 mm. The Błędów Desert is formed of fluvioglacial sand with an admixture of gravel from the Pleistocene. The sand is underlain by Tertiary carbonate rocks (Alexandrowiczowa 1962).

In the Early Holocene, this area was reinforced by forest vegetation dominated by Scots pine (*Pinus sylvestris*). In the Middle Ages, with the development of mining and metallurgy of silver and lead, as well as due to cattle grazing and the gathering of litter for economic purposes, the study area became completely deforested. The groundwater table also became lowered as a result of mining (ca. 30 m below ground level). All of these factors contributed to the destruction of the soil cover and exposed sand to drifting (Figure 2a, b). In the middle of the 20th century, the shifting sand surface area in the study locality reached 15 km^2. To stabilize the sand shifting, the Błędów Desert reforestation mainly with *Pinus sylvestris* was initiated in the 20th century (Figure 2c) (Rahmonov *et al.* 2006).

Fieldwork and laboratory analysis. In order to analyze the effects of changes in the natural environment on morphology and soil properties across the studied deflation surface (Figure 1b), five pedons were selected (Table 1). Reference pedon No. 1 (Figure 2d) was selected at a distance of ca. 0.5 km from the Błędów Desert in a plantation forest (age of forest stand: ca. 100 years) (Figure 2c). It was an area with reference soil representing the natural soils found in the study area. Pedons No. 2 and 3 were then selected in an active deflation hollow (Figure 2b): pedon No. 2 (Figure 2e) – without vegetation, pedon No. 3 (Figure 2f) – partly stabilized by xeric sand grasslands (*Koeleria* Pers. sp., *Corynephorus* L. sp.). Pedons No. 4 and 5 represent surfaces of shifting sand stabilized at different times due to reforestation: pedon No. 4 (Figure 2g) – soils fixed ca. 30 years ago after the planting of pine, pedon No. 5 (Figure 2h) – soils fixed after the planting of pine ca. 100 years ago.

The studied pedons were first excavated in the field, described, and then sampled. One large, representative bulk sample (ca. 2 kg) was collected from each genetic horizon. In addition, undisturbed soil samples were collected for micromorphologic analysis.

The bulk samples were air dried, gently crushed using a wooden rolling pin, and then sieved through a 2 mm steel sieve. Soil samples from O horizons were milled after the living parts of plants in the samples had been removed. The particle size distribution was determined by wet sieving (sand fractions) and the hydrometer method (silt and clay fractions) (Gee

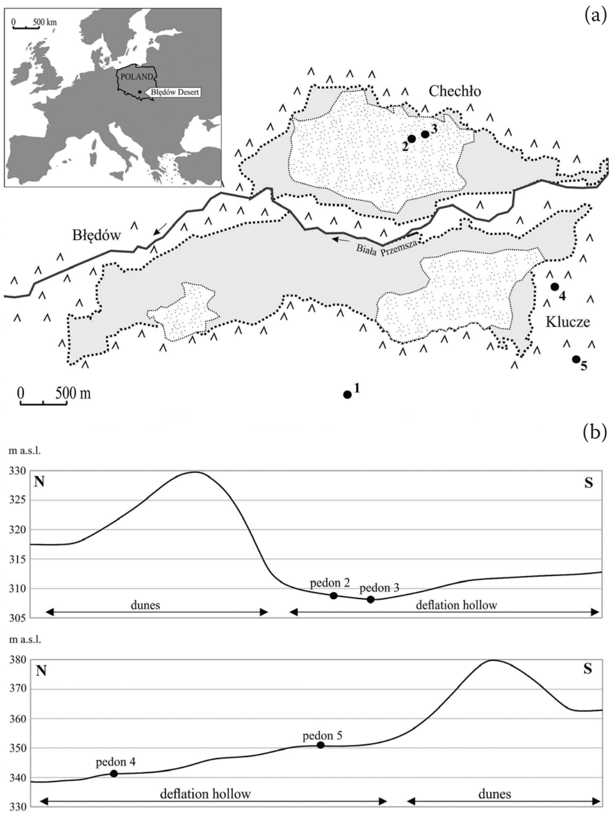

Figure 1. Location of study sites: (a) location map; (b) position of study sites in relief – scheme

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& Bauder 1986). Total carbon content (C_{tot}) and total nitrogen content (N_{tot}) were determined via dry combustion gas chromatography using a CHNS analyzer (vario MICRO cube; Elementar Analysensysteme GmbH, Langeselbold, Germany). Next, pH was measured in deionized water (1:2.5 soil/water ratio) (Thomas 1996). The optical density of the oxalate extract (ODOE) was measured according to Van Reeuwijk (2002). Micromorphologic studies were then performed using a polarizing microscope using thin sections (76 mm × 51 mm × ca. 25 µm; vertical orientation). In the micromorphologic study, terminology given by Stoops (2003) was used. Soils were classified according to the WRB system (IUSS Working Group WRB 2014).

RESULTS

Soil morphology. A thick (8 cm) dark humus A horizon situated beneath a thick ectohumus organic O horizon, formed of forest litter at different stages of decomposition (Oi-Oe-Oa), was found in the reference pedon No. 1 (Figure 2d). The next horizon was a thick bright eluvial E horizon (Table 1). There was also a sequence of illuvial B horizons (total of 25 cm), which consisted of a brownish-black Bshm horizon with cementation features as well as a reddish Bs horizon divided into Bs1 and Bs2 subhorizons found below the E horizon. A BC horizon began below 55 cm, which served as a transition to parent material C, which was light yellow-grey fluvioglacial sand. Single grain structure and loose consistence were typical of the entire profile excluding Bshm and Bs1 horizons, where massive structure and very hard (Bshm horizon) or slightly hard (Bs1 and Bs2 horizons) consistence were observed (Table 1).

Pedons representing the deflation hollow, where wind erosion (deflation) as well as accumulation processes remain active (No. 2 and 3) have morphology similar to that of the reference pedon from a certain depth (Figures 2e, f). From depths of 32 and 22 cm, respectively, a sequence of buried Bshm-Bs-BC-C horizons occurs, whose colour, structure, and consistence are the same as those of pedon No. 1 (Table 1). The uppermost parts of both pedons are formed of layered sand material, showing single grain structure and loose consistence (Table 1).

In pedon under the ca. 30-year pine stand (No. 4, Figure 2g) a weakly developed organic Oi horizon and a humus A horizon occur (Table 1), while in the pedon under the ca. 100-year forest stand (No. 5, Figure 2h) a horizon sequence Oi-Ah-A-E1 occurs to a depth of 20 cm. Both mentioned pedons show distinct layering below the A horizon (No. 4) and below the E1 horizon (No. 5). Some parts of pedon No. 5 differ from each other slightly in colour; therefore,

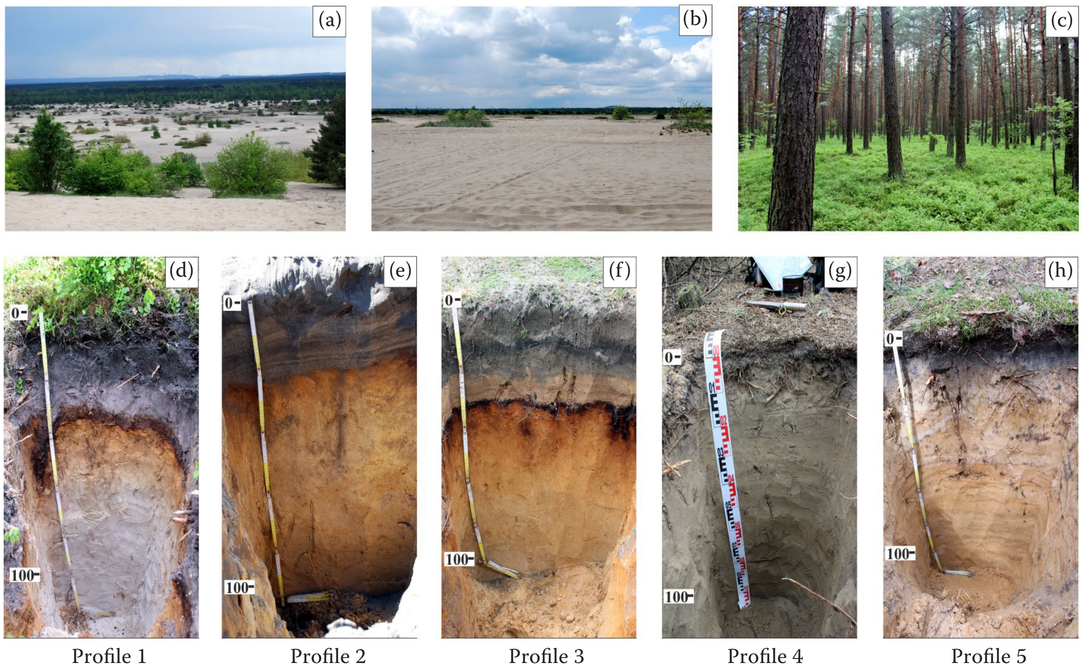

Figure 2. Study area: (a) deflation hollow – general view; (b) deflation hollow; (c) plantation forestry (planted in 1912); (d) pedon No. 1; (e) pedon No. 2; (f) pedon No. 3; (g) pedon No. 4; (h) pedon No. 5

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Table 1. Properties of studied soils

Horizon	Depth (cm)	Munsell colour (moist)	Structure/ consistence/ roots	Other features	Fine soil (%) sand	silt	clay	pH	C_{tot} (%)	C/N	ODOE
Pedon No. 1. Albic Ortsteinic Podzol (Arenic); 50°19'24''N; 19°30'57''E; 318 m a.s.l.; plantation forest (*Pinus sylvestris*, planted in 1912)											
Oi	0–1	slightly decomposed organic matter						4.6	47.10	27	–
Oe	1–4	moderately decomposed organic matter						3.9	46.27	28	–
Oa	4–8	highly decomposed organic matter						3.7	35.72	28	–
A	8–16	10YR 4/1	SG/LO/+++	–	94	6	0	4.4	0.99	–	–
E	16–30	7.5YR 5/2	SG/LO/++	–	97	3	0	4.8	0.25	–	0.028
Bshm	30–34	7.5YR 1.7/1; 7.5YR 4/6	SG, MA/VHA/+	CC-FO	91	9	0	4.8	3.31	30	0.475
Bs1	34–36	7.5YR 4/6; 7.5YR 2/3	SG, MA/VHA/+	–	94	5	0	4.9	–	–	0.132
Bs2	36–55	10YR 5/8	SG/SHA/+	–	97	3	0	4.7	–	–	0.018
BC	55–65	10YR 7/4; 10YR 6/6; 7.5YR 4/6	SG/LO/–	–	98	2	0	5.0	–	–	–
C1	65–105	10YR 8/3	SG/LO/–	L	98	1	0	5.2	–	–	–
C2	105–150+	10YR 8/2	SG/LO/–	L	97	2	0	5.2	–	–	0.013
Pedon No. 2. Podzol (Arenic, Areninovic); 50°21'29''N; 19°31'7''E; 310 m a.s.l.; no vegetation											
C1	0–7	2.5Y 4/3	SG/LO/–	L	99	1	0	5.2	0.15	–	–
C2	7–14	2.5Y 5/3	SG/LO/–	L	117	3	0	5.2	0.13	–	–
C3	14–22	2.5Y 4/3	SG/SHA/–	L	98	2	0	5.2	0.10	–	0.018
Bshm/Bsb	22–30	10YR 5/6; 7.5YR 4/6	SG/SHA/–	CB-FO	98	1	0	5.8	0.23	–	0.020
BCb	30–60	10YR 6/6	SG/SHA/–	–	99	0	0	5.9	0.10	–	–
C1	60–70	10YR 7/4	SG/LO/–	L	99	1	0	6.0	–	–	–
C2	70–130+	10YR 7/4	SG/LO/–	L	100	0	0	6.5	–	–	0.009
Pedon No. 3. Ortsteinic Podzol (Arenic, Areninovic); 50°21'29''N; 19°31'9''E; 309 m a.s.l.; Xeric sand grasslands (*Koeleria* Pers. sp., *Corynephorus* L. sp.)											
AC1	0–12	2.5Y 4/3	SG/LO/+++	L	98	2	0	6.0	0.46	11	–
AC2	12–18	2.5Y 3/3	SG/LO/+++	L	96	4	0	5.9	0.60	14	–
C1	18–23	2.5Y 4/3	SG/LO/++	L	98	2	0	6.1	0.21	–	0.009
C2	23–32	10YR 5/4	SG/SHA/+	L	98	2	0	6.1	0.14	–	0.023
Bshmb	32–34	5YR 2/3; 5YR 4/8	AB/VHA/+	CC-FO	94	7	0	5.9	1.16	24	0.333
Bsb1	34–36	7.5YR 4/6; 7.5YR 5/8; 5YR 2/3	AB/HA/+	–	97	3	0	6.1	–	–	0.061
Bsb2	36–46	10YR 6/8; 10YR 5/6; 10YR 3/2; 7.5YR 5/8	SG/SHA/–	–	97	3	0	5.4	–	–	0.016
Bsb3	46–65	10YR 6/8; 10YR 4/2; 7.5YR 3/4	SG/SHA/–	–	98	2	0	5.7	–	–	–
BCb1	65–80	10YR 7/6	SG/SHA/–	–	99	2	0	5.2	–	–	–
BCb2	80–100	10YR 7/6	SG/SHA/–	–	98	1	0	5.2	–	–	–
C	100–130+	10YR 7/4	SG/SHA/–	L	99	2	0	5.2	–	–	0.010
Pedon No. 4. Arenosol (Aeolic); 50°20'25''N 19°52'38''E; 341 m a.s.l.; plantation forest (*Pinus sylvestris*, planted in 1992)											
Oi	0–1	slighly decomposed organic matter						4.4	42.12	47	–
A	1–5	2.5Y 4/2	SG/LO	–	95	5	0	5.0	1.19	–	–
C1	5–20	2.5Y 5/3	SG/LO/++	L	100	1	0	5.1	0.15	–	–
C2	20–38	2.5Y 5/4	SG/LO/+	L	100	0	0	5.3	–	–	–

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Table 1 to be contunued

Horizon	Depth (cm)	Munsell colour (moist)	Structure/ consistence/ roots	Other features	Fine soil (%)			pH	C_{tot} (%)	C/N	ODOE
					sand	silt	clay				
C3	38–75	2.5Y 5/4	SG/LO/–	L	100	1	0	5.7	–	–	–
C4	75–130+	2.5Y 5/3	SG/SHA/–	L	99	1	0	4.9	–	–	–
Pedon No. 5. Albic Arenosol (Aeolic); 50°19'57"N; 19°32'58"E; 363 m a.s.l.; plantation forest (*Pinus sylvestris*, planted in 1922)											
Oi	0–2	slightly decomposed organic matter						4.2	50.25	34	–
Ah	2–9	2.5Y 2/1	SB/LO/++	–	77	22	2	5.5	9.98	24	–
A	9–13	2.5Y 4/1; 2.5Y 4/3; 2.5Y 3/1	SG/LO/++	–	94	5	2	4.6	1.23	–	–
E1	13–20	2.5Y 5/3	SG/LO/+++	L	97	2	1	4.6	–	–	–
E2	20–25	2.5Y 5/4	SG/LO/+++	L	92	8	0	5.0	–	–	0.060
B1	25–40	2.5Y 6/4; 2.5Y 7/4; 10YR 6/8; 2.5Y 5/4	SG/LO/+	L	98	2	0	4.7	–	–	0.059
B2	40–55	10YR 6/4; 10YR 4/3; 10YR 7/4	SG/LO/+	L	97	3	0	4.7	–	–	–
B3	55–65	10YR 5/6; 10YR 4/6	SB/SHA/+	L	94	4	1	4.8	–	–	–
C1	65–80	10YR 5/8	SG/SHA/+	L	89	8	2	5.2	–	–	–
C2	80–140+	10YR 6/6	SG/LO/–	L	93	6	1	5.1	–	–	0.014

Structure: SG – single grain; MA – massive; AB – angular blocky; SB – subangular blocky; Consistence: LO – loose; SO – soft; SHA – slightly hard; HA – hard; VHA – very hard; Roots: +++ – many; ++ – common; + – few; – – absence
Other features: L – layering of sand; CC-FO – cementation continuous (> 90%) iron-organic matter, CB-FO – cementation broken (< 50%) iron-organic matter; C_{tot} – content of total carbon; ODOE – optical density of oxalate extract

they can be distinguished: E horizons and B horizons – both with single grain structure and loose consistence. The parent material of these soils consists of layered aeolian sand (Table 1).

Micromorphologic studies of individual genetic horizons show that they are made of the same material, but differ in terms of pedogenic features (Figure 3). The soil material is composed mostly of somewhat rounded and well-rounded quartz grains (Figures 3a–c, d, l, k). There is also a small quantity of feldspar, mica (muscovite), chlorite, and heavy minerals (tourmaline, garnet, zircon). In coarse material, remains of poorly decomposed roots and charcoal maintaining their tissue structure (Figures 3h, j) are observable. The fine fraction shows concentrations of amorphous humus as well as compounds of iron, manganese, and aluminum (Figures 3d, f h, l). Eluvial E horizons can be characterized by single-grain microstructure, while angular blocky microstructure occurs in illuvial B horizons. In illuvial B horizons, distinctive pedofeatures can be readily observed. Concentrations of iron and manganese compounds and humus occur in the form of coatings (hypocoatings and quasi-coatings), black (7.5YR 1.7/1) and very dark, red-brown (5YR 2/3) in colour in the 'ortstein' Bshm horizon (Figures 3b, d–g, l–o) and brown (7.5YR 4/6) in colour in the Bs horizon (Figure 3c). The presence of iron infillings, Fe-Mn nodules, iron bridges binding quartz grains (Figure 3n), humus infillings, and zones of depletion or enrichment in iron compounds were also observed. Finally, the eluvial E horizon and parent material horizons do not exhibit micromorphologic pedofeatures (Figure 3a).

Physical and chemical properties of soils. All the studied soil profiles possess a texture consisting of mostly medium-grained sand (Table 1). The sand content (2.0–0.05 mm) was more than 90%, silt content (0.05–0.002 mm) did not exceed 10%, and clay content (< 0.002 mm) was less than 4%. Most of the studied soils have acid soil reaction. The topmost part (1–16 cm) of the reference pedon (No. 1) and the Oi litter horizon in pedon No. 5 were characterized by strongly acid pH. The lower part (below 22 cm) of soil fixed by xeric sand grassland (pedon No. 2) and most of pedon No. 3 (to a depth of 65 cm) had a moderately acidic pH.

Total carbon (C_{tot}) content measured in ectohumus O horizons was higher than 35% (Table 1), while in

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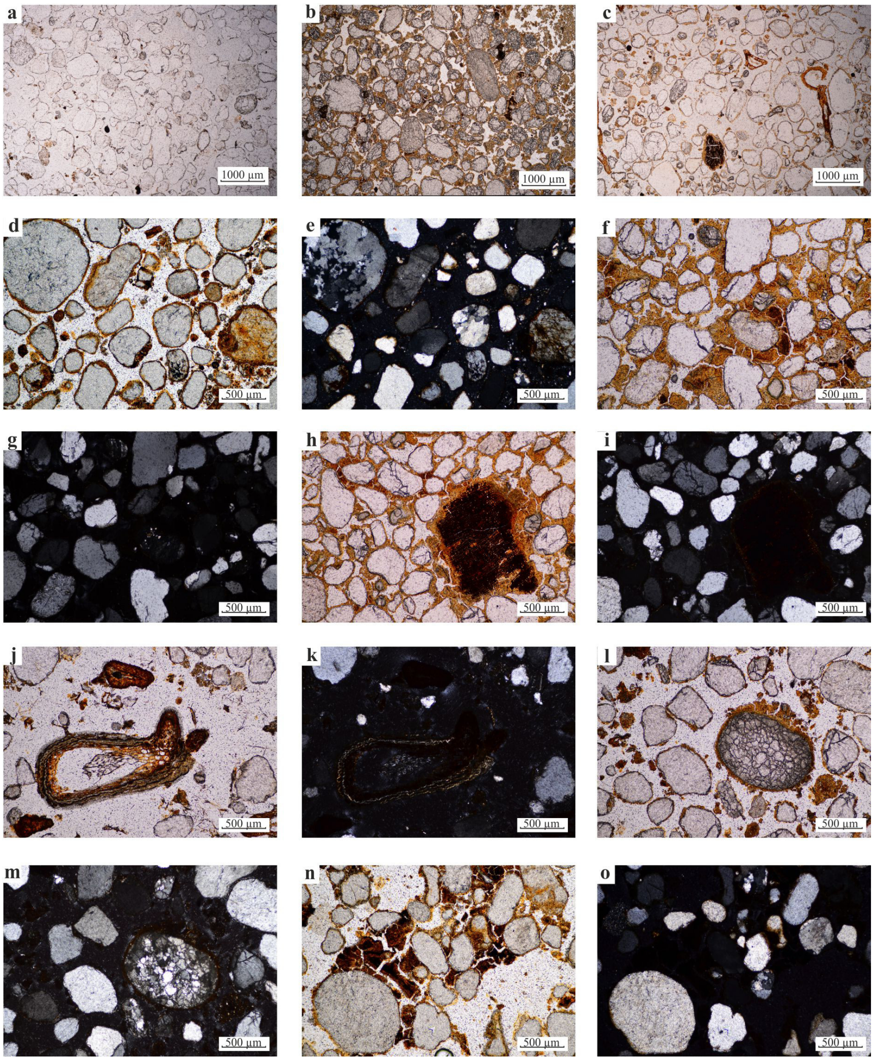

Figure 3. Micromorphologic view of selected soil horizons and selected pedofeatures: (a) eluvial E horizon, plane polarised light (PPL); (b) illuvial Bshm horizon – upper part, PPL; (c) illuvial Bs horizon, PPL; (d) iron coatings (hypo- and quasi-coatings) on rounded quartz grains, PPL; (e) as (d) in crossed polarised light (XPL); (f) cementation in illuvial Bshm horizon, PPL; (g) as (f) in XPL; (h) charcoal enriched with Fe compounds, PPL; (i) as (h) in XPL; (j) fragments of organic matter with a visible tissue system, PPL; (k) as (j) in XPL; (l) iron coating of grains, PPL; (m) as (l) in XPL; (n) Fe-organic matter bridges between quartz grains; (o) as (n) in XPL

A horizons C_{tot} ranged from 0.5 to 1.5%, and in the Ah humus horizon in pedon No. 5, it was 9.98% (Table 1). In B horizons, C_{tot} ranged from 3.31% in the Bshm horizon in the reference pedon (No. 1) to 1.16% in the Bshm horizon in pedon No. 3. In organic O horizons, the C/N ratio ranged from 27–28 (pedon No. 1) to 30–47 (pedons No. 4 and 5). In the Ah horizon, the C/N ratio was 24, while in AC horizons it was 11–14 (pedon No. 3). In B horizons, the C/N ratio was 30 and 24, respectively, for profiles No. 1 and 3.

The optical density of the oxalate extract (ODOE) in the reference pedon No. 1 ranged from 0.013 in the parent material horizon to 0.475 in the enriched Bshm horizon (Table 1). Only in pedon No. 3 was the ODOE value similar throughout and ranged, respectively, from 0.010 to 0.333. ODOE was very low for all other studied pedons (Table 1).

DISCUSSION

The studied soils are typical of shifting sand areas in West and Central European countries (Sparrius *et al.* 2013), and were described for Belgium (Maddelein & Lust 1992), Denmark (Stützer 1998; Mikkelsen *et al.* 2007), the Netherlands (Elgersma 1998), and Poland (Rahmonov & Oleś

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2010; Jankowski &Sewerniak 2013) with respect to both their morphology (Table 1, Figures 2d–h) and micromorphology (Figure 3) as well as their chemical properties (Table 1).

Perfect grain separation of the soil mineral material – as indicated by the particle size distribution (Table 1) and micromorphologic investigations (Figure 3) – as well as the perfect roundness of quartz grains (Figure 3) all indicate an aeolian origin of the soil material (Fedoroff *et al.* 2010). There exists parallel layering in the studied pedons, which differentiates aeolian deflation hollows from dunes, where the material is cross-bent (Szczypek & Wach 1989; Nichols 2009).

Morphology and properties of the reference pedon (No. 1; Figure 2d) illustrate the development of soils without both the effects of contemporary aeolian processes as well as the effects of anthropogenic reforestation in areas of shifting sand. Podzolization was found to occur in the reference pedon No. 1, which is a common phenomenon in this part of Europe in areas formed of fluvioglacial and aeolian sands (Lundström *et al.* 2000; Degórski 2004). Such soils developed with varying intensity throughout the entire Holocene in this area (Degórski 2004). A characteristic feature of the studied reference pedon is a highly developed illuvial B horizon including the cementation of its uppermost part (Bshm horizon – Table 1), where the rate of ODOE was more than 0.45 (Table 1). This indicates strongly advanced podzolization (Kabała *et al.* 2010).

A high degree of eluviation within the E horizon as well as a high degree of illuviation within the B horizon were confirmed by micromorphologic analysis, particularly with regard to the quantity, quality, and arrangement of fine material (Wilson & Righi 2010) (Figure 3). The colour of the fine soil material and other key morphologic characteristics (Table 1, Figure 2d) clearly show the immobilization of Fe- and Al-organic compounds in the illuvial Bshm horizon. These compounds, transported vertically in the form of organic complexes, were released in the course of microbial decomposition of these ligands. The next step consisted of precipitation of imogolite-type material and ferrihydrite (Lundström *et al.* 2000).

The uppermost parts of pedons No. 2 and 3 were eroded as deep as the illuvial B horizon in the active deflation hollow. Soil morphology (Bhsm-Bs-BC-C) characteristic of the reference pedon occurs at greater depths (Figures 2e, f), while younger parallel-layering sand covers older soil as deep as 32 cm in pedon No. 2 and 22 cm in pedon No. 3.

This interpretation of soil evolution emphasizes the special role of the cemented Bshm horizon, which is probably a barrier to the progression of erosion due to its massive structure and mechanical strength (Kaczorek & Sommer 2003; Bockheim 2011). Aeolian processes, both erosion and accumulation, act above the Bshm horizon in the deflation hollow and their present-day activity is demonstrated clearly by the layering of material to a depth of the occurrence of the 'ortstein' horizon (Table 1, Figures 2e, f).

Iron compounds in combination with organic matter and humus compounds serve as materials that cement the Bshm horizon, thus yielding 'ortstein' material. This is evidenced by the results of micromorphologic analysis (Wilson & Righi 2010) (Figure 3), and – indirectly – by the C_{tot} content in the Bshm horizon (Table 1). The development of the Bshm horizon had most likely occurred before the anthropogenic lowering of the groundwater level, because under conditions of restricted drainage and periods of drying there occurs a complexation of dissolved organic carbon with Fe and Al compounds, which then dehydrate and harden (Kaczorek *et al.* 2004; Bockheim 2011). However, additional cementing via the consolidation of organic compounds and combinations thereof with Fe also occurred as an indirect result of the lowering of the groundwater level, which evoked changes in the soil-water conditions in this area (drying) and probably caused greater cementation of ortstein in dry periods (De Coninck 1980; Kaczorek *et al.* 2004).

Shifting sand in the Błędów Desert can be stabilized by the spontaneous growth of vegetation (e.g. pedon No. 3), and through anthropogenic reforestation (pedons No. 4 and 5). In steady-state morphogenetic conditions (no erosion, no deflation), soil-forming processes occur in the form of accumulation of organic matter and podzolization.

In the case of a natural succession of vegetation, soil formation takes place in parallel with plant succession; however, it occurs at a much lower rate than vegetation succession (Elgersma 1998; Rahmonov & Oleś 2010; Jankowski & Sewerniak 2013). In the studied active deflation hollow, lacking vegetation cover (pedon No. 2), the presence of a biological soil crust (a community of cryptogams from the *Algae* and *Cyanophyta* groups, which restrain deflation and stabilize the ground), which allows further development of vegetation (Rahmonov & Oleś 2010) and initiates the development of soils in shifting sand, were not observed. The sand shifts and thus the

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surface is unstabilized. In this soil, the organic matter does not even start to accumulate to form an AC horizon, and spontaneous plant succession is thus cut off because of unfavourable conditions. A clear accumulation of soil organic matter in the form of an AC horizon – C_{tot} content therein was approximately 0.5% (Table 1) – occurred in the studied deflation hollow characterized by xeric sand grassland (soil No. 3). A new pedon developed over the remains of the previous pedon (buried soil) eroded to the Bshm horizon. With the exception of the buried B and BC horizons, podzolization was not observed in pedons No. 2 and 3 under present-day aeolian conditions.

A clear accumulation of organic matter in the soil can be observed in anthropogenic reforestation areas in the studied deflation hollow. In the approximately 100-year-old forest (*Pinus sylvestris*) (pedon No. 5), under a 2-cm organic O horizon (litter), a 7-cm Ah horizon (C_{tot} 9.98%) and a 4-cm humus A horizon (C_{tot} 1.23%) have been detected (Figure 2h, Table 1). This shows that the formation of a sequence of organic and humus horizons is still in process even after 100 years. In the case of a much younger stand, where the reforestation occurred less than 30 years ago (pedon No. 4), there exist a 1-cm organic O horizon and a 4-cm humus A horizon containing 1.19% C_{tot} (Figure 2g, Table 1). In addition, there is a slightly marked morphologic eluvial E horizon distinguished by brighter colours (13–25 cm), underlain by a poorly marked, coloured iluvial B horizon (25–65 cm) in pedon No. 5. The brightness of the soil colour at the depth of 13–25 cm is sufficient to determine 'albic' diagnostic material; however, both the colour as well as the ODOE value in the B horizon are insufficient to find a spodic diagnostic horizon (IUSS Working Group WRB 2014). This observation is consistent with studies from Great Britain (James & Wharfe 1989), which indicate that 'immature podzols' can form within 20 to 100 years. Likewise, findings by Stützer (1998) that a well-developed eluvial E horizon grows rapidly (ca. 100 years) confirm this opinion. Otherwise, the evolution to 'mature' podzol, with a well-developed spodic horizon lasts much longer and depends on various environmental conditions. In sandy areas visible differentiation of podzol horizons developed in 300 to 1000 years (Lundström *et al.* 2000), while the development of a full podzol profile can last even 10 000 years (Barett & Schaetzl 1992; Lundström *et al.* 2000; Wilson 2001; Mokma *et al.* 2004). It is important to note that the development of podzolization is determined by earlier development of soil biota; first, because the presence of litter delivering organic fulvic acids is necessary to initiate the podzolization process, and second, the degradation of aluminosilicates and vertical movement of Fe- and Al-organic compounds occur through soil macropores, e.g. pores left following the loss of roots as well as those created by macrofaunal activity (Stützer 1998).

The above-described evidence of soil-forming processes shows that in the conditions found in the Błędów Desert, the process of soil organic matter accumulation is rapid, while the podzolization process occurs much more slowly. There is a marked increase both in the thickness of organic O horizons as well as in organic matter content in humus A horizons in pedons found in a reforestation area. The process of podzolization would most likely begin following the accumulation of a sufficient amount of organic matter in soils (Lundström *et al.* 2000; Jankowski & Sewerniak 2013).

CONCLUSIONS

There exists a variety of soils at various stages of development across the deflation plain in the area of anthropogenically-induced shifting sands in the studied Błędów Desert. An organomineral horizon is formed over the course of several years on stabilized surfaces (both natural and anthropogenic) and this is followed by the onset of podzolization. One hundred years, even under conditions favouring podzolization, is not enough for a spodic horizon to develop, unlike e.g. an albic horizon. Soil-forming processes can affect the dynamics of aeolian processes due to effects associated with a well-developed spodic horizon with 'ortstein' material (Bshm horizon), which probably serves as a barrier limiting wind erosion to a certain depth. The development of the Bshm horizon may be supported by antropogenic changes (i.e. lowering) in the groundwater level. The analysis of soil morphology and micromorphology is a useful tool for disclosing the history of changes in the environment.

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