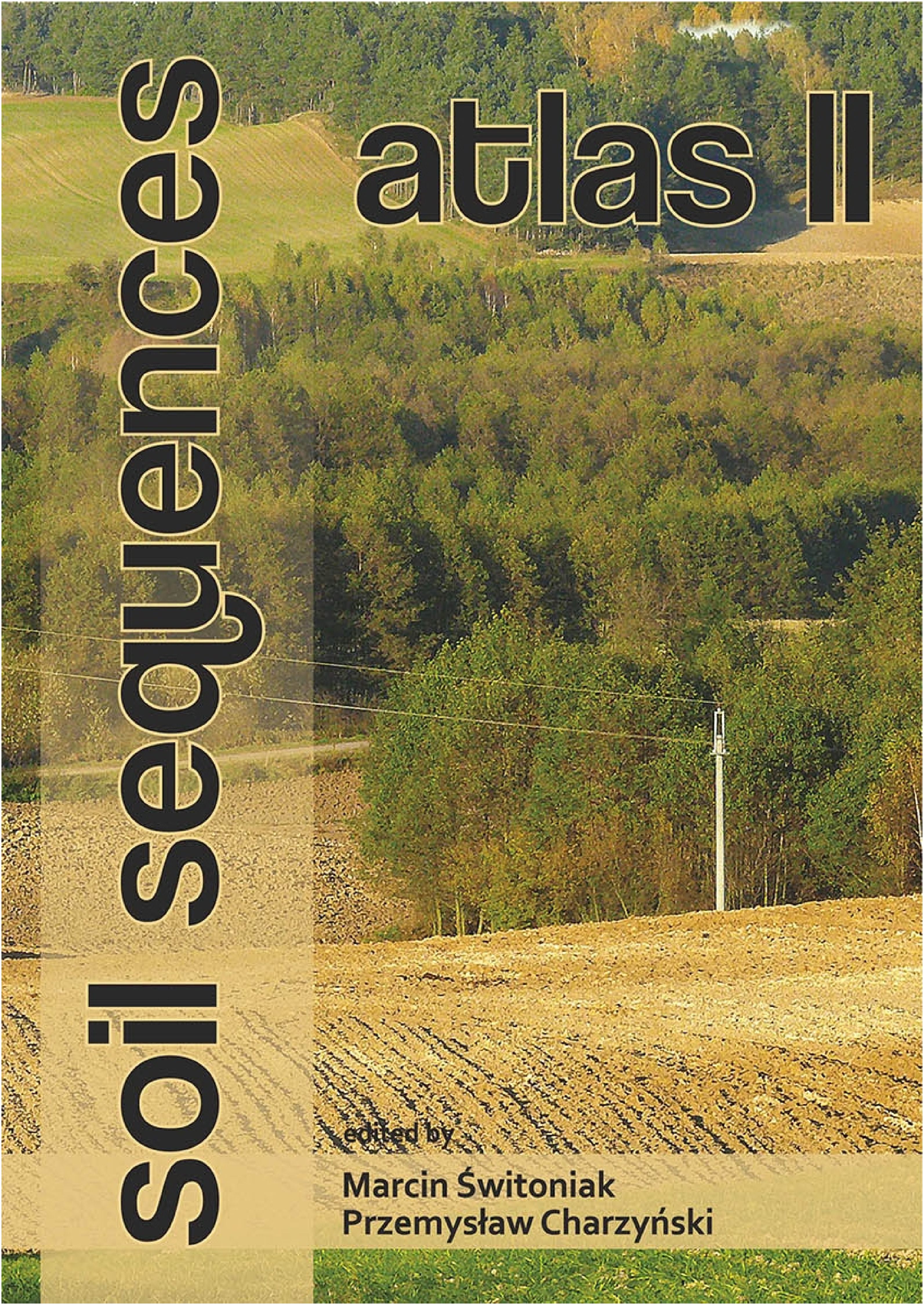

soil sequences atlas II

edited by

Marcin Świtoniak
Przemysław Charzyński

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Soil Sequences Atlas II
M. Świtoniak, P. Charzyński (Editors)
First Edition

Contents

FOREWORD

This is the second book in the series of Soil Sequence Atlases. The first volume was published in 2014. Main pedogeographic features are presented in the form of sequences to give a comprehensive picture of soils – their genesis and correlations with the environment in typical landscapes of Central Europe from Estonia furthest north, through Latvia, Lithuania, Poland, Germany, Czechia, Slovakia and Hungary to the southernmost Slovenia. Soils of natural landscapes – loess and sand (continental dunes) – are presented, as well as those of plains of various origin, karst lands, low mountains, and anthropically modified soils.

Each chapter presents soil profiles supplemented by landscape information and basic analytical data. Then, genetic interpretations of soil properties related to soil forming agents are given as schematic catenas.

When one factor changes while the others are more or less stable, the soil sequence can be recognised. Depending on the dominant soil-forming factor affecting repeated soil patterns, different types can be distinguished. Chapters are arranged roughly in accordance with the main soil-forming process in sequences, and referring to the WRB key (peat formation, vertic and gleyic process, podzolisation, humus accumulation, clay illuviation), with one small exception – the Technosols have been placed at the end of book.

The main objective of this book is to present the diversity of relations between soil and landscape, climate, hydrology and human relations, and to present interpretations reflecting the World Reference Base for Soil Resources (2015) classification with comments on the choice of qualifiers. Sixteen Reference Soil Groups are featured, and represented by 67 soil profiles.

The secondary objective is pedological education. One of the aims of soil science education is to explain to students the relations between landscape and soil cover. The patterns of soil units within landscapes are to some extent predictable. The collected data is intended as a useful educational tool in teaching soil science, supporting understanding of the reasons for the variability of soil cover, and also as a WRB classification guideline.

The Atlas was developed as part of the EU Erasmus+ FACES project (Freely Accessible Central European Soil).

Marcin Świtoniak

Przemysław Charzyński

List of acronyms

Al_o – aluminium extracted by an acid ammonium oxalate solution
Al_t – iron extracted by solution of $HClO_4$–HF
BS – base saturation
CEC – cation exchange capacity
CEC_{clay} – CEC of the clay
$EC_{1:2}$ – electrical conductivity of a 1:2 soil-water extract
$EC_{1:2.5}$ – electrical conductivity of a 1:2.5 soil-water extract
EC_e – electrical conductivity of the soil saturation extract
Eh – redox potential related to the standard hydrogen electrode
ESP – exchangeable sodium percentage
FAO – Food and Agriculture Organization of the United Nations
Fe_d – iron extracted by a dithionite-citrate-bicarbonate solution
Fe_o – iron extracted by an acid ammonium oxalate solution
Fe_t – iron extracted by solution of $HClO_4$–HF
HA – potential (hydrolytic) acidity ($pH_{8.2}$) by the Kappen method
IUSS – International Union of Soil Science
N_t – total nitrogen
OC – organic carbon
pH_a – pH measurement referred to the actual soil moisture
pH_e – pH of saturation paste
pH_{ox} – pH measurement after incubation of soil samples under laboratory conditions within two months
pH_{pox} – pH measurement after oxidation with 30% H2O2
rH – the index used to assess redox conditions in water and soils calculated from pHa and Eh values (negative logarithm of the hydrogen partial pressure)
SAR – sodium adsorption ratio
SP – moisture content at saturation (saturation percentage)
S_t – total sulphur
TEB – total exchangeable bases

Methods

The soils were classified according to WRB 2014[1]. The soil morphology descriptions and symbols of soil horizons are given after Guidelines for Soil Description[2]. The samples were taken from selected soil horizons and after preparation (drying, separation of root and sand fraction >2 mm by sieving) it was analyzed in the laboratory. Texture was determined by (i) combining the Bouyoucos[3] hydrometer and sieve method or (ii) by pipette and sieve method. Organic carbon (OC) content was determined by the wet dichromate oxidation method, and total nitrogen (Nt) content by the Kjeldahl method. The reaction was measured in H_2O and 1 M KCl in 1:2.5 suspension for mineral samples, and 1:10 suspension for organic samples. Calcium carbonate ($CaCO_3$) content was determined by Scheibler volumetric method. Potential (hydrolythic) acidity (HA) was determined by Kappen method and exchangeable cation (bases) content was estimated by leaching with 1 M ammonium acetate with a buffer solution pH 8.2. Pedogenic forms of iron and aluminum were extracted: Fe_t and Fe_d by $HClO_4$–HF, Fe_d by sodium dithionite–citrate–bicarbonate[4] and Fe_o and Al_o by ammonium oxalate buffer solution[5]. Other soil analyses were performed according to the standard methods[6]. Color has been described according to Munsell[7]. It was recorded (i) in the moisture condition (single value) or (ii) in the dry and moisture condition (double values).

[1] IUSS Working Group WRB, 2014. World Reference Base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Report No. 106. FAO, Rome.
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[3] Bouyoucos, G.M., 1951. Particle analysis by hydrometer method. Agronomy Journal 43, 434–438.
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[6] Van Reeuwijk, L.P. 2002. Procedures for soil analysis. 6th Edition. Technical Papers 9. Wageningen, Netherlands, ISRIC – World Soil Information.
[7] Munsell Soil Colour Charts, 2009. Grand Rapids, Michigan USA.

STUDY AREAS

NUMBER OF CHAPTER - REGION AND COUNTRY:

1 – PEAT BOGS IN MOUNTAIN AREAS, STOŁOWE MOUNTAINS, POLAND
2 – AGRICULTURAL GLACILIMNIC LANDSCAPES, SĘPOPOL PLAIN, POLAND
3 – MILL POND BASIN, CHEŁMNO LAKELAND, POLAND
4 – DUNES AND BOGS, PALUMAA PLATEAU, ESTONIA
5 – DUNES, CURONIAN SPIT, LITHUANIA
6 – INLAND DUNES, TORUŃ BASIN, POLAND
7 – DUNES ON BARRIER ISLANDS, SPIEKEROOG, GERMANY
8 – LOESS REGION, ZDANICKY LES, CZECHIA
9 – GREAT HUNGARIAN PLAIN, NAGY-SÁRRÉT, HUNGARY
10 – AGRICULTURAL AREAS, ZEMGALE PLAIN, LATVIA
11 – SLOPE NICHES, TORUŃ-EBERSWALDE ICE-MARGINAL VALLEY, POLAND
12 – KARST PLATEAU AND RIMAVSKÁ BASIN, SLOVAKIA
13 – SOUTHERN SLOPES OF THE VILLÁNY HILLS, HUNGARY
14 – FOOT SLOPES OF THE POLHOGRAJSKO HILLS AND LJUBLIANA BASIN, SLOVENIA
15 – ASH SETTLING PONDS OF THE "PĄTNÓW" AND THE "KONIN" THERMAL POWER STATIONS, POLAND
16 – ASH SETTLING PONDS OF THE "ŁAZISKA" THERMAL POWER STATIONS, POLAND

Organic soils within an afforested peat bog in a mountain area (the Stołowe Mountains, Poland)

Bartłomiej Glina, Łukasz Mendyk, Adam Bogacz

The Stołowe Mountains (central Sudetes) is a unique sedimentary tableland in the south-western part of Poland (Fig. 1). The presence of block covers, debris flows and fine-grained solifluction covers, developed as an effect of periglacial conditions are characteristic for this mountain range (Kabała et al., 2011). Peatlands are located at an elevation of 500–900 m a.s.l. (Kaszubkiewicz et al., 1996) and represents all ecological types – from fens to peat bogs. The total area of peatlands is 132 ha, which represents only a residual portion of former much larger complexes (Glina et al., 2016). Degradation of mires is the result of intensive forestry drainage at the turn of the 19th and 20th centuries (Gałka et al., 2015; Glina et al., 2017). A soil catena was located within the Długie Mokradło bog, one of the largest peatlands in the Stołowe Mountains (Marek 1998).

Fig. 1. Location

Lithology and topography

The main part of the Stołowe Mountains is built of thick sandstone layers from the Upper Cretaceous and fine-grained sedimentary rocks: marls, claystones and siltstones (Migoń and Kasprzak 2015). The altitude in this mountain range varies from 400 m a.s.l. to 919 m a.s.l. (Migoń et al., 2011). The study peatland is located in the northwestern part of the Stołowe Mountains, between Skalniak (summit-plateau; 915 m a.s.l.) and Błędne Skały (rock labyrinth). The mineral bedrock of this area consists of weathered sandstone, covered by shallow peat mantle from 0.40 to 1.40 m (Glina et al., 2017).

Land use

Described peat bog was covered with spruce forest representing the *Calamagrostio villosae-Piceetum sphagnetosum* SCHLÜTER 1969 community. The forest floor layer is dominated by the peat-forming plant species, e.g. *Sphagnum* mosses (e.g., *S. fallax, S. girgensohni*, *S. flexuosum*, *S. russowii*, *S. riparium*), *Polytrichum commune* and *Eriophorum vaginatum* (Glina 2014).

Climate and hydrology

According to the Köppen-Geiger climate classification, this region is located in the fully humid continental climate zone, with warm summer (Kottek et al., 2006). The mean annual air temperature is between 4°C and 6.5°C. The average temperature of the coldest month (January) is –3.0°C, while the warmest month is July (15.0°C). The mean annual precipitation ranges from 750 to 920 mm (Pawlak 2008). The growing season begins in the second or third decade of April and usually lasts 190 days (Gałka et al., 2014). Sources of the Czermnica stream are located within the studied peat bog (Adynkiewicz-Piragas et al., 2011), which partly supply the edge parts of the peatland with water in the form of occasional flooding.

Profile 1 – Hyperdystric Drainic Sapric **Histosol**
Localization: summit of the sandstone plateau- inclination 3°, edge part of the peat bog covered with open spruce forest, 831 m a.s.l.; **N** 50°28'27.8" **E** 16°17'21.3"

Morphology:

He1 – 0–10 cm, *histic* horizon, moderately decomposed peat, brownish black (10YR 3/2; 10YR 3/2), slightly moist, amorphous-fibrous structure, slightly moist, very fine and few roots, clear and wavy boundary;

He2 – 10–14 cm, *histic* horizon, moderately decomposed peat, brownish black (10YR 3/1; 10YR 3/1) moist, amorphous-fibrous structure, clear and wavy boundary;

Ha1 – 14–17 cm, *histic* horizon, strongly decomposed peat, brownish gray (10YR 4/1; 10YR 4/1), moist, amorphous structure, many sand grains, clear and smooth boundary;

Ha2 – 17–27 cm, *histic* horizon, strongly decomposed peat, brownish black (10YR 3/1; 10YR 3/1), moist, amorphous structure, gradual boundary;

Ha3 – 27–34 cm, *histic* horizon, strongly decomposed peat, dark brown (10YR 3/3; 10YR 3/4), moist, amorphous structure, gradual boundary;

Ha4 – 34–40 cm, *histic* horizon, strongly decomposed peat, brownish black (10YR 3/1; 10YR 3/1), wet, amorphous structure, few sand grains, gradual boundary;

C – 40–(60) cm, underlying mineral horizon*,* sand, gray (5Y 4/1; 5Y 5/1), wet, single grain structure;

Table 1. Texture (underlying mineral horizon)

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
C	40–(60)	0	2	8	19	40	17	2	4	3	5	S

Table 2. Chemical and physicochemical properties

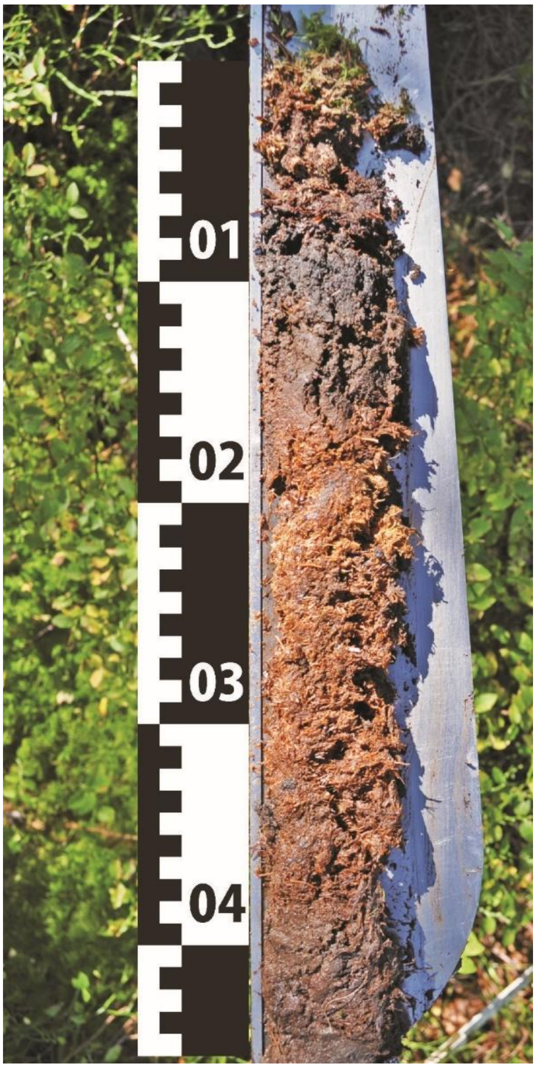
Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
He1	0–10	210	14.1	14.9	3.4	3.0	-
He2	10–14	250	10.0	25.0	3.6	3.1	-
Ha1	14–17	205	8.01	25.6	3.7	3.1	-
Ha2	17–27	231	12.0	19.3	3.8	3.1	-
Ha3	27–34	225	13.0	17.3	3.8	3.1	-
Ha4	34–40	284	15.1	18.9	3.9	3.2	-
C	40–(60)	68.2	3.22	21.2	4.3	3.8	-

- $CaCO_3$ absent

Table 3. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	EA	CEC	BS [%]
		[cmol(+)·kg^{-1}]							
He1	0–10	2.00	0.59	0.27	0.62	3.48	12.9	16.3	21.3
He2	10–14	2.56	0.56	0.28	0.83	4.23	13.4	17.6	24.1
Ha1	14–17	1.52	0.11	0.18	0.55	2.36	5.92	8.28	28.5
Ha2	17–27	1.60	0.14	0.17	0.30	2.21	7.98	10.2	21.7
Ha3	27–34	1.60	0.11	0.24	0.26	2.21	5.62	7.83	28.3
Ha4	34–40	1.20	0.18	0.22	0.68	2.28	13.3	15.5	14.7

Profile 2 – Hyperdystric Ombric Drainic Hemic Fibric **Histosol**
Localization: summit of the sandstone plateau- inclination 3°, edge part of the peat bog covered with open spruce forest, 833 m a.s.l. **N** 50°28'28.5" **E** 16°17'27.5"



Morphology:

Hi1 – 0–4 cm, *histic* horizon, weakly decomposed peat, dark brown (10YR 3/4; 10YR 3/3), slightly moist, fibrous structure, slightly moist, very fine and few roots, clear and wavy boundary;

He1 – 4–14 cm, *histic* horizon, moderately decomposed peat, brownish black (10YR 3/2; 10YR 3/2), amorphous-fibrous structure, wet, few sand grains, clear and wavy boundary;

He2 – 14–19 cm, *histic* horizon, moderately decomposed peat, yellowish brown (10YR 5/8; 10YR 5/6), fibrous-spongy structure, very wet, clear and wavy boundary;

Hi2 – 19–32 cm, *histic* horizon, weakly decomposed peat, brown (10YR 4/6; 10YR 4/4), fibrous-spongy structure, very wet, clear and wavy boundary;

Hi3 – 32–39 cm, *histic* horizon, weakly decomposed peat, dull yellowish brown (10YR 5/3; 10YR 5/4), fibrous-spongy structure, very wet, gradual boundary;

He3 – 39–45 cm *histic* horizon, moderately decomposed peat, dull yellowish brown (10YR 5/3; 10YR 5/4), fibrous-spongy structure, very wet, gradual boundary;

C – 45–(60) cm underlying mineral horizon, sand, light gray (5Y 8/1; 5Y 7/1), very wet, single grain structure;

Table 4. Texture (underlying mineral horizon)

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
C	45–(60)	0	3	5	22	37	19	2	3	6	3	S

Table 5. Chemical and physicochemical properties

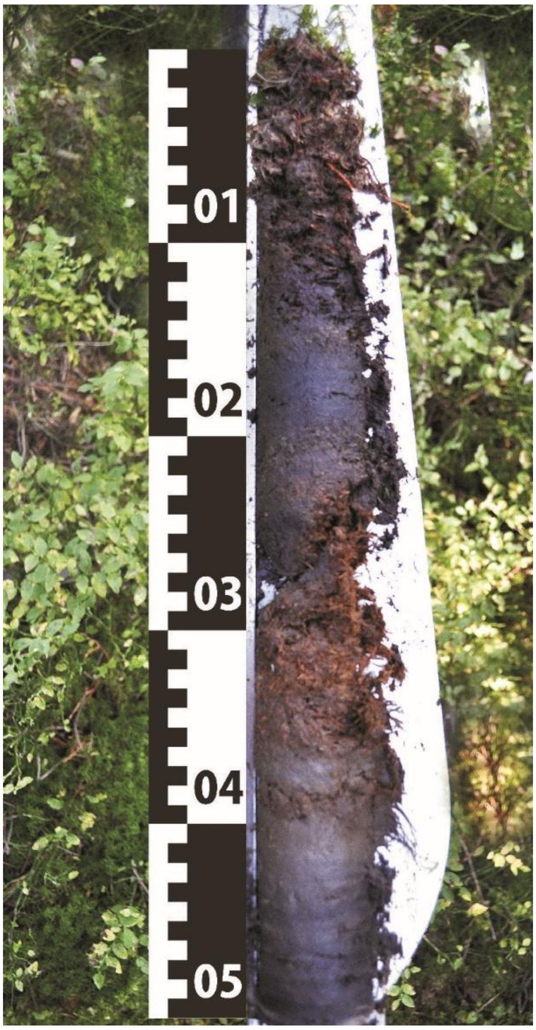
Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Hi1	0–4	467	15.6	29.9	3.9	3.1	-
He1	4–14	406	15.1	26.9	3.7	3.2	-
He2	14–19	420	11.6	36.2	3.9	3.6	-
Hi2	19–32	432	10.4	41.5	4,0	3.7	-
Hi3	32–39	325	16.9	19.2	4.2	3.9	-
He3	39–45	285	13.4	21.3	4.1	3.9	-
C	45–(60)	91.2	2.71	33.7	4.2	3.9	-

- $CaCO_3$ absent

Table 6. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	EA	CEC	BS
		[cmol(+)·kg^{-1}]							[%]
Hi1	0–4	3.20	0.65	0.44	1.83	6.12	9.02	15.1	40.4
He1	4–14	1.60	0.38	0.28	0.58	2.84	18.2	21,0	13.5
He2	14–19	1.84	0.20	0.35	0.51	2.90	17.2	20.1	14.4
Hi2	19–32	2.56	0.39	0.40	1.06	4.40	16.4	20.8	21.1
Hi3	32–39	0.80	0.57	0.24	1,00	2.61	10.7	13.3	19.6
He3	39–45	0.96	0.34	0.16	0.56	2.01	4.30	6.35	31.7

Profile 3 – Hyperdystric Ombric Drainic Fibric **Histosol**
Localization: summit of the sandstone plateau- inclination 3°, central part of the peat bog covered with open spruce forest, 834 m a.s.l. **N** 50°28'27.9" **E** 16°17'31.5"



Morphology:

Hi1 – 0–11 cm, *histic* horizon, weakly decomposed peat, dark brown (10YR 3/4; 10YR 3/3), fibrous structure, wet, very fine and few roots, clear and wavy boundary;

He – 11–20 cm, *histic* horizon, moderately decomposed peat, brownish black (10YR 3/2; 10YR 3/1), amorphous-fibrous structure, wet, clear and wavy boundary;

Hi2 – 20–32 cm, *histic* horizon, weakly decomposed peat, brown (10YR 4/4; 10YR 4/4), spongy-fibrous structure, very wet, clear and wavy boundary;

Hi3 – 32–40 cm, *histic* horizon, weakly decomposed peat, brown (10YR 3/2; 10YR 3/1), spongy-fibrous structure, very wet, clear and wavy boundary;

Ha – 40–53 cm, *histic* horizon, strongly decomposed peat, black (10YR 2/1; 10YR 2/1), amorphous structure, very wet, clear and smooth boundary;

C – 53–(70) cm, underlying mineral horizon, sand, gray (5Y 5/1; 5Y 5/1), wet, single grain structure;

Table 7. Texture (underlying mineral horizon)

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
C	53–(70)	0	1	4	26	40	17	2	2	3	5	S

Table 8. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Hi1	0–11	450	11.9	37.8	4.0	3.4	-
He	11–20	414	15.5	26.7	3.9	3.2	-
Hi2	20–32	392	14.8	26.5	3.8	3.4	-
Hi3	32–40	371	14.6	25.4	3.8	3.4	-
Ha	40–53	291	9.71	30.0	3.9	3.5	-
C	53–(70)	67.2	1.89	35.6	4.1	3.7	-

- $CaCO_3$ absent

Table 9. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	EA	CEC	BS [%]
		[cmol(+)·kg^{-1}]							
Hi1	0–11	2.72	0.53	0.38	2.15	5.78	18.2	23.9	24.1
He	11–20	0.96	0.32	0.2	0.52	2,00	16.8	18.8	10.6
Hi2	20–32	0.96	0.09	0.17	0.55	1.77	15,0	16.8	10.6
Hi3	32–40	1.68	0.17	0.2	0.41	2.46	13.2	15.7	15.7
Ha	40–53	2.16	0.18	0.24	0.7	3.28	14.6	17.9	18.4

Profile 4 – Hyperdystric Ombric Drainic Fibric **Histosol**
Localization: The central part of the Długie Mokradło bog, summit - inclination 2.5°, spruce forest, 842 m a.s.l. **N** 50°28'25.1" **E** 16°17'43.8"

Morphology:

He – 0–14 cm, *histic* horizon, moderately decomposed peat, brown (10YR 4/4; 10YR 4/6), wet, amorphous-fibrous structure, gradual boundary;

Hi1 – 14–29 cm, *histic* horizon, weakly decomposed peat, dull yellowish brown (10YR 5/3; 10YR 4/3), wet, fibrous structure, clear and wavy boundary;

Hi2 – 29–45 cm, *histic* horizon, weakly decomposed peat, yellowish brown (10YR 5/8; 10YR 5/6), very wet, fibrous structure, clear and wavy boundary;

Hi3 – 45–53 cm, *histic* horizon, weakly decomposed peat, dark brown (10YR 3/3; 10YR 3/4), very wet, fibrous structure, clear and wavy boundary;

Ha – 53–64 cm, *histic* horizon, strongly decomposed peat, dark brown (10YR 3/2; 10YR 3/1), very wet, amorphous structure, clear and smooth boundary;

C – 64–(80) cm, underlying mineral horizon, sand, light gray (5Y 8/1; 5Y 7/1), moist, single grain structure;

Table 10. Texture (underlying mineral horizon)

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
C	64–(80)	0	0	6	36	27	16	2	3	3	7	S

Table 11. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [$g\cdot kg^{-1}$]	Nt [$g\cdot kg^{-1}$]	C/N	pH		$CaCO_3$ [$g\cdot kg^{-1}$]
					H_2O	KCl	
He	0–14	419	12.0	34.9	4.0	3.8	-
Hi1	14–29	368	9.80	37.6	4.2	4,0	-
Hi2	29–45	415	9.91	41.9	4.0	3.7	-
Hi3	45–54	410	13.9	29.5	4.1	3.6	-
Ha	54–65	201	7.41	27.1	4.0	3.5	-
C	64–(80)	72.3	2.14	33.8	4.1	3.7	-

- $CaCO_3$ absent

Table 12. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	EA	CEC	BS
		[cmol(+)·kg^{-1}]							[%]
He	0–14	1.76	0.37	0.26	1.19	3.57	19.0	22.6	15.8
Hi1	14–29	1.28	0.15	0.22	1.01	2.66	44.4	47.1	5.71
Hi2	29–45	3.68	0.23	0.40	2.69	7.00	15.2	22.2	31.5
Hi3	45–54	2.00	0.17	0.21	1.46	3.83	11.8	15.6	24.5
Ha	54–65	2.08	0.22	0.20	1.03	3.53	10.2	13.7	25.7

Profile 5 – Hyperdystric Drainic Fibric **Histosol**

Localization: The edge part of the Długie Mokradło bog, summit - inclination 1.5°, open spruce forest, 847 m a.s.l. **N** 50°28'22.8" **E** 16°17'48.8"

Morphology:

Hi1 – 0–14 cm, *histic* horizon, weakly decomposed peat, brownish black (10YR 3/2; 10YR 3/1), moist, amorphous-fibrous structure, clear and wavy boundary;

Ha1 – 14–23 cm, *histic* horizon, strongly decomposed peat, dark brown (10YR 4/2; 10YR 4/1), wet, amorphous structure, many sand grains, clear and wavy boundary;

Hi2 – 23–38 cm, *histic* horizon, weakly decomposed peat, brown (10YR 4/6; 10YR 4/4), wet, spongy-fibrous structure, clear and wavy boundary;

Hi3 – 38–43 cm, *histic* horizon, weakly decomposed peat, dark reddish brown (5YR 3/3; 5YR 3/2), wet, spongy-fibrous structure, clear and wavy boundary;

Ha2 – 43–50 cm, *histic* horizon, strongly decomposed peat, brownish black (10YR 3/2; 10YR 3/1), very wet, amorphous structure, few sand grains, clear and smooth boundary;

C – 50–(70) cm, underlying mineral horizon, sand, gray (5Y 4/1; 5Y 5/1), very wet, single grain structure;

Table 10. Texture (underlying mineral horizon)

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
C	50–(70)	0	4	16	21	25	23	3	2	3	3	S

Table 11. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
He	0–14	306	12.8	23.9	3.9	3.0	-
Hi1	14–23	216	8.70	24.8	3.5	2.9	-
Hi2	23–38	346	10.5	33.0	3.6	3.0	-
Hi3	38–43	436	10.8	40.4	3.7	3.2	-
Ha	43–50	431	11.6	37.2	3.7	3.1	-
C	50–(70)	69.8	2.71	25.8	3.9	3.1	-

- CaCO3 absent

Table 12. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	EA	CEC	BS
		[cmol(+)·kg^{-1}]							[%]
He	0–14	1.76	0.34	0.24	0.98	3.32	9.40	12.7	26.1
Hi1	14–23	1.44	0.22	0.18	0.43	2.27	13.6	15.8	14.3
Hi2	23–38	1.44	0.13	0.23	0.36	2.16	12.8	14.9	14.4
Hi3	38–43	0.96	0.09	0.18	0.57	1.81	25.8	27.6	6.54
Ha	43–50	0.80	0.09	0.18	0.25	1.32	25.4	26.7	4.95

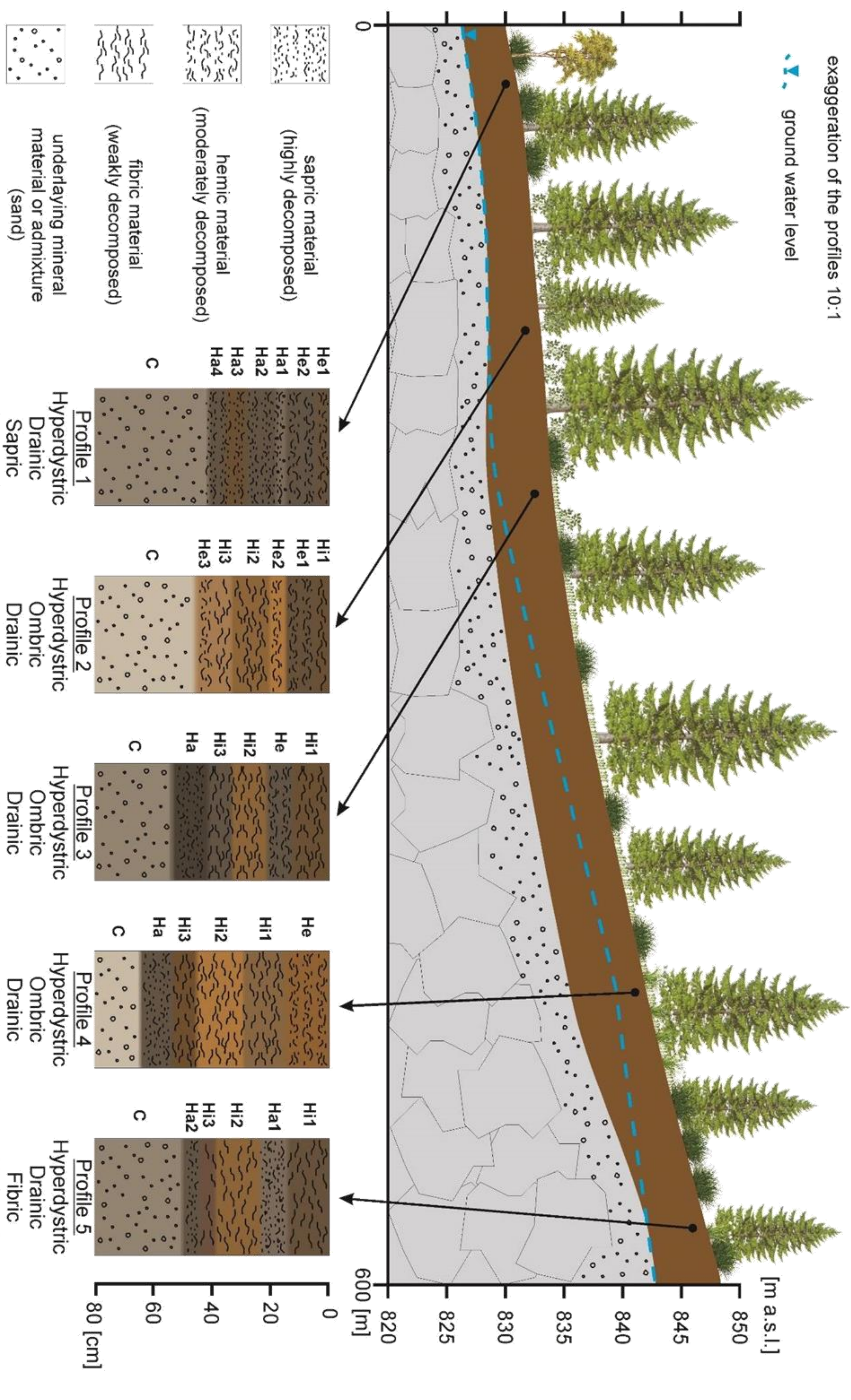


Fig. 2. Hydro-toposequence of soils within the afforested peatland in Stołowe Mountains

Soil genesis and systematic position

The palaeoecological research conducted by Glina et al. (2017) showed that peat accumulation within the Długie Mokradło bog, thus the formation of organic soils started in the Subboreal chronozone (*ca.* 3301 BC). Based on palaeobotanical and geochemical analyses, strong perturbation (e.g., fire events, water-table fluctuation, drainage) during the formation of the peatland was described. It was the result of climate shifts and human activity in the Central Sudetes. Due to this phenomena, the acceleration of peat subsidence and mineralisation of organic matter was observed, that is why peat deposit within the Długie Mokradło bog is quite shallow.

The studied soils originated from organic materials of various botanical composition (e.g., *Eriophorum spp., Politrychum spp., Sphagnum spp.* remains) are characterized by high organic matter content. The high organic carbon content (≥ 20%) and thickness of organic layers (≥ 40 cm) allows to classify all of the described soils to the **Histosols** soil reference group (IUSS Working Group WRB, 2015). The various stage of peat decomposition observed within soil profiles, as an effect of water-table fluctuations were described by ***Sapric*** (strongly decomposed peat), ***Hemic*** (moderately decomposed peat) and ***Fibric*** (weakly decomposed peat) qualifiers. According to WRB 2015, the organic material decomposition is expressed by the presence (by volume) of recognizable plant tissue. In the case of soil profile 2, two qualifiers were used – ***Hemic Fibric,*** due to sub-dominance of peat of two different decomposition stages. It must be emphasized that the use of two different qualifiers to describe the peat decomposition is not a common practice. The Długie Mokradło bog is supplied with water, both by rainwater and flowing surface water (Czermnica stream). Soil profiles 2, 3 and 4 located in the central part of the mire are exclusively fed by rainwater, which is expressed by the ***Ombric*** principal qualifier. Meanwhile, soils located in the marginal part of the peatland (profiles 1 and 5) are saturated with rainwater as well as with flowing surface water. Due to the mixed type of water supply, we cannot use any suitable qualifier (***Ombric, Rheic***). Very low pH_{water} recorded in all soil profiles (3.7–4.2) justified the use of the ***Hyperdystric*** qualifier. For drained and extensively used organic soils, the development of coarse granular or blocky structure and an increase in bulk density in the uppermost soil horizons are very common (***Murshic*** qualifier). In the studied soil profiles, however, such changes in physical properties and structure were not observed. Thus, we can indicate strong artificial drainage (1–2 m spacing of drainage ditches) of the study peatland by using the ***Drainic*** qualifier.

Soil sequence

The above-described peat bog soil morphology and classification is the effect of different types of topography position and hydrological conditions during the peat-accumulation process as well as the human impact in the last millennia. The spatial arrangement of soil profiles represent a typical **hydro-toposequence**. The marginal part of the peatland is covered with organic soils (profiles 1, 2 and 5) with some admixture of mineral material in the top part of the profiles (common or few sand grains in the organic material), as an effect of seasonal flooding by the Czermnica stream. The changing water-table during the formation of the studied soils is confirmed by alternating incidences of soil horizons composed of different decomposed organic materials. In general, the surface soil horizons were built of ***Hemic*** or ***Fibric*** peat, while the bottom organic layers consists of strongly decomposed peat – ***Sapric***. However, the ***Sapric*** peat predominates in profile 1.

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Agricultural areas within glacilimnic landscapes of NE Poland (Sępopol Plain)

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Sępopol Plain is a mesoregion in north-eastern Poland, in the macroregion of Staropruska Lowland, which borders on Masurian Lakeland in the south (Fig. 1). This mesoregion is located within the youngest Pomeranian phase of the Vistula Glaciation (Marks, 2012). It represents specific, for this region, glacilimnic young glacial landscape.

Fig. 1. Location

Lithology and topography

Glacilimnic deposits, represented mainly by clay formations, have small thickness (about 1–2 m). They occur on the hilltops and slopes of moraines. They do not form a tight cover, but occur in five former glacilimnic basins (Kondracki, 1972). This type of landscape comprises Sępopol Plain and some areas in the northern part of Masurian Lakeland. Depressions of ground moraine are extensive with land level differences up to 5 m (in this case ca. 27 m), and small slope gradients amounting to 2–7°. The depressions are surrounded by ice-dammed and boulder formations. The landscape is strongly diversified. Sępopol Plain forms an extensive basin without well-developed morainic forms and lakes. In approximately 92% of the Sępopol Plain area, slope gradients do not exceed 6%. Land depressions are not very scattered and slope gradient as well as erosion threat are low (Kondracki, 1972). Gotkiewicz and Smołucha (1996b) referred to this area as the zone of ice-dammed lake origin. In this landscape, the soils were formed from loam and clay, the origin of which was associated with deglaciation and ice-dammed lakes (Kondracki, 1972; Uggla and Witek, 1958).

Land use

Sępopol Plain is a typical agricultural area. Arable fields comprise approx. 53%, and permanent grasslands approx. 24% of the region's area. The region has favorable conditions for agricultural production, associated with high fertility of soils and favorable land relief. The afforestation rate of Sępopol Plain, as a result of the typical agricultural character of this region, is low and amounts to approximately 15% (Gotkiewicz and Smołucha, 1996a).

Climate

Sępopol Plain represents a lakeland climate with the prevailing influence of continental climate (Hutorowicz et al., 1996). According to Kottek et al. (2006), the region is located in the fully humid zone with temperate and warm summer. The average annual temperature for the period of 1951–1970 is about 7°C. The average temperature of the coldest month (January) is –3.5°C, while the warmest month is July (17.5°C). The average annual precipitation is 550–600 mm. As much as 360–410 mm of precipitation falls in the period from April to September (Hutorowicz et al., 1996).

Profile 1 – Haplic **Vertisol** (Aric, Grumic, Humic, Hypereutric, Endostagnic)
Localization: Glacilimnic plain, upper slope, arable field, 91 m a.s.l.,
N 54°02'54", **E** 21°05'32"

Morphology:

Ap – 0–30 cm, plough humus horizon, clay, brownish black (7.5YR 4/2, 7.5YR 3/2), moist, strong granular structure, very fine and common roots, clear and smooth boundary;

A2 – 30–46 cm, humus horizon, clay, black (10YR 3/2, 10YR 2/2), moist, fine strong prismatic structure, fine and common roots, gradual and wavy boundary;

Bigk – 46–100 cm, *vertic* material, heavy clay, yellowish brown (2.5Y 6/3, 2,5Y 5/4), moist, massive structure, fine and very few roots, common soft concretions of secondary carbonates, gradual and wavy boundary;

Cigk – 100–160 cm, *calcaric* parent material, heavy clay, olive brown (2.5 Y 5/3, 2.5 Y 4/4), moist, massive structure, common soft concretions of secondary carbonates, gradual and wavy boundary;

Cigk2 – 160–(200) cm, *calcaric* parent material, silty clay, dark olive (5Y 5/4, 5Y 4/4), moist, massive structure, few soft concretions of secondary carbonates;

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ap	0–30	0	1	2	5	7	10	11	21	32	43	C
A2	30–46	0	0	2	3	5	9	9	24	33	48	C
Bigk	46–100	0	0	1	2	4	4	2	9	11	78	HC
Cigk	100–160	0	0	1	2	4	3	2	19	21	69	HC
Cigk2	160– (200)	0	0	1	1	2	5	2	39	41	50	SiC

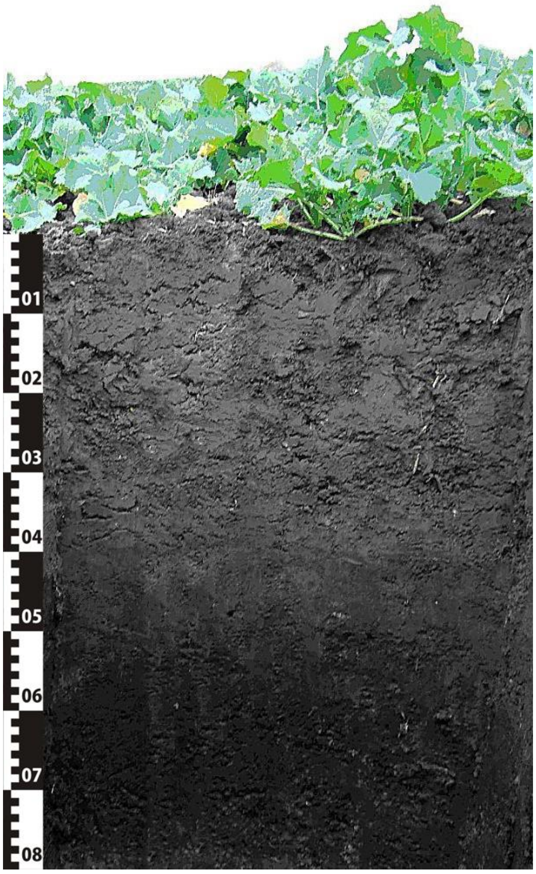
Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Ap	0–30	18.7	1.81	10	7.6	7.0	18
A2	30–46	19.5	1.93	10	7.7	7.0	13
Bigk	46–100	1.8	0.20	9	8.0	7.1	101
Cigk	100–160	-	-	-	8.1	7.2	164
Cigk2	160– (200)	-	-	-	8.1	7.2	138

Table 3. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	HA	CEC	CEC_{clay}	BS [%]
		[cmol(+)·kg^{-1}]								
Ap	0–30	19.6	2.89	1.07	0.09	23.6	0.67	24.3	41.3	97
A2	30–46	20.2	2.98	0.56	0.18	24.0	0.57	24.5	36.9	98
Bigk	46–100	33.0	3.63	0.66	0.35	37.6	0.40	38.0	47.9	99
Cigk	100–160	41.8	4.13	0.87	0.38	47.2	0.84	48.0	69.6	98
Cigk2	160– (200)	39.7	4.24	0.80	0.22	45.0	1.19	46.2	92.3	97

Profile 2 – Vertic **Phaeozem** (Clayic, Aric, Anocolluvic, Anopachic) over Sapric Drainic **Histosol** (Calcaric)
Localization: Glacilimnic plain, foot slope, arable field, 64 m a.s.l.,
N 54°02’44”, **E** 21°05’30”



Morphology:

Ap – 0–30 cm, plough *colluvic* material, plough humus horizon, clay, brownish black (2.5Y 4/2, 2.5Y 3/1), moist, fine strong granular structure, very fine and common roots, abrupt and smooth boundary;

A2 – 30–55 cm, *colluvic* material, humus horizon, clay, brownish black (10YR 3/2, 10YR 2/2), moist, strong prismatic structure, fine and common roots, irregular and wavy boundary;

A3 – 55–85 *colluvic* material, humus horizon, heavy clay, greenish black (5G 3/1, 5G 1.7/1), moist, fine strong granular structure, fine and few roots, clear and wavy boundary;

2Oab – 85–(150) cm, buried *histic* horizon, highly decomposed fen peat (sapric), black (7.5Y 3/1, 5Y 2/1), moist;

Table 4. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ap	0–30	0	0	1	5	8	4	6	30	36	46	C
A2	30–55	0	0	1	3	5	2	2	30	32	57	C
A3	55–85	0	0	0	3	6	2	1	19	20	69	HC

Table 5. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [$g \cdot kg^{-1}$]	Nt [$g \cdot kg^{-1}$]	C/N	pH		$CaCO_3$ [$g \cdot kg^{-1}$]
					H_2O	KCl	
Ap	0–30	29.8	3.29	9	7.5	6.7	4
A2	30–55	21.8	2.50	8	7.7	6.8	10
A3	55–85	19.5	2.38	-	7.7	6.9	7
2Oab	85–(150)	207	8.44	-	7.5	6.9	5

Table 6. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	TEB	HA	CEC	CEC_{clay}	BS
		[cmol(+)·kg^{-1}]								[%]
Ap	0–30	20.0	3.72	1.94	0.09	25.7	0.67	26.4	34.7	97
A2	30–55	20.0	3.70	1.33	0.09	25.1	0.64	25.8	31.9	97
A3	55–85	20.8	3.72	0.90	0.26	25.7	0.53	26.2	28.1	98
2Oab	85–(150)	27.9	4.52	0.51	0.34	33.3	1.32	34.6	-	96

Profile 3 – Haplic **Vertisol** (Aric, Hypereutric, Grumic)
Localization: Glacilimnic plain, middle slope, arable field, 80 m a.s.l.,
N 54°02’26”, **E** 21°05’09”

Morphology:

A – 0–30 cm, plough humus horizon, clay, brownish gray (10YR 5/3, 10YR 5/1), moist, strong granular structure, very fine and common roots, abrupt and smooth boundary;

Bik – 30–80 cm, *vertic* material, heavy clay, dull redish brown (2.5YR 5/3, 2.5YR 4/4), moist, coarse strong prismatic structure, fine and common roots, few soft concretions of secondary carbonates, gradual and wavy boundary;

Cik – 80–150 cm, *calcaric* parent material, heavy clay, dark redish brown (5YR 4/6, 5YR 3/6), moist, massive structure, fine and few roots, few soft concretions of secondary carbonates, gradual and wavy boundary;

Cik2 – 150–(180) cm, *calcaric* parent material, silty clay, redish brown (5YR 5/6, 5YR 4/8), coarse strong prismatic structure, few solid concretions of secondary carbonates.

Table 7. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ap	0–30	0	2	2	5	7	5	6	21	27	52	C
Bik	30–80	0	0	2	4	6	5	8	7	15	68	HC
Cik	80–150	0	0	1	2	3	4	2	20	22	68	HC
Cik2	150– (180)	0	0	0	1	1	3	2	52	54	41	SiC

Table 8. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Ap	0–30	16.4	1.94	8	7.5	6.9	46
Bik	30–80	1.1	0.15	7	8.0	7.1	56
Cik	80–150	-	-	-	8.1	7.2	125
Cik2	150– (180)	-	-	-	8.1	7.2	145

Table 9. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	HA	CEC	CEC_{clay}	BS
		[cmol(+)·kg^{-1}]								[%]
Ap	0–30	21.5	3.06	0.92	0.09	25.6	0.65	26.2	39.3	97
Bik	30–80	26.6	3.62	0.67	0.25	31.1	0.19	31.3	45.5	99
Cik	80–150	24.0	3.80	0.72	0.08	28.6	0.22	28.8	42.4	99
Cik2	150– (180)	30.3	4.61	0.96	0.25	36.9	1.02	38.0	92.7	97

Profile 4 – Calcic **Vertisol** (Hypereutric, Grumic)
Localization: Glacilimnic plain, deciduous forest, upper slope, 96 m a.s.l. ,
N 54°02’28”, **E** 21°03’58”

Morphology:

Oe – 4–0 cm, moderately decomposed organic matter;

A – 0–28 cm, humus horizon, clay loam, brownish black (7.5YR 5/4, 7.5YR 2/2), moist, fine moderate granular structure, medium and coarse common roots, gradual and wave boundary;

Bik – 28–85 cm, *vertic* material, heavy clay, dark brown (7.5YR 4/4, 7.5YR 3/4), moist, coarse strong prismatic structure, fine and medium common roots, few soft concretions of secondary carbonates, gradual and wavy boundary, few soft and solid concretions of secondary carbonates;

Cik – 85–120 cm, *calcaric* parent material, heavy clay, dull reddish brown (5YR 5/4, 5YR 4/4), moist, strong prismatic structure, medium and few roots, few soft concretions of secondary carbonates, gradual and wavy boundary;

Cik2 – 120–(150) cm, *calcaric* parent material, heavy clay, dull reddish brown (5YR 5/3, 5YR 4/3), moist, strong columnar structure, medium and few roots, few soft concretions of secondary carbonates;

Table 10. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
A	0–28	0	1	2	6	10	8	12	30	42	31	CL
Bik	28–85	0	0	0	1	2	2	5	20	25	70	HC
Cik	85–120	0	0	0	2	3	5	4	18	22	68	HC
Cik2	120– (150)	0	0	0	1	3	3	4	11	15	78	HC

Table 11. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [$g \cdot kg^{-1}$]	Nt [$g \cdot kg^{-1}$]	C/N	pH		$CaCO_3$ [$g \cdot kg^{-1}$]
					H_2O	KCl	
A	0–28	37.6	4.11	9	6.6	6.0	1
Bik	28–85	1.6	0.16	10	7.6	6.8	175
Cik	85–120	-	-	-	8.3	7.2	104
Cik2	120– (150)	-	-	-	8.1	7.2	141

Table 12. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	HA	CEC	CEC_{clay}	BS [%]
		[$cmol(+) \cdot kg^{-1}$]								
A	0–28	27.9	4.93	0.61	0.09	33.6	2.76	36.3	74.6	92
Bik	28–85	32.1	4.52	1.33	0.26	38.2	0.67	38.9	54.8	98
Cik	85–120	30.2	4.11	0.82	0.25	35.4	0.46	35.8	52.6	99
Cik2	120– (150)	32.2	3.78	0.62	0.35	36.9	0.50	37.4	47.9	99

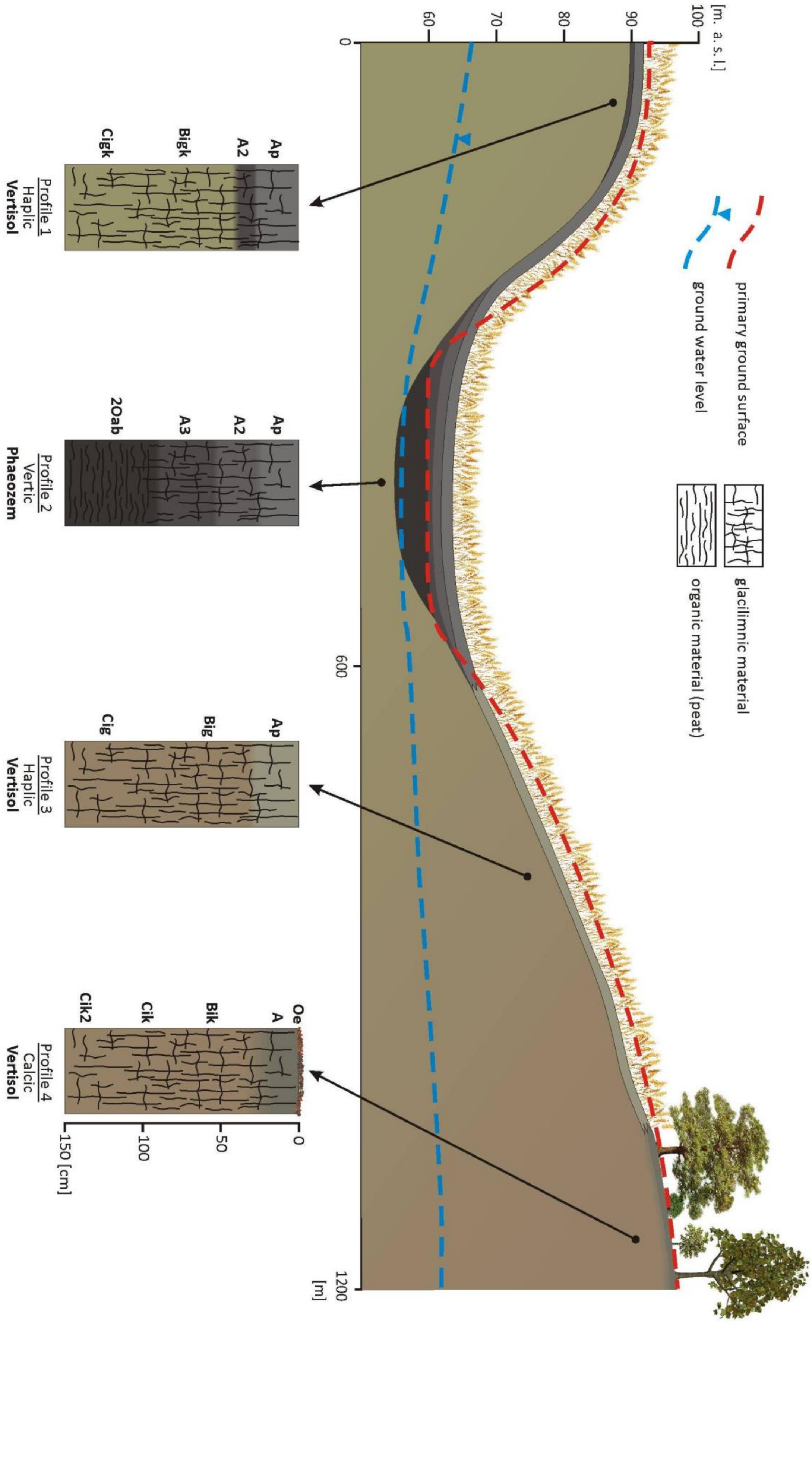


Fig. 2. Hydrotoposequence of soils within agricultural areas of glacilimnic landscapes

Soil genesis and systematic position

The soils occurring on Sępopol Plain are mainly related to the presence of glacilimnic sediments. These sediments, clays and heavy loams, have become the parent material of **Cambisols**, less frequently **Luvisols**, as well as ***Gleyic*** **Mollisols** and **Vertisols**. The land depressions are filled with **Histosols**. As a result of anthropogenic denudation, soils developed from colluvial materials were formed (Gotkiewicz et al., 2004). Vertisols were formed from swelling clay minerals, and they contain at least 30% of the clay fraction. The clay fraction on Sępopol Plain is composed mainly of silicate minerals of the 2:1 type of illite and illite/smectite groups (Długosz et al., 2009; Orzechowski et al., 2014). The origin of these soils is associated, in addition to the parent material, with water conditions. In these soils, there is a periodic change in the soil volume, depending on soil moisture. Drying and shrinkage lead to the formation of soil cracks and multiple fissures of more than 0.5 cm wide and up to 150 cm deep (Łabaz and Kabała, 2014). On the surface, the soil material is crushed to grainy structure. As a result of a variety of factors, soil aggregates are swept down to the developed fissures. This phenomenon is called "self-deepening" of the humus horizon. During the rainfall, water flows into fissures and the material that was swept down swells. This causes internal tension and compression of the material. Consequently, prismatic parts are rubbed against each other and smooth, shiny surfaces, so-called slickensides, are formed.

Soil properties of glacilimnic ladscapes were affected by Pleistocene processes of morpho- and lithogenesis and Holocene processes of pedogenesis. Most soils occurring in the glacilimnic areas were characterized by the clay or heavy loam texture with clay content of 41–78%. **Vertisols** – IUSS Working Group WRB (2015), represented by Profile 1 and 3, were the dominant soil unit in this landscape. The Bi horizon of these alkaline soils had specific cracks and slikensides of 2–3 cm wide and up to 1 m deep. Properties of this horizon met most of the criteria for the *vertic* horizon. Therefore, the ***Haplic*** principal qualifier was applied. **Vertisols** of the described region are usually used as arable fields, therefore the ***Aric*** subqualifier was used. The aggregate structure occurring in the humus horizon enabled us to use the ***Grumic*** subqualifier. These soils contain more than 1% of organic carbon in soil fine material up to 50 cm down the soil profile (***Humic*** subqualifier). High base saturation in the whole soil profile allows to use of the ***Hypereutric*** suplementary qualifier. Based on the color of soil parent materials, olive brown and dark olive, below 100 cm, the ***Endostagnic*** subqualifier was used.

The properties of the second soil (Profile 2), which has a *mollic* horizon with base saturation of 96–98%, and lacks a *calcic* horizon, enabled us to qualify this soil as **Phaeozem**. This soil was formed as a result of erosion of **Vertisols** located on the upper and middle slope. Erosion processes led to accumulation of quite thick colluvium (85 cm) on the foot slope (***Anocolluvic***). The clay texture of slope deposits, as well as cracks and slikensides was indicated by the ***Vertic*** qualifier. Colluvial material is lying on the fossil soil ***Sapric Drainic*** **Histosol** ***(Calcaric)***.

Profile 4 represents **Vertisol** under deciduous forest. The main qualifier is ***Calcic***. This indicates accumulation of secondary carbonates ($CaCO_3$) in glacilimnic sediments. The amount of $CaCO_3$ in subsurface horizons and parent material ranged between 140.7 and 175.2 $g \cdot kg^{-1}$. The occurrence of stable aggregate structure in the humus horizon enabled us to use the ***Grumic*** subqualifier. High base saturation in the whole soil profile allows to use the ***Hypereutric*** supplementary qualifier.

Soil sequence

Areas with diversified land relief are vulnerable to the translocation of soil material on the slope, induced and accelerated by agricultural use (Sinkiewicz, 1998; Sowiński, 2014). In order to determine the functionality of such areas, linear structure of soil cover, i.e. soil toposequences should be applied. Slopes that are used in agriculture in young glacial landscape are typical eroded catenas (De Alba et al., 2004). When they are agriculturally used, they are converted to downward-translocation catenas (Świtoniak, 2014; Świtoniak et al. 2016).

Glacilimnic landscape of Sępopol Plain is characterized by slightly diversified soil cover (Fig. 2). Among soil parent materials, glacilimnic clays (clay and heavy clay texture) and boulder loams (clay loam texture) prevail. Holocene pedogenetic processes led to the formation of **Vertisols**, which occurred in the upper, middle and foot slope. **Histosols** formed from fen peats occurred in land depressions.

Translocation of soil material on the slope, as a result of agricultural use, plays a key role in the modification of slope soil cover of rural landscapes. It leads to the transformation of primary soil cover and formation of typical soil toposequences (Smólczyński and Orzechowski, 2010; Smólczyński at al., 2015; Sowiński and Lemkowska, 2009). Colluvial soils, which are accumulated at lower parts of slopes and local depressions are an important chain in these soil structures. In the studied soil catena, colluvial material (85 cm thickness) was deposited on fen peats.

The soil sequence in the studied catena is as follows: ***Haplic*** **Vertisol** ***(Aric, Hypereutric, Grumic, Humic, Endostagnic) – Vertic*** **Phaeozem** ***(Clayic, Aric, Anocolluvic, Anopachic)*** on ***Sapric Drainic*** **Histosol** ***(Calcaric) – Haplic*** **Vertisol** ***(Aric, Hypereutric, Grumic) – Calcic*** **Vertisol** ***(Hypereutric, Grumic)***.

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Soils developed within the former mill pond basin (Chełmno Lakeland, north-central Poland)

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The study area includes the former Oleszek mill pond basin, located in the mesoregion of Chełmno Lakeland (Kondracki 2009). The Struga Rychnowska valley is a subglacial channel formed by meltwater during the Pomeranian phase of the Vistulian glaciation (16–17 kyr BP; Fig.1; Niewiarowski 1990; Marks 2012). In the centuries following the melting of the dead ice filling the channel (about 12 kyr BP), there was a natural water body (Niewiarowski 1990). In the 18th century, the water mill was located and the depression within the channel was used as a mill pond. The mill operated until the 1920s. After that period, the basin served as a storage reservoir for about 30 years (Podgórski 2004).

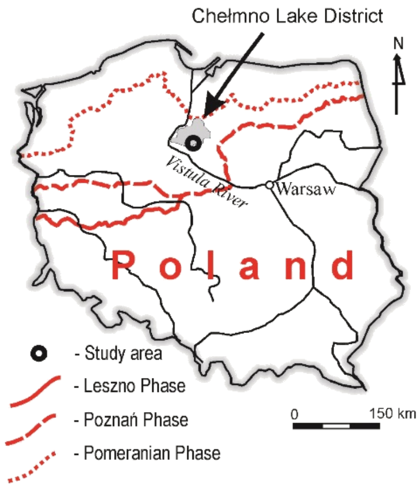

Fig. 1. Location

Lithology and topography

The edges of the channel are 95 m a.s.l. The channel borders on a morainic plateau (glacial till) in the east and on an outwash plain (fluvioglacial sands and gravels) in the west. The bottom of the channel is situated at 79–81 m a.s.l. and consists of various deposits: melt-out sands, Holocene alluvial organo-mineral deposits. Specific deposits have been sedimented in some parts of the channel used as mill pond; locally, there are also shallow colluvium covers (Topographic Map of Poland, 1:10 000, WMS server, geoportal.gov.pl; Geomorphologic Map of Poland, 1:50 000, sheet Kowalewo, no. 324; Podgórski 2004).

Land use

Two communities of riparian forest were identified in the area of the former mill pond. The ash-alder (*Fraxino-Alnetum*) forest was identified in the upper part of the basin. This community is typical of small stream valleys and is known as the potential natural vegetation in this area (Matuszkiewicz 2008). The lower part of the basin is covered with willow forest (*Salicetum albo-fragilis*), which is rather typical of medium and large river valleys. The adjacent areas of the morainic plateau are used as arable land, while the outwash plain is covered with Scots pine-dominated forest.

Climate

According to Kottek et al. (2006), the region is located in the temperate warm climate zone, fully humid with warm summer. The average annual temperature is 7.6°C. The average temperature of the coldest month (January) is −3.7°C, while the warmest month is July – 17.8°C. The average annual sum of precipitation is 542 mm. The February is the driest month (24 mm), while the highest precipitation is recorded in July – 75 mm (1982–2010, climate.data.org).

Profile 1 – Greyzemic Orthofluvic Gleyic **Phaeozem** (Geoabruptic, Epiloamic, Nechic)
Localization: bottom of the Struga Rychnowska valley, proximal part of the former mill pond, riparian forest (*Fraxino-Alnetum*), 80.7 m a.s.l., **N** 53°07'46.8" **E** 18°47'59.0"

Morphology:

Ah(p) – 0–27 cm, *mollic* horizon, fine sandy loam, black (10YR 4/2; 10YR 2/1), fine moderate granular structure, slightly moist, very fine and fine roots, single earthworms, abrupt and smooth boundary;

Ah(p) – 27–42 cm, loam, brownish black (10YR 4/2; 10YR 3/2), slightly moist, fine moderate subangular structure, slightly moist, many Fe concretions in root canals, clear and smooth boundary;

A/C – 42–65 cm, loamy medium sand, brownish black (2.5YR 6/2; 2.5YR 3/2), fine moderate subangular structure, slightly moist, single medium roots, many Fe concretions, abrupt and smooth boundary;

Cl1 – 65–78 cm, loam, brownish black (2.5Y 6/1; 2.5Y 3/2), medium angular structure, moist, common shells of snails and mussels, single Fe concretions, abrupt and smooth boundary;

Clc – 78–88 cm, coarse sand, dark brown (10YR 5/3; 10YR 3/3), single grain structure, wet, dead tree roots, common shells of snails and mussels, common Fe concretions in root canals, abrupt and smooth boundary;

L – 88–100 cm, limnic material mud mixed with moderately decomposed peat, black (10YR 3/1; 10YR 2/1), amorphous structure, wet, abrupt and smooth boundary;

Cl2 – 100–128 cm, loamy fine sand, brownish black (2.5Y 5/1; 2.5Y 3/1), single grain structure, wet, clear and wavy boundary;

Cl3 – 128–(150) cm, clay, dark greyish yellow (2.5Y 6/1; 2.5Y 4/2), massive structure, wet;

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ah(p)	0–27	0	2	6	16	28	15	14	10	4	5	FSL
Ac	27–42	0	1	4	12	14	11	21	16	9	12	L
A/C	42–65	2	7	11	34	26	6	5	3	3	5	LMS
Cl1	65–78	0	1	2	11	11	10	15	20	13	17	L
Clc	78–88	1	8	24	43	12	2	2	4	1	4	COS
Cl2	100–128	0	0	2	15	54	8	7	5	4	5	LFS
Cl3	128–(150)	0	0	4	6	6	0	1	7	23	53	C

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Ah(p)	0–27	35.8	3.57	10	7.8	7.3	17.7
Ac	27–42	25.7	2.62	10	8.3	7.5	37.1
A/C	42–65	7.01	0.61	11	8.5	8.0	18.1
Cl1	65–78	26.5	2.49	10	8.0	7.5	54.0
Clc	78–88	9.92	0.89	11	7.9	7.7	12.2
L	88–100	174	12.4	14	n.d.	n.d.	8.70
Cl2	100–128	21.8	2.10	10	8.0	7.7	41.4
Cl3	128–(150)	6.69	0.48	14	8.4	7.5	9.38

Profile 2 – Hypereutric **Gleysol** (Anoloamic, Colluvic, Profundihumic, Katolimnic)
Localization: toeslope of the valley of Struga Rychnowska, proximal part of the former mill pond, riparian forest (*Fraxino-Alnetum*), 81.0 m a.s.l., **N** 53°07'44.4" **E** 18°47'58.1"

Morphology:

Ah – 0–38 cm, *mollic* horizon, fine sandy loam, brownish black (10YR 4/2; 10YR 2/2), medium moderate granular structure, slightly moist, common dead tree roots, few wood fragments, single shells of snails and mussels, single Fe concretions, clear and wavy boundary;

L1 – 38–53 cm, *limnic* material, fine sandy loam brownish black (2.5YR 4/2; 2.5YR 3/1), slightly moist, medium strong subangular structure, wood fragments, common shells of snails and mussels, common Fe concretions around wood fragments, abrupt and smooth boundary;

L2 – 53–100 cm, *limnic* material, black (2.5YR 3/2; 2.5YR 2/1), slightly moist, amorphous structure, single shells of mussels, gradual boundary;

L3 – 100–122 cm, *limnic* material, fine loamy sand, black (2.5YR 4/1; 2.5YR 2/1), moist, fine weak subangular structure, common wood fragments, common fine dead roots, common shells of mussels, abrupt and smooth boundary;

Cl – 122–(150) cm, clay loam, dark greyish yellow (2.5YR 6/2; 2.5YR 4/2), moist, massive structure.

Table 4. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Ah	0–38	6	3	6	21	32	12	9	8	4	5	FSL
L1	38–53	1	1	9	19	24	17	13	8	6	3	FSL
L3	100–122	2	1	3	19	49	9	7	5	3	4	LFS
Cl	122–(150)	8	1	2	6	13	11	9	15	10	33	CL

Table 5. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Ah	0–38	23.0	1.90	12	7.8	7.1	1.00
L1	38–53	130	11.2	12	7.9	7.4	102
L2	53–100	159	12.7	13	7.4	7.0	39.3
L3	100–122	25.2	1.84	14	8.0	7.7	14.4
Cl	122–(150)	8.57	0.52	16	8.4	7.7	111

Profile 3 – Rheic Sapric **Histosol** (Calcaric, Katolimnic, Orthomineralic, Loaminovic)
Localization: bottom of the valley of Struga Rychnowska, central part of the former mill pond, riparian forest (*Salicetum albo-fragilis*), 79.4 m a.s.l. **N** 53°07'43.2" **E** 18°48'09.0"

Morphology:

(A)L1 – 0–14 cm, loam, brownish black (10YR 4/2; 10YR 2/2), slightly moist, medium moderate granular structure, common fine and single medium roots, common shells, clear and smooth boundary;

(A)L2 – 14–33 cm, loam, brownish black (10YR 4/2; 10YR 3/1), slightly moist, medium moderate granular structure, common single fine and medium roots, common fine shells of snails and mussels, single Fe concretions around roots, clear and wavy boundary;

Lcm – 33–56 cm, *histic* horizon, *limnic* material, black (2.5Y 3/1; 2.5Y 2/1), moist, amorphous structure, common roots, many leaves and twigs fragments, common fine shells of snails and mussels, Fe concretions around roots, clear and wavy boundary;

Lc – 56–74 cm, *limnic* material, black (2.5Y 2/1; 2.5Y 2/1), moist, amorphous structure, leaves and twigs fragments, abrupt and smooth boundary;

Lm – 74–94 cm, *limnic* material, brownish black (2.5Y 4/1; 2.5Y 3/2), wet, amorphous structure, leaves and twigs fragments, fine dead roots, fine shells of snails and mussels, clear and wavy boundary;

L – 94–105 cm, *limnic* material, fine sand, black (2.5Y 3/1; 2.5Y 2/1), wet, single grain structure, fragments of undecomposed plants, fine dead roots, single shells of snails and mussels, clear and wavy boundary;

Cl – 105–120 cm, fine sand, dark olive (5Y 6/3; 5Y 4/4), wet, single grain structure;

Cr – 120–(150) cm, fine sand, dark olive (5Y 6/3; 5Y 4/4), wet, single grain structure;

Table 6. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Cl	105–120	0	0	2	18	53	13	8	3	1	2	FS
Cr	120–(150)	1	1	2	34	58	1	0	1	0	3	FS

Table 7. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
(A)L1	0–14	132	13.1	10	8.1	7.4	143
(A)L2	14–33	132	12.3	11	8.1	7.5	173
Lcm	33–56	276	19.7	14	7.8	7.5	214
Lc	56–74	473	30.9	15	7.2	6.9	31.8
Lm	74–94	134	13.1	10	7.9	7.9	411
L	94–105	25.8	2.17	12	7.9	7.5	43.8
Cl	105–120	1.21	0.16	8	8.5	8.1	5.00
Cr	120–(150)	6.23	0.32	19	8.1	7.6	38.2

Profile 4 – Hypereutric Endofluvic **Gleysol** (Endoarenic, Hyperhumic, Anolimnic)
Localization: bottom of the valley of Struga Rychnowska, central part of the former mill pond, riparian forest (*Salicetum albo-fragilis*), 79.2 m a.s.l. **N** 53°07'40.9" **E** 18°48'10.3"

Morphology:

(A)L – 0–47 cm, *limnic* material, brownish black (10YR 4/3; 10YR 2/2), moist, medium moderate granular structure, common fine roots, single coarse roots, clear and wavy boundary;

L – 47–54 cm, *limnic* material, loamy medium sand, yellowish gray (2.5Y 4/1; 2.5Y 2/1), moist, medium weak subangular structure, common fine dead roots, undecomposed plant remains, Fe concretions around roots, clear and smooth boundary;

Cl – 54–65 cm, medium sand, yellowish gray (2.5Y 5/1; 2.5Y 3/1), moist, single grain structure, single shells of mussels, clear and wavy boundary;

Clc – 65–(90) cm, medium sand, dull yellow orange (10YR 6/4; 10YR 3/4), wet, single grain structure, single medium roots, single plant remains, single Fe concretions.

Table 8. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
L	47–54	1	3	11	39	26	1	7	8	2	3	LMS
Cl	54–65	2	5	15	52	22	1	1	2	1	1	MS
Clc	65–(90)	2	4	17	55	20	1	2	1	0	0	MS

Table 9. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
(A)L	0–47	170	15.2	11	8.0	7.3	120
L	47–54	28.6	2.25	13	7.8	7.6	59.1
Cl	54–65	8.98	0.64	14	8.5	8.2	24.3
Clc	65–(90)	n.d.	n.d.	n.d.	8.7	8.5	2.00

Profile 5 – Calcaric **Gleysol** (Amphiloamic, Profundihumic, Katolimnic, Novic)
Localization: bottom of the valley of Struga Rychnowska – distal part of the former mill pond, riparian forest (*Salicetum albo-fragilis*), 79.0 m a.s.l. **N** 53°07'37.6" **E** 18°48'10.7"

Morphology:

A(L) – 0–14 cm, loamy fine sand, brownish black (10YR 4/2; 10YR 3/2), moist, medium moderate granular structure, fine common roots, crushed shells, earthworms, single Fe concretions around roots, clear and smooth boundary;

L1 – 14–34 cm, *limnic* material, fine sandy loam, brownish black (10YR 4/3; 10YR 2/2), moist, medium moderate granular structure, fine roots of shrubs, common shells of snails, brick fragments, clear and wave boundary;

L2 – 34–68 cm, *limnic* material, fine sandy loam, brownish black (2.5Y 5/4; 2.5Y 3/2), moist, amorphous structure, fine single roots, plant remains, common shells of snails and mussels, clear and wave boundary;

L3 – 68–210 cm, *limnic* material, black (2.5Y 3/3; 2.5Y 2/1), wet, amorphous structure, common dead roots, common shells of snails and mussels, clear and smooth boundary;

Cr – 210–(240) cm, gravelly medium sand, black (2.5Y 6/1; 2.5Y 3/2), wet, single grain structure.

Table 10. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
(A)L	0–14	2	2	5	22	40	10	10	7	1	3	LFS
L1	14–34	3	1	2	9	26	17	19	15	5	6	FSL
L2	34–68	0	0	4	10	21	16	22	15	7	5	FSL
Cr	210–(240)	20	4	6	41	39	4	2	1	2	1	GMS

Table 11. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [$g \cdot kg^{-1}$]	Nt [$g \cdot kg^{-1}$]	C/N	pH		$CaCO_3$ [$g \cdot kg^{-1}$]
					H_2O	KCl	
(A)L	0–14	34.1	2.91	12	7.9	7.5	19.0
L1	14–34	41.5	3.84	11	8.3	7.7	57.0
L2	34–68	93.9	7.23	13	8.1	7.6	169
L3	69–210	165	9.97	17	7.3	7.0	43.0
Cr	210–(240)	10.3	0.61	17	8.3	8.1	18.0

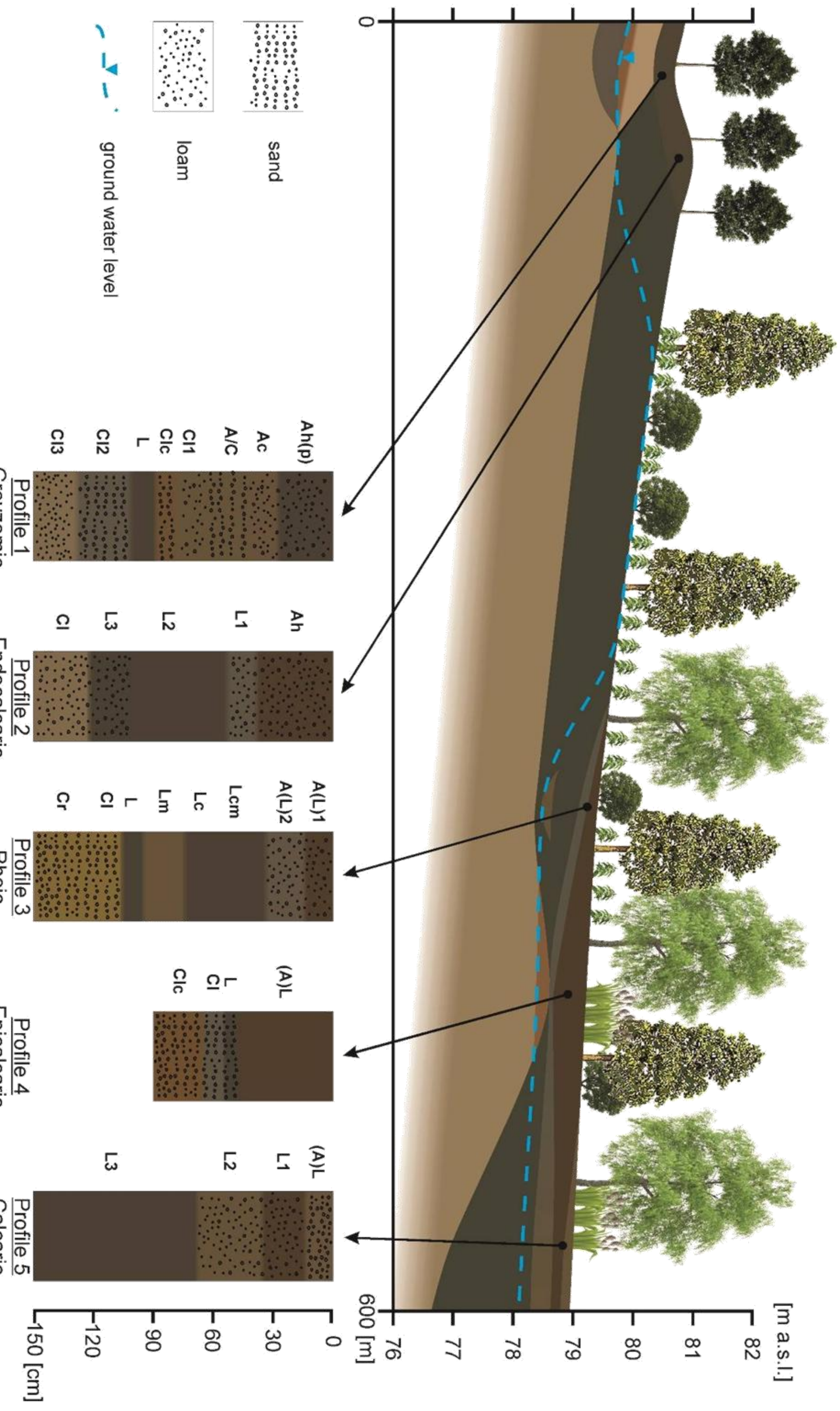

Fig. 2. Litho-hydrosequence of soils within the former mill pond basin

Soil genesis and systematic position

The genesis and origin of sediments deposited in the studied part of the subglacial channel had the strongest influence on the morphology, thus on the systematic position of soils within the former Oleszek mill pond basin. The above-mentioned deposits could be divided into the following groups: mineral sediments of the subglacial channel bed (outwash sand or glacial till), fluvio- and limnogenic organo-mineral materials of the natural reservoir and organo-mineral sediments accumulated in the mill pond, characterized by partially fluvic and limnic genesis, often mixed with colluvium (Mendyk et al., 2015). The Oleszek mill pond is a classic, flow-through reservoir using a unique topography of the valley to store the water behind the dam built perpendicularly to its longitudinal axis. Sediments accumulated in such water bodies are often characterized by a number of distinctive features. Generally, the organic matter content increases and the diameter of sedimented particles decreases along the transect from the proximal (water inflow) to the distal (water outflow) parts of the basin in response to the decrease in water energy (e.g. Jonczak and Florek 2013; Mendyk et al., 2015). The comparison of sediments of the former Oleszek mill pond basin with natural sediments led the authors to the following conclusions: 1) the middle parts of profiles 2, 3, 4 and 5 are similar to limnetic muds, 2) the top part of these soils are more similar to the telmatic muds (Mendyk et al., 2015). The former are formed in e.g. oxbow lakes, while the latter are typical of flood plains of semi-natural rivers (Okruszko 1969; Roj-Rojewski 2003, 2009).

Profile 1 is located in the upper part of the former pond where incoming water of the Struga Rychnowska stream had a relatively high energy. It is developed from the organo-mineral alluvium intersected with the thin layer of organic mud. It was classified as **Phaeozem** due to the presence of the *mollic* diagnostic horizon. The occurrence of uncoated sand grains in the lower half of the surface horizon enabled us to use the ***Greyzemic*** qualifier. The fluvic genesis of soil material and still visible layering is expressed with the ***Orthofluvic*** qualifier. The ***Gleyic*** qualifier was used to highlight the *gleyic* properties, starting in this case at a depth of 65 cm and being present up to the bottom of the soil profile (150 cm, so it is more than 25 cm thick). Because of the abrupt textural difference at a depth of 65 cm (Table 1) and no connection with the argic horizon, the ***Geoabruptic*** qualifier was applied. The supplementary qualifier ***Epiloamic*** provides information about the loamy texture in the upper part of the profile (0–42 cm, Table 1). The ***Nechic*** qualifier is used as an indicator of uncoated mineral grains within the top 5 cm of the mineral soil surface.

The surface horizon of Profile 2 also meets the criteria of the *mollic* diagnostic horizon. Nonetheless, the *gleyic* properties were recognized at a depth below 40 cm, which enables us to classify this soil profile as **Gleysol**. Due to very high values of pH, both in distilled water (7.4–8.4) and KCl (7.0–7.7, Table 4), we used the ***Hypereutric*** qualifier. Loamy texture (FSL) of the two top horizons (0–38, 38–53, Table 3) is the reason for using the ***Anoloamic*** supplementary qualifier. In addition, the surface horizon is developed (at least partially) as a consequence of *colluvic material* accumulation resulting from the erosion of the steep slope (***Colluvic*** supplementary qualifier). High organic matter content (from 23.0 to 159 $g \cdot kg^{-1}$ of organic carbon) in the top 100 cm from the mineral soil surface allowed to use the ***Profundihumic*** qualifier. The ***Katolimnic*** supplementary qualifier was used due to the presence of *limnic material* in all the soil genetic horizons from 38 to 122 cm.

Profile 3 was characterized by the highest content of the organic matter. Layers consisting of the *organic material* had a combined thickness of slightly more than 40 cm within the top 100 cm of the soil profile (33–74 cm, Table 6), that is why the soil was classified as **Histosol.** This material was strongly decomposed (***Sapric***), which is a typical feature of the limnetic muds (Okruszko 1969). Due to the very high groundwater level (stagnating on the soil surface during the cold season of the year), the ***Rheic*** qualifier was applied. High content of carbonates (32–411 $g \cdot kg^{-1}$) in the upper 100 cm led us to use the ***Calcaric*** qualifier. Similarly to Profile 3, the l*imnic material* was present in the major part of the soil profiles (***Katolimnic***). The occurrence of *mineral material* at the soil surface and in the bottom part of the profile, interlayered with *organic material* was emphasized with the ***Orthomineralic*** qualifier. The ***Loaminovic*** qualifier provides information that the top part (0–33 cm), built of the material accumulated probably after the period of the mill functioning, features loamy texture (determined in the field).

Gleyic properties were recognized at a depth below 40 cm in Profile 4, which led us to classify this soil profile as **Gleysol.** Another resemblance to Profile 2 is visible when analysing the values of soil pH (7.8 to 8.7 in distilled water, Table 8), based on which the ***Hypereutric*** qualifier was used again. The bottom part of the profile (54–90 cm) was built of the *fluvic material* (***Endofluvic***) with sand texture (Table 7, ***Endoarenic***). The surface layer (two top horizons, 0–54 cm, Table 8) of the organic matter, with the large admixture of *limnic material*, was the reason for using the two last qualifiers: ***Hyperhumic*** and ***Anolimnic***.

The high ground water level and the occurrence of Fe oxides concretions indicate *gleyic properties* corresponding to the **Gleysols** reference soil group. The content of carbonates exceeding 20 $g{\cdot}kg^{-1}$ (2%) between 14 and 210 cm allowed us to use the ***Calcaric*** qualifier. ***Amphiloamic*** indicates that part of the profile characterized by loamy texture starts somewhere in the upper 50 cm (14 cm in this case) and ends within the next 50 cm of depth (68 cm, Table 9). High organic carbon content (34 to 165 $g{\cdot}kg^{-1}$) in the upper 100 cm of the profile was highlighted by the ***Profundihumic*** qualifier. In this case, organic matter-rich material was represented by thick layers of limnic muds, as in Profiles 2, and 3 (***Katolimnic***). They are covered with some fluvio-limnic deposits with admixture of the colluvic material coming from the nearby dam (***Novic***).

Soil sequence

The above-described soil transect developed as a result of several different overlapping processes (Mendyk et al. 2015), including mainly the sedimentary processes, such as alluvial and mud-forming processes which led to accumulation of the major parts of the analyzed soil profiles. They took part in the natural water body existing in the basin as well in the Oleszek mill pond. After the discharge of the reservoir, the gleyic processes have progressed in all of the profiles. Some surface horizons (Profiles 2 and 5) were formed as an effect of the colluvial process. Due to different ground water table levels in the profiles and the large variability of the soil materials in the presented pedons, this is a good example of the **litho-hydrosequence** common in the young glacial landscapes (subglacial channels) influenced by hydro-technological constructions.

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Area with hydrotoposequence of sandy soils on Palumaa Plateau

Endla Reintam, Marcin Świtoniak, Alar Astover, Merrit Shanskiy, Raimo Kõlli

The study area is located on the plateau of South Estonia. It consists of Devonian sandstone denudations at high river banks and is mainly covered by moraine and ice lake sediments from the last, Weichselian, glaciation of the Lower Pleistocene (Raukas, Kajak 1997). It represents an area of sandy soils and bogs on ice lake sediments with the landscape rich in dry boreal pine forests and boreal heaths. According to Arold (2005), the study area is located on the Palumaa Plateau, south from the Ugandi Plateau in the Meenikunno Nature Protection Area (Fig. 1).

Fig. 1. Location

Lithology and topography

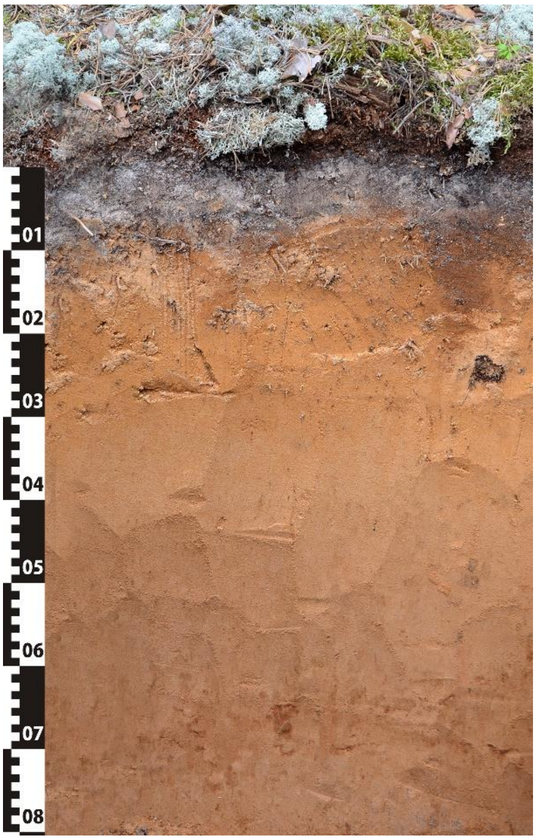
The area of Palumaa is 827 km^2, accounting for 1.82% of the whole area of Estonia (Arold, 2005). The 40% of moraine from the last ice age is covered here by sandy ice lake deposits with a depth of 0.80–2.0 m. The specific feature of the area is related to the high percentage of valleys (9.3%) in the southern part. Meenikunno is located in the catchment area of the Võhandu river. Meenikunno is covered mostly by swamps (1448 ha). Meenikunno was created mostly as a result of the swamping of the dry, sandy land, which started in the boreal climatic period more than 8000 years ago. The peatland layers are saturated with water, under which there is only a partial layer of sand, which gives the impression of hanging in the air. This means that the groundwater is deep (1–2 m below the bog bottom) and there is a dry layer under the bog. The process of forming the bog has lasted thousands of years and continues very actively to this day, with hollows and 3 bog lakes developed, a bog pool currently being developing, and large numbers of islands – the largest of which are Pikksaar and Pähklisaar. The peat cover is 7 meters over sand, aleuroliths and middle Devonian Gauja stratum sandstones, passed with Northeast-southwester fault zone. On this line, on the foot of the oozy scents the closed depressions are locating. The depth of the depressions reaches 2.5 m, the diameter is 50 m and they are circular or oval-shaped (Raukas, Kajak 1997). The average height of the Palumaa plateau is 60–70 m from the sea level, being lower in the east by 40–45 m and reaching up to 120 m in the south-east. In the southern part, there are hummocks formed during the glaciation in small ice lakes with a relative height of 10–24 m. In till, the carbonate-free material from sandstone and aleuroliths dominates, resulting in reddish-brown color. Sands are silicate-rich suitable for glass production.

Land use

The Meenikunno bog with an approximate area of 1,500 hectares is predominantly covered with scattered woods, but there are also several bog pools and lakes (Kamarusjärv, Middle Suujärv and Big Suujärv) (Arold, 2005). Bog islands, with old pine trees, are abundant. On the other hand, the largest island, Pähnisaar, is covered with groves of birches and aspens. The area around the bog is predominantly covered with pine forest. Peat moss is the main species forming the peat.

Profile 1 – Albic **Podzol** (Arenic, Hypoendostagnic)

Localization: Dunes, hummock, middle slope - inclination 5°, pine forest under nature protection, 81 m a.s.l., **N** 57°56'41.2" **E** 27°19'54.8"



Morphology:

Oe – 5–0 cm, moderately decomposed organic material, abrupt and wavy boundary;

E – 0–8 cm, *albic* material, fine sand, gray (10YR 5/1), weak subangular blocky fine structure, very few medium and few fine roots, clear and wavy boundary;

Bhs – 8–12 cm, *spodic* horizon, fine sand, (5YR 4/6), moderate subangular blocky fine structure, very few medium and few fine roots gradual boundary;

Bs – 12–30 cm, fine sand, strong brown (7.5YR 5/8), weak subangular blocky fine structure, few fine roots, gradual boundary

BC – 30–58, fine sand, reddish yellow (7.5YR 6/8), single grain structure, very few fine roots, gradual boundary;

BC(g) – 58–80, fine sand, light brown (7.5YR 6/4) yellowish red mottles (5YR 4/6), single grain structure, gradual boundary;

C – 80–(120), fine sand, light brown (7.5YR 6/5), single grain structure;

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
O	5–0	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.
E	0–8	n.o.	1.4	5.3	30.2	55.1	6	2	0	0	0	FS
Bhs	8–12	n.o.	1.4	3.5	27.9	58.2	5	4	0	0	0	FS
Bs	12–30	n.o.	0.7	3.1	33	56.2	4	3	0	0	0	FS
BC	30–58	n.o.	1.1	3.3	31.5	58.1	4	2	0	0	0	FS
BC(g)	58–80	n.o.	0.5	2.8	34	55.7	5	2	0	0	0	FS
C	80–(120)	n.o.	0.4	1.9	22	65.7	6	4	0	0	0	FS

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
O	5–0	327	15.2	22	3.6	2.8	n.o
E	0–8	7.9	00.4	20	4.2	3.4	n.o
Bhs	8–12	-	-	-	4.7	4.4	n.o
Bs	12–30	-	-	-	4.9	4.6	n.o
BC	30–58	-	-	-	5	4.6	n.o
BC(g)	58–80	-	-	-	5.4	4.7	n.o
C	80–(120)	-	-	-	5.4	4.7	n.o

Profile 2 – Folic Albic **Podzol** (Arenic, Oxyaquic)

Localization: Dunes, hummock, lower slope - inclination 1°, pine forest under nature protection, 76 m a.s.l., **N** 57°56'40.7" **E** 27°19'54.8"

Morphology:

Oe – 11–0 cm, moderately decomposed organic material, *folic* horizon, abrupt and smooth boundary;

E – 0–10 cm, *albic* material, fine sand, gray (7.5YR 6/1), single grain structure, very few medium and few fine roots, clear and wavy boundary;

Bhs – 10–15 cm, *spodic* horizon, fine sand, dark reddish brown (5YR 3/4), weak subangular blocky fine structure, very few medium and few fine roots, clear and wavy boundary;

Bs – 15–40 cm, fine sand, strong brown (7.5YR 5/8), single grain structure, very few medium and few fine roots, clear boundary;

BC – 40–(70) cm, fine sand, brown (7.5YR 5/6), single grain structure, very few fine roots, *oxyaquic*, water table;

Table 3. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
Oe	11–0	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.
E	0–10	n.o.	1.3	38	48	4	3	0	0	0	0	FS
Bhs	10–15	n.o.	1.5	33.1	49.8	5	6	0	0	0	0	FS
Bs	15–40	n.o.	1.2	32.1	45.7	9	7	0	0	0	0	FS
BC	40–(70)	n.o.	–	–	–	–	–	–	–	–	–	FS

Table 4. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Oe	11–0	495	21.9	23	3.1	2.1	n.o.
E	0–10	4.3	00.2	22	3.9	3.1	n.o.
Bhs	10–15	n.o.	n.o.	n.o.	4.1	3.6	n.o.
Bs	15–40	n.o.	n.o.	n.o.	4.6	4.4	n.o.
BC	40–(70)	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.

Profile 3 – Dystric Epifibric Endohemic **Histosol** (Hyperorganic)
Localization: High bog in depression between dunes, peat moss pine vegetation, 72 m a.s.l.,
N 57˚56’40.5’’ **E** 27˚19’53,5’’

Morphology:

Hi – 0–60 cm, *histic* horizon, slightly decomposed fibric organic material, gradual boundary;

He – 60–(120) cm, *histic* horizon, moderately decomposed hemic organic material;

Table 5. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Hi	0–60	464	19.0	24	3.4	2.5	n.o.
He	60–(120)	470	20.4	23	3.4	2.5	n.o.

Climate

The climate of the study area is boreal. The mean air temperature of the region is +4.5°C. The average air temperature of the coldest month (February) is –6 to –7°C and of the warmest month (July) between +16.0°C and +17°C. The mean annual precipitation is 600–700 mm and the growing season generally lasts for 170–185 days. The amount of precipitation spreads almost equally throughout the year and is more than two times higher than evapotranspiration. The snow cover is characterized by large territorial and temporal variations (75–135 days: from the beginning of January to the end of March).

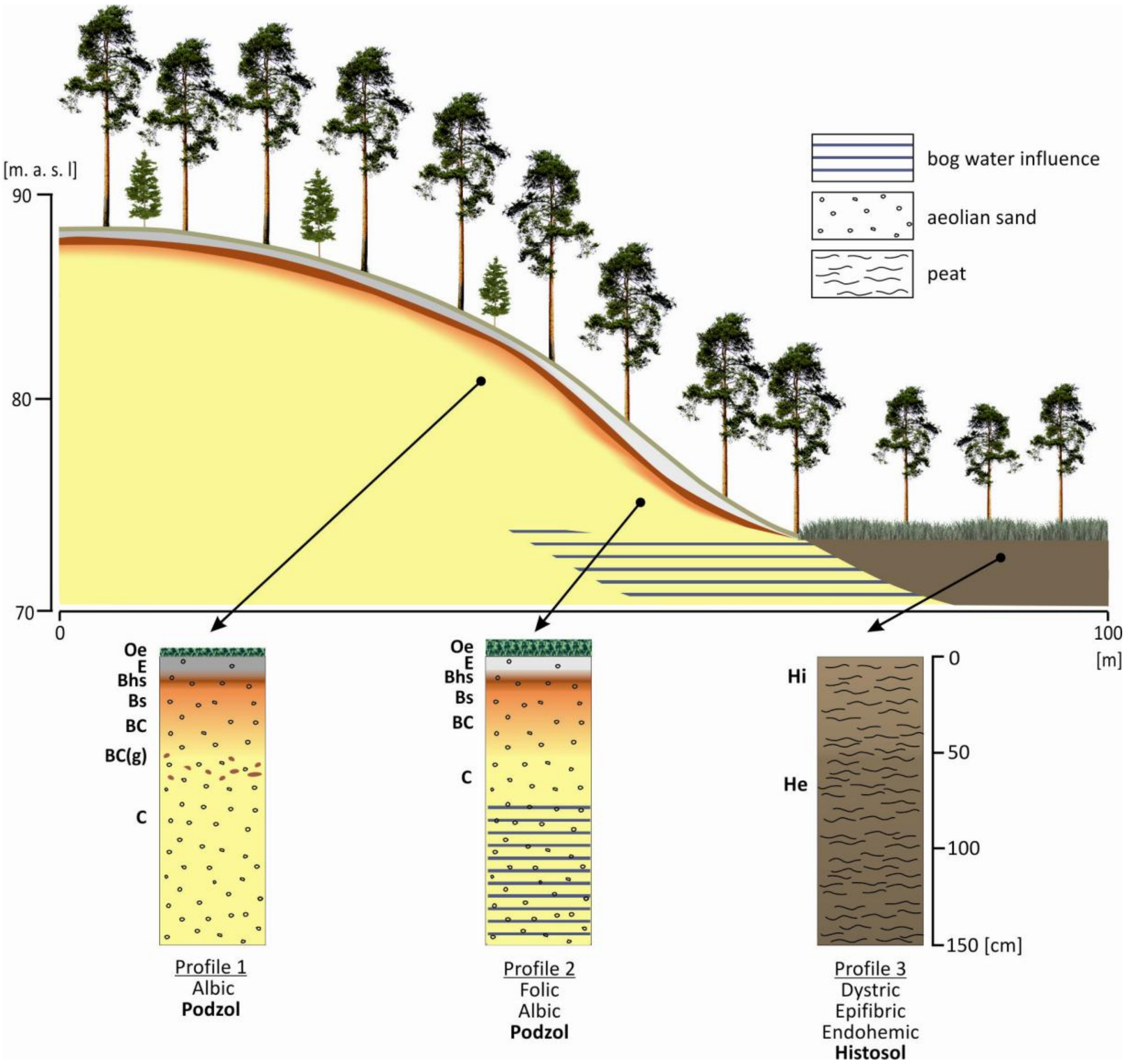


Fig. 2. Hydrotoposequence of sandy soils on Palumaa Plateau

Soil genesis and systematic position

The investigated soil profiles represent the typical soils of Palumaa Plateau with sandy dunes covered by pine forest without grass cover. Profile 1 is typical for upper, drier part of sandy dunes. Soil is formed on fine dune sands (Table 1) covered with 5 cm deep moderately decomposed organic matter. There is no humus horizon present. Eluvial horizon (E) and illuvial horizons (Bhs, Bs) are well developed. The profile is Oe–E–Bhs–Bs–BC–BC(g)–C, with pH_{H2O} 4.7 (Table 2), thickness of 4 cm and moist Munsell color 5YR 4/6. The existing Bhs horizon at a depth of 8 cm meets the requirements of the diagnostic – *spodic* – horizon and thus the requirements of **Podzols** (IUSS Working Group WRB, 2015). The overlying eluvial horizon qualifies as *albic* material with Munbsell color 10YR 5/1 in moist conditions. Between 58–80 cm, there is evidence of *stagnic* properties (BC(g)), as the color of yellowish red mottles is redder and stronger compared to the surrounding material. Soil-forming processes are evident down to 80 cm. The texture of the whole profile is sand (98%), with only slight 1–2% changes in sand and silt content through the profile, justifying the soil qualifier ***Arenic***.

Profile 2 is similar to Profile 1 with the same texture of parent material (Table 3), chemical properties (Table 4) and basic profile: Oe–E–Bhs–Bs–BC (Fig. 4) located on the lower slope of the dune. The main differences are in the thickness of horizons. The organic matter layer (Oe) on the top of mineral material with the thickness of 11 cm meets the criteria of the *folic* horizon (IUSS Working Group WRB, 2015). The eluvial horizon with *albic* material is 2 cm and the illuvial Bhs *spodic* horizon is 1 cm thicker compared to Profile 1. Starting from 70 cm, the soil was saturated with water (Profile 2). As there are no visible changes in the soil color pattern, no *stagnic* or *gleyic* properties can be added to the profile and thus the criteria of ***Oxyaquic*** are met.

In general, the soil profiles are typical of ***Albic*** **Podzols** formed on sands under coniferous forest (Lundström et al. 2000). Sands of Palumaa Plateau are poor in minerals; quartz dominates (Raukas, Kajak 1997). In the investigated area, the groundwater is more than 10 m deep. In such conditions, pine is the dominant species among those able to survive. However, pine needles are poor in cations and rich in tannins (Astover et al. 2012). The result of decomposition of such material are strong fulvic acids, which form soluble complexes with aluminium and iron, thus enhancing weathering, followed by illuviation caused by precipitation and adsorption processes occurring at greater depths. Estonian climate with average rainfall of 600–700 mm is suitable for this process. Fine sand (Tables 1, 3) supports water infiltration. However, the eluvial (E, 8 cm) and illuvial (Bhs, 4 cm) horizons of Profile 1 are more weakly developed than the same horizons of Profile 2. This may result from a relatively fast movement of rain water through the profile as it is located on the slope of a dune, as well of organic matter from trees. It leaves less organic reagents to react with parent material than in the case of soils of lower slopes (Profile 2). The extent of podsolization is also in correlation with the average temperatures of the region, decreasing the intensity and possible active period for reactions (Lundström et al. 2000; Reintam, 2001). For that reason, **Podzols** of northern areas are less developed than **Podzols** of southern regions (Lundström et. al, 2000).

Profile 3 is situated at the lowest location in the landscape. There are only two horizons represented in this profile: Hi–He. As the total thickness of organic matter is more than 120 cm and it is saturated with water, it meets the requirements of the *histic* horizon and also **Histosols**. It is possible to divide the *histic* horizon into two according to the degree of decomposition of organic matter. The upper part (0–60 cm) consists of more than two thirds of recognizable plant tissues, meeting the qualifier ***Epifibric***. The lower part (below 60 cm) consists of less than two thirds of recognizable plant tissue, meetinf the qualifier ***Endohemic***. The strongly acidic reaction (Table 5) gives the prefix ***Dystric***. The total thickness of the peat in the Meenikunno bog increases to 6 m (Meenikunno, 2012) and thus the qualifier ***Hyperorganic*** is justified. The peats saturated with water are dominated by poorly humified (20%) cotton-grass – *Sphagnum* and grass peats (Raukas, Kajak 1997). The bog is mostly covered with scattered pine woods. The formation of the Meenikunno bog is not typical – bog peat has sedimented directly on the sand and the formation of mires started right from the raised bog stage. The sand beneath the peat is not saturated with water as the groundwater table is deep down (Meenikunno, 2012). Raised bogs accounts for some 80% of the total area of mires in this region (Raukas, Kajak 1997). Histosols represent 23.7% of the total area covered by soils in Estonia; 36% of Histosols are high mires similar to the study area (Kõlli et al., 2010).

Soil sequence

The above-described transect shows transformations of soil cover on sandy deposits of Palumaa Plateau. Properties of all analyzed profiles were influenced by rainwater as groundwater doesn't reach the profiles. The differences between Profile 1 and Profile 2 are mainly caused by the intensity of podsolization and side water infiltrating from the bog – Profile 3. The decomposition of organic matter is more intense in Profile 1 as the rainwater quickly infiltrates deeper into the profile. Stagnic properties are the effect of a periodically raised flow from the side. Profile 2 is influenced by a higher volume of water retained in the mire by peat, which reduces the decomposition of organic matter and increases the thickness of the organic matter layer on the top of the mineral material. Profile 2 clearly indicates the formation process of Profile 3 – formation of a bog peat. The sequence from ***Albic*** **Podzol** (***Arenic, Hypoendostagnic***) to ***Folic Albic*** **Podzol** (***Arenic, Oxyaquic***) to ***Dystric Epifibric Endohemic*** **Histosol** (***Hyperorganic***) represents typical soil formation with changing water saturation conditions at low pH on deep sandy deposits.

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Soils of eastern slope of the Curonian Spit dune in Juodkrantė old-growth forest

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The study area comprises the eastern slopes of the Curonian Spit aeolian dune near Juodkrantė (Fig. 1). The formation of the Curonian Spit started no later than 8,500–8,300 years BP during the transgression of Lake Ancylus or the first transgression of the Litorina Sea (L1), whereas the main geological-geomorphological features of the modern spit developed approximately 6,900–6,300 years BP, i.e. during the regression that followed the maximal transgression of the Litorina Sea (L2) (Bitinas et al., 2002; Bitinas and Damušytė, 2004; Gelumbauskaitė and Šečkus, 2005; Damušytė, 2011). The latest significant changes in the relief of the Curonian Spit have occurred more than 200 years ago when the formation of the protective coastal foredune ridge began. The studied soil sequence is located in the northern part of Juodkrantė old-growth forest (in Lithuanian called *Sengirė*) and reflects peculiarities of zonal processes of the coastal aeolian sand dune formation in the middle-latitude maritime climate.

Fig. 1. Location

Lithology and topography

The width of the Curonian Spit near the Juodkrantė settlement is about 1700 m. It is characterized by a typical landscape transect that reflects the natural geomorphological formation processes of the Curonian Spit and its transformation due to anti-erosion measures applied by man. In the relief of the dune complexes of the Curonian Spit, one can see more clearly (than in other places, e.g. Vistula Spit or other spits) zones altering in the direction of sea-gulf: beach, protective foredune, coastal dune ridge, front dune deflation-accumulation plain (*palvė*), dune massifs, near coastal palvė, beach on the lagoon side (Curonian Spit, 1999; Olšauskas and Olšauskaitė Urbonienė, 2009).

The Great coastal dune ridge near Juodkrantė rises to about 42 m a.s.l., while at the interdune area it drops to 6 m a.s.l. Both at coastal and lagoon sides, the dune deflation-accumulation plain (*palvė*) is formed as a concave plain whose inclination does not exceed 0.5°. The steepness of the windward (eastern) slope of the great coastal dune ridge reaches about 35°. Meanwhile, the leeward (western) slope has a considerably more gentle inclination – up to 12–13°. The interdune area is formed by deflection processes, therefore its mean inclination varies within about 5–6°.

Profile 1 – Dystric Albic Folic **Arenosol**

Localization: Curonian spit, Juodkrantė, aeolian dune, summit, inclination 0,5°, coniferous forest, 36 m a.s.l., **N** 55º33'13.0" **E** 21º06'55.6"

Morphology:

O – 11–0 cm, organic horizon, clear and smooth boundary;

AE – 0–9/25 cm, fine sand, single grain structure, brown (7.5YR 5/2), slightly moist, common roots diffuse boundary;

BC – 9/25–31 cm, medium sand, single grain structure, light brown (7.5YR 6/3), slightly moist, common roots, gradual boundary;

C1 – 31–55 cm, fine sand, single grain structure, very pale brown (10YR 7/4), moist, few roots, clear and smooth boundary;

C2 – 55–(120) cm, fine sand, single grain structure, very pale brown (10YR 7/4), moist, very few roots;

Table 1. Texture

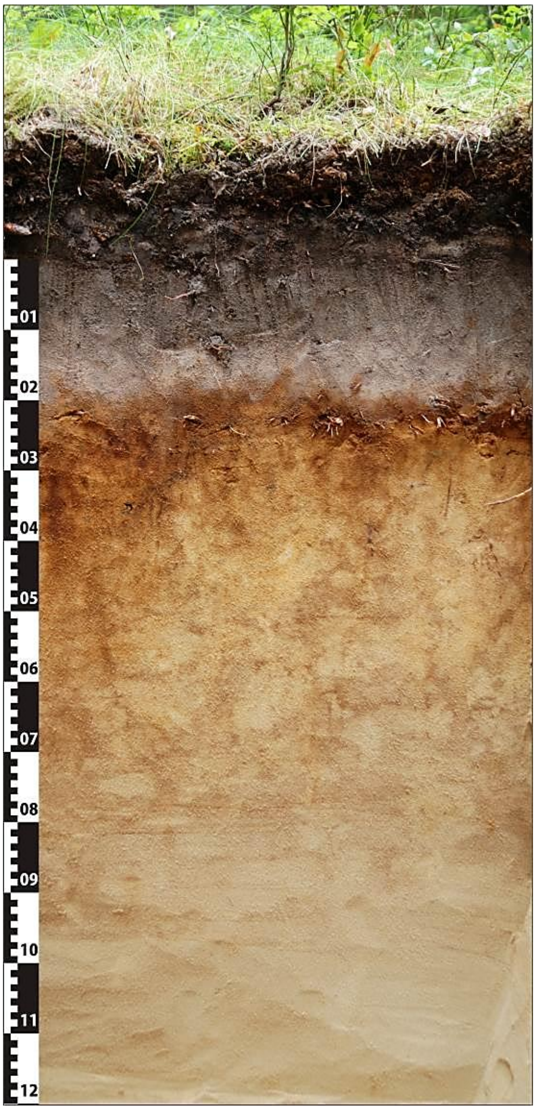
Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
O	11–0	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.
AE	11–25	0	0.3	4.0	40.4	54.3	1.0	0	0	0	0	S
BC	25–31	0	2.0	8.2	38.7	50.1	0	1.0	0	0	0	S
C1	31–55	0	0.6	4.0	39.7	54.7	0	1.0	0	0	0	S
C2	55–(120)	-	-	-	-	-	-	-	-	-	-	-

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
O	11–0	433.77	17.84	24	3.9	2.9	n.o.
AE	11–25	2.91	0.18	16	4.3	3.4	n.o.
BC	25–31	-	-	-	4.4	3.9	n.o.
C1	31–55	-	-	-	3.6	4.9	n.o.
C2	55–(120)	-	-	-	-	-	-

Profile 2 – Albic **Podzol** (Arenic)

Localization: Curonian spit, Juodkrantė, aeolian dune, slope-inclination 5–6°, coniferous forest, 7 m a.s.l., **N**55° 33' 11.376'' **E**21° 7' 8.58''



Morphology:

O – 9–0 cm, organic material;

AE1 – 0–5 cm, humus horizon, medium sand, black (10YR 2/1), fine weak granular / single grain structure, common roots, abrupt smooth boundary;

AE2 – 5–8 cm, humus horizon, loamy fine sand, light gray (10YR 9/1), fine weak granular / single grain structure, common roots, abrupt smooth boundary;

E – 8–22 cm, *albic* material, medium sand, single grain structure, gray (10YR 6/1), very few roots, clear irregular boundary;

Bhs – 22–30 cm, *spodic* horizon, medium sand, single grain structure, yellowish red (5YR 4/6), few roots, diffuse boundary;

Bs – 30–60 cm, illuvial accumulation of sesquioxides, medium sand, single grain structure, brownish yellow (10YR 6/8), few roots, gradual boundary;

BC – 60–100 cm, transition zone from illuvial horizon to parent material, medium sand, single grain structure, light yellowish brown (10YR 6/5), gradual boundary;

C – 100–(120) cm, parent material, medium sand, single grain structure, very pale brown (10YR 7/5), visible aeolian stratification, gradual boundary;

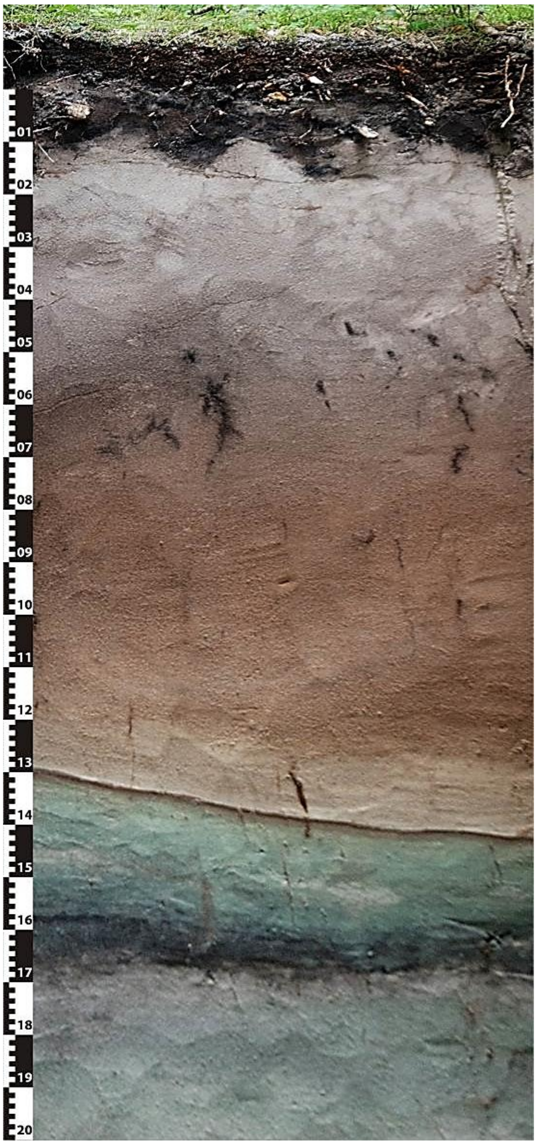
Table 4. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
O	9–0	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.
AE1	0–5	0	3.5	4.1	17.1	59.3	8.0	2.0	2.0	2.0	2.0	
AE2	5–8	-	-	-	-	-	-	-	-	-	-	-
E	8–22	0	0.2	0.7	12.2	83.9	1.0	1.0	1.0	0	0	S
Bhs	22–30	0	0.1	0.5	14.3	84.1	0	1.0	0	0	0	S
Bs	30–60	0	0	0.4	15.2	83.4	0	1.0	0	0	0	S
BC	60–100	0	0.1	1.2	22.0	76.7	0	0	0	0	0	S
C	100–(120)	0	0	1.6	14.0	83.4	0	1.0	0	0	0	S

Table 5. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
O	9–0	435.61	19.41	22	3.9	3.7	n.o.
AE1	0–5	21.46	0.85	25	3.9	3.3	n.o.
AE2	5–8	-	-	-	-	-	-
E	8–22	-	-	-	4.6	3.7	n.o.
Bhs	22–30	-	-	-	4.5	4.0	n.o.
Bs	30–60	-	-	-	5.2	4.6	n.o.
BC	60–100	-	-	-	5.5	4.6	n.o.
C	100–(120)	-	-	-	5.4	4.7	n.o.

Profile 3 – Folic Albic **Podzol** (Arenic) over Dystric **Gleysol** (Arenic)
Localization: Curonian spit, Juodkrantė, aeolian dune, depression between two slopes, coniferous forest, 5 m a.s.l., **N** 55° 33' 12.4596'' **E** 21° 7' 11.1108''



Morphology:

O – 10–0 cm, organic horizon,

A – 0–15 cm, humic horizon, sandy loam, black (10YR 2/1), fine weak subangular structure, root abundance gradual wavy boundary;

E – 15–35 cm, *albic* material, fine sand, light gray (10YR 7/1), single grain structure, gradual wavy boundary;

Bh – 35–60 cm, *spodic* horizon, fine sand, gray (7.5YR 5/1), structure very weak subangular, clear boundary;

Bhs – 60–85 cm, *spodic* horizon, fine sand, brown (7.5YR 4/4), very weak subangular structure, clear boundary;

Bs – 85–120 cm, illuvial horizon, fine sand, yellowish brown (10YR 5/4), very weak subangular structure, clear boundary;

BC – 120–130 cm, transitional horizon, fine sand, very weak subangular structure, clear boundary;

BhC – 130–132 cm, transitional horizon, fine sand, dark brown (10YR 3/3), very weak subangular structure, abrupt boundary;

Cr – 132–140 cm, strong reduction, green (5G 5/6), fine sand, single grain structure, clear boundary;

Cr2 – 140–150 cm, strong reduction, green (5G 5/6), fine sand, single grain structure, clear boundary;

2Ab – 150–158 cm, buried humus horizon, fine sand, very weak subangular structure, clear boundary;

2Cr3 – 158–170 cm, parent material with strong reduction, light greenish grey (10GY 8/2), fine sand, single grain structure, clear boundary;

2Cr4 – 170–(200) cm, parent material with strong reduction, light greenish grey (10GY 8/2), fine sand, single grain structure, clear boundary;

Table 6. Texture

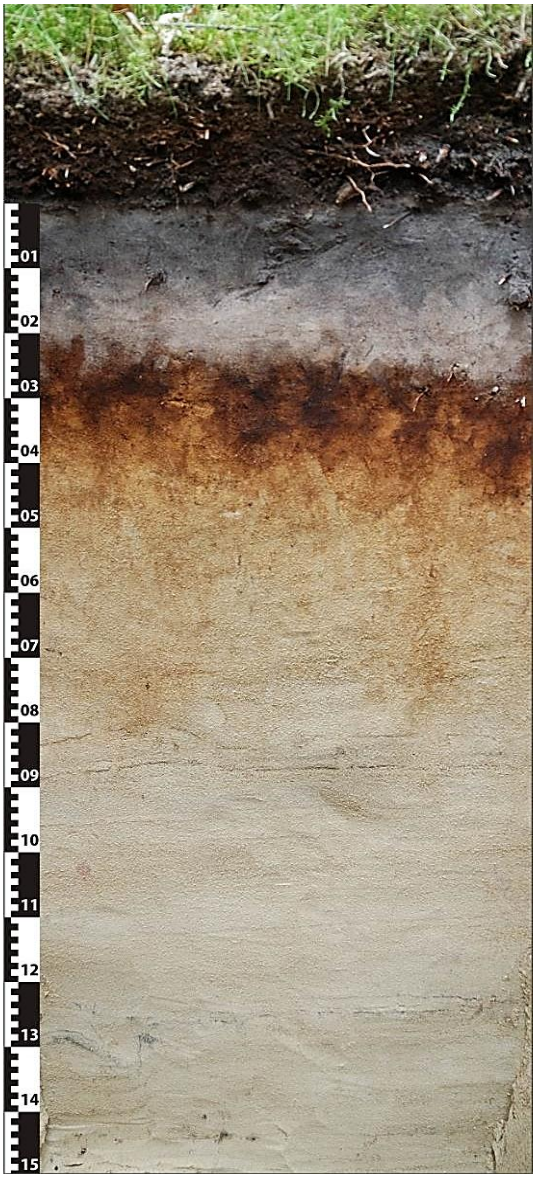
Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
A	0–15	0	4.0	5.3	15.1	62.6	6.0	2.0	2.0	2.0	1.0	S
E	15–35	0	1.0	4,7	16.2	76.1	1.0	1.0	0	0	0	S
Bh	35–60	0	0.1	1.7	15.2	82.0	0	1.0	0	0	0	S
Bhs	60–85	0	0.1	1.0	18.2	79.7	0	1.0	0	0	0	S
Bs	85–120	0	0.2	3.5	21.4	73.9	0	1.0	0	0	0	S
BC	120–130	0	0.1	0.4	6.3	92.2	1.0	0	0	0	0	S
BhC	130–132	0	0.4	0.6	4.9	92.1	1.0	1.0	0	0	0	S
Cr	132–140	0	0.1	0.3	5.8	89.8	2.0	1.0	1.0	0	0	S
Cr2	140–150	0	0.2	0.6	4.8	90.4	1.0	1.0	1.0	1.0	0	S
2Ab	150–158	0	0	2.1	7.0	83.9	3.0	1.0	1.0	1.0	1.0	S
2Cr3	158–170	0	0.1	5.7	16.4	75.8	1.0	1.0	0	0	0	S
2Cr4	170–(200)	-	-	-	-	-	-	-	-	-	-	-

Table 7. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
O	10–0	225.6	12.1	19	3.9	2.6	n.o.
A	0–15	43.09	1.6	27	3.9	3.0	n.o.
E	15–35	-	-	-	4.7	4.0	n.o.
Bh	35–60	-	-	-	4.7	4.0	n.o.
Bhs	60–85	-	-	-	4.5	4.2	n.o.
Bs	85–120	-	-	-	4.9	4.4	n.o.
BC	120–130	-	-	-	4.9	4.4	n.o.
BhC	130–132	-	-	-	4.8	4.3	n.o.
Cr	132–140	-	-	-	5.0	4.3	n.o.
Cr2	140–150	-	-	-	5.1	4.3	n.o.
2Ab	150–158	6.86	0.42	16	5.1	4.2	n.o.
Cr3	158–170	-	-	-	5.1	4.3	n.o.
Cr4	170–(200)	-	-	-	-	-	-

Profile 4 – Folic Albic **Podzol** (Arenic, Endoeutric)

Localization: Curonian spit, Juodkrantė, aeolian dune, medium slope-inclination 8°, coniferous forest, 14 m a.s.l., **N** 55°34’06’’ **E** 21°07’14’’



Morphology:

O – 12–0 cm, organic horizon;

AE – 0–10 cm, humus horizon, fine sand, very dark gray (10YR 3/1), weak single grain / subangular and angular blocky structure, biological features very few, clear and wavy boundary;

E – 10–18 cm, *albic* material, fine sand, light gray (10YR 7/2), single grain structure, biological features very few, clear and wavy boundary;

Bhs – 18–30 cm, *spodic* horizon, fine sand, very dark brown (5YR 2/3), weak single grain / subangular and angular blocky structure, gradual and wavy boundary;

Bs – 30–60 cm, illuvial horizon, fine sand / medium sand, dark yellowish brown (10YR 4/4), single grain structure, gradual and wavy boundary;

C – 60–150 cm, parent material, medium sand, pale yellow (2.5Y 8/2), single grain structure;

Table 8. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
O	12–0	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.	n.o.
AE	0–10	0	1.3	4.1	15.3	74.3	3.0	1.0	1.0	0	0	S
E	10–18	0	1.9	5.6	13.8	76.7	1.0	1.0	0	0	0	S
Bhs	18–30	0	1.6	5.1	16.7	75.6	0	1.0	0	0	0	S
Bs	30–60	0	0.2	2.1	9.8	86.9	0	1.0	0	0	0	S
C	60–150	0	0.2	2.1	12.8	83.9	1.0	0	0	0	0	S

Table 9. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
O	12–0	412.36	19.12	21	3.6	2.8	n.o.
AE	0–10	9.34	0.69	13	4.2	3.3	n.o.
E	10–18	-	-	-	4.3	3.6	n.o.
Bhs	18–30	-	-	-	4.7	4.1	n.o.
Bs	30–60	-	-	-	5.2	4.5	n.o.
C	60–150	-	-	-	5.4	4.6	n.o.

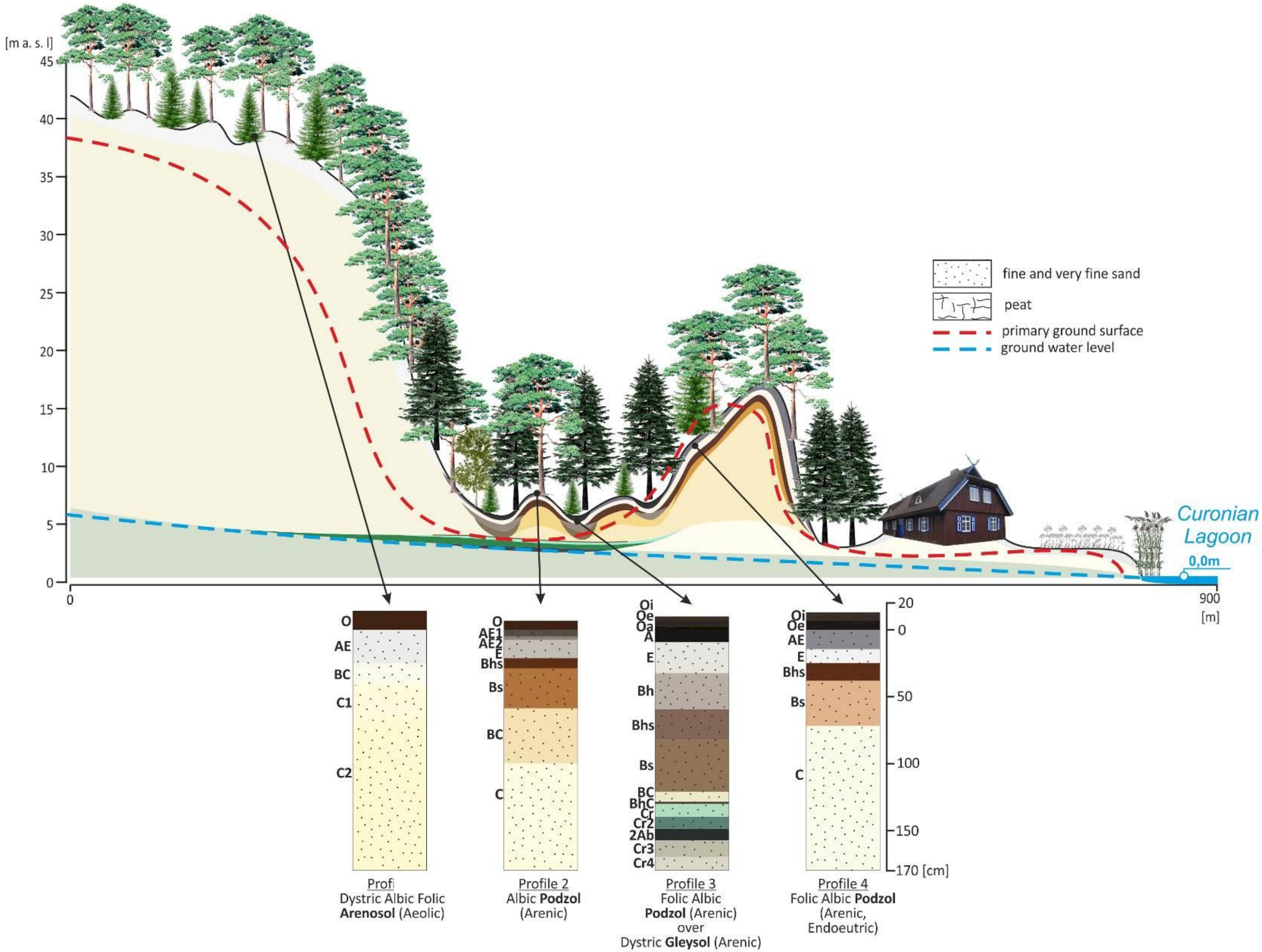


Fig. 2. Hydrolithotoposequence of soils within eastern slope of the Curonian Spit Aeolian dune in Juodkrantė old-growth forest

Sediments of the Curonian Spit are of marine origin but of various textures – their lithology varies from sandy-pebble to mud sediments and peat (Badyukova et al., 2007; Buynevich et al, 2007). Moreover, the differences in the mineral composition of the aeolian and marine sand are less important than those in their grain-size composition, which shows the specific qualities of what has been blown in and what has been blown around, as well as the relative age of the sand and complexity of the aeolian processes (Morkūnaitė et al., 2011). Accordingly, the dune deflation-accumulation plain (*palvė*), both at coastal and lagoon sides, is built of sand and pebble, while the great coastal dune ridge near Juodkrantė is mainly formed by the medium sized sands.

Land use

Since the Curonian Spit sand dunes are under constant threat from natural forces (wind and water), this is the main reason for the differentiation of flora and fauna, and of all natural complexes (Curonian Spit, 1999; Povilanskas et al., 2011).

Although the Curonian Spit was originally afforested, trees were cut down and high dunes have been formed from bare moving sand, brought mainly by west and south-west winds from the Baltic Sea. The vegetation on dunes consists of relatively drought-tolerant species with adaptations to habitats exposed to heat and tolerant of moving sand. The Curonian Spit dunes are recognized as a distinct geographical vegetation unit, and the villages and nature reserves are nominated as a UNESCO World Heritage Site (Kalinauskaitė and Laaka-Lindberg, 2013).

The vegetation type in the Juodkrantė area is old-growth forest, i.e. a climax plant habitat. Theoretically, the site can be regarded as an area protected by the EU NATURA–2000 programme. According to historic maps, the old-growth forest at the localities of Juodkrantė, Nida, and Šarkuva exist for more than 300 years (Gudelis, 1989–1990). However, the relict areas of the old-growth *Pinus sylvestris* forest are now very small, occupying only a few square kilometers in the vicinity of the Juodkrantė settlement (Morkūnaitė et al., 2011).

The eastern slope of the great coastal dune ridge is covered with coniferous forest consisting of different age stands with an admixture of few deciduous species (Curonian Spit, 1999; Kavoliutė, 2004; Kalinauskaitė and Laaka-Lindberg, 2013; Povilanskas et al., 2011). The 50 year old planted *Vaccinio-myrtillo-Pinetum* forest covers the upper parts of the slope. The Scots pine (*Pinus sylvestris*) with an admixture of single Norway spruce (*Picea abies*) dominates in the canopy layer, while the understory is covered with the Norway spruce (*Picea abies*) and rowan (*Sorbus aucuparia*). The protected species – twinflower (*Linnaea borealis*) – can be found in this forest.

The 100 year old *Vaccinio-myrtillo-Pinetum* forest covers the middle part of the slope, however, only the Scots pine (*Pinus sylvestris*) grows there. The lowest location (i.e., the deflation depression) of the same slope is covered with Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) with an admixture of single pedunculate oak (*Quercus robur*) and downy birch (*Betula pubescens*) in the canopy layer while the understory – with Norway spruce (*Picea abies*), rowan (*Sorbus aucuparia*) and alder buckthorn (*Frangula alnus*).

Climate

The study area belongs to the Baltic Sea Coastal (Pajūrio) climatic region and the Curonian Spit (Kuršių Nerijos) sub-region (Bukantis, 2016). Compared with the remaining territory of Lithuania, the Curonian Spit is distinguished by a specific climate with mild and often snowless winters, frequent strong winds and storms, a longer period of above-zero temperatures (Česnulevičius et al., 2017). The average annual temperature is 8.0°C. The average temperature of the coldest month (February) is −1.5°C, while the warmest month is July and August (18.4°C). The mean annual amount of precipitation is one of the largest in Lithuania – about 770 mm. The snow cover lasts about 60 days, while the sunshine duration is the longest in Lithuania – 1990 hours.

Soil genesis and systematic position

The investigated soil profiles represent the diversity of soil cover in the Curonian Spit and the factors affecting the formation of different soil typological units. The interaction between the main soil-forming factors (i.e., glauconite enriched sandy parent material, humid climate with prevailing south-west winds and vegetation – coniferous forests), which support zonal soil-forming processes, plays a significant role here. As a consequence, this leads to the differentiation of the podzolization process depending on the soil topographical location, slope exposition, vegetation age and characteristics. However, at the local scale, the ground water level influences the development of intrazonal soil-forming processes. The occurrence of two main soil reference groups – **Arenosols** and **Podzols** – is a typical of the Curonian Spit in terms of the above-mentioned soil-forming processes' interactions (Vaisvalavičius et al., 2014).

In the upper part of the Great Dune Ridge, the grey hair-grass (*Corynephorus canescens*) and wavy hair-grass (*Deschampsia flexuosa*) meadows dominated until the second half of the 20th century (Kavoliute, 2004). Due to the constant drift of sand, soil-forming processes became slower (i.e., accumulation of organic material) and the podzolization did not take place. The ***Protic*** and ***Dystric*** **Arenosols** formed there at that time (Buivydaite et al., 2001; Vaisvalavičius et al., 2014). However, in the second half of the 20th century, soil-forming processes have changed when the coniferous forests were planted in the area of the Curonian Spit. This obviously was a surface stabilizing factor and, afterwards, the accumulation of slightly decomposed organic matter together with the podzolization process started. Due to the relatively young age of the trees (50–70 years), only the ***Albic*** **Arenosols** are identified under such conditions because zonal soil-forming processes are weakly expressed in this part of soil catena.

The old-growth forest (*Sengirė*) has survived on the eastern slope of the Great Dune Ridge. It grows south of the Amber Bay (*Gintaro įlanka*) along the entire Juodkrantė settlement territory. The trees are up to 300 years old and there is evidence that the soil-forming processes in this forest have occurred for at least 300 years without the influence of human activities. As a result, the podzolization process took place in this part of the soil catena. The leaching was stimulated here by a few main factors – the acid organic forest litter, acid nature of parent material, cold and humid climate. Therefore, various **Podzols** formed at the higher topographical sites, while at the lower slope places – ***Gleyic*** **Podzols** and ***Dystric*** **Gleysols** (***Arenic***). Some small areas of ***Sapric*** **Histosols** are identified at the lowest, very wet sites of the slope (Buivydaite et al., 2001; Vaisvalavičius et al., 2014).

The upper part of the eastern slope of the great sand dune is covered by **Arenosols** (IUSS Working Group WRB. 2015). Because of its topographic position, soil suffers from the strong aeolian affect. This is reflected (Table 1, Profile 1) in soil parent material texture with dominant 0.5–0.25 mm (38–40%) and 0.25–0.1 mm (50–55%) fractions. There is also 1–0.5 mm sand fraction (4–8%). The finer sand fractions are drifted, and coarser – accumulated. Such soils in Lithuania prevail in the sand deposits of different origin and age. Due to various environmental factors, sand deposits are dynamic, hence the soils can be referred to as intrazonal. In the case of the emerging Curonian Spit, sands are quite young (approximately 5000 years old), permanently exposed by aeolian processes during the Holocene period and redeposited as the sand dunes of maritime origin. These soils were formed under ambivalent basic conditions: 1) on the drifting dunes without permanent vegetation cover or 2) under the grass cover where the accumulation of organic matter and humification took place. Therefore, soils can be identified as ***Protic*** **Arenosols**. A very weakly developed soil with a thin (about 10 cm) greyish AE horizon can be observed in the profile, which is characteristic of some **Arenosols** in Lithuania too. However, profile 1 cannot be described as an example of all **Arenosols**. It characterizes mainly the coastal aeolian relief, where soil formation processes are at the initial stage. The podzolization process begins, which is common to zonal soils. This is visible at a depth of 9–25 cm – a bleached AE horizon occurs. As a consequence of humid and cold climate, and the acid parent material (pH 3.9–4.4), a thick *folic* horizon (O) is formed on the soil surface. Depending on the humidity, this horizon at the Curonian Spit can vary in the range of 10–20 cm. In the soil profile, C1 and C2 horizons appears, and native features of a thin diagonally layered parent material are visible. They indicate that the soil is of aeolian origin and has been permanently exposed to aeolian processes. The humidity, continuous sand drifting and genesis of maritime sand determine the acidity of parent material. Therefore, the examined soil (profile 1) can be classified as ***Dystric Albic Folic*** **Arenosol**. The exception are only **Arenosols** that were formed on the coastal foredune or the front dune deflation-accumulation plain (*palvė*). Due to the high saturation of the sea salts, their pH is > 5.5, so they are often included in the ***Eutric Tidalic*** **Arenosols**.

The **Podzols** formed in the aeolian sand covered with forest (profile 2). Compared to Profile 1, obvious differences in the development of this soil are visible. They result from a longer time of development and a shorter time of aeolian process. Profile 2 could be compared not only with Profile 1 but also with Profile 3. **Podzol** formation started more than several centuries ago due to the land surface stability, because of the coniferous forest formation, and, in particular, the location in the relief – on the eastern slope of the great sand hill. The reason is that the examined ***Albic*** **Podzol** (***Arenic***) profile is developed on the wave of the great coastal dune ridge at the eastern slope in the microclimate protected from the wind. Therefore, although the duration of soil formation is relevant for podzolization, however, a relatively steep slope of dune gets less rainfall precipitation, which makes slower pace of the podzolic process. This is evidenced by the soil morphology (profile 3). It is identified by a relatively thin (5 cm) O horizon when compared to **Podzols** of the Curonian Spit, a very thin (8–22 cm) and weakly expressed E horizon, weakly expressed Bhs and Bs horizons. The color of the lower part of the C horizon (10YR 7/5) testifies to the relatively shallow occurrence of the ground water, which affects the pine and spruce biotope formation. However, because the parent material texture is medium sand and the capillary forces in soil are weak, it has no stronger effect on soil formation.

Profile 3 is formed by deflation on the lowest part of the investigated catena. A soil characteristic shows the formation of soil in depression between sand dunes, influenced by groundwater. This soil also illustrates the interaction between the soil formation and geomorphological processes in the aeolian relief with the geological environment. Interaction between the podzolization (zonal soil formation) process and hydromorphic soil moisture regime and *gleyic* properties formation (interzonal soil formation processes) is visible. This location is identified by buried soil: ***Folic Albic*** **Podzol** (***Arenic***) over ***Dystric*** **Gleysol** (***Arenic***). It is a mature **Podzol** profile with its inherent soil formation properties. Due to the hydromorphic regime of the soil, the differentiation of the O horizon into Oh-Oe-Oa sub-horizons is characteristic according to the degree of organic matter degradation. The Ah horizon is thick (15 cm) and humus-rich, however, the intense leaching and hydromorphic soil moisture regime is vividly expressed in the very thick (15–35 cm) E horizon. Also, a clear differentiation of the illuvial zone is characteristic in this profile, which leads to the Bh-Bhs-Bs horizon's complex formation. The development of the Bhs horizon and the relative increase in organic matter (LOI–0.86) together with the emerald green color of the BC horizon indicate the groundwater level at a depth of 120–130 cm and, afterwards, the formation of a geochemical barrier due to the capillary water moving upward. This leads to the Bhs horizon formation in a depth of 60 to 85 cm. Having leached from the entire BC horizon, the iron accumulates in the very bottom of the same horizon above the ground water geochemical barrier and the glauconitic layer, and forms a thin humus-iron-enriched BhC horizon.

The Cr soil horizon is distinguished by characteristic sand of maritime origin and emerald green color, the intensity of which depends on the secondary clay mineral glauconite. This mineral is widespread in sand of the Curonian Spit and gives a yellowish greenish tint, which is rarely notable in **Arenosols** and **Podzols** with automorphic moisture regime. The higher concentrations of glauconite are found in gleyic sandy soils, impacted by groundwater. Glauconite is common in the fine silt (0.05–0.002 mm) fraction and can easily migrate with soil moisture. Glauconite entered the soil from the sea glauconite deposits on littorals. Its presence in the soil indicates the importance of lithology in the soil formation and its effect on soil chemical properties.

The influence of geomorphological processes (drifting of sand) in the Curonian Spit is vivid by the abrupt textural change of the soil profile. The ongoing aeolian process changes the condition of soil formation and facilitates the renewal of the soil, while at the same time create new geochemical barriers and affects the formation of new environmental surroundings. A clear example of these processes is the occurrence of the humus 2Ab horizon at a depth of 150–158 cm. The underlain Cr4-Cr3 soil horizons indicate the previous podzolic processes and current hydromorphic and gleyic processes.

Profile 4 reflects the specific zonal characteristics of the soil formation in the Lithuanian coastal aeolian relief under mature coniferous forest. The soil profile was created on the windward side of the central slope part of the great coastal dune ridge. The organic O horizon of the soil profile is well developed (10–15 cm of thickness) and typical of this region, as soil receives a full portion of precipitation due to its location outside the shade of the main slope, and additional watering from the upper part of the slope. Since the soil is formed on the maritime, slightly ferric sand, strongly rinsed by water, transferred by wind (in the humid, relatively warm climate conditions), the podzolic process is less expressed than in the **Podzols** formed in the 13,000 to 15,000 year old Lithuanian continental glaciolacustrine-eolian sand (Vaisvalavicius et al., 2014). This is evidenced by the presence of a relatively thick (18–30 cm) and friable Bhs horizon. Meanwhile, the Bs horizon (30–60 cm) contains only a small amount of iron. The layered soil structure in the C horizon reflects the aeolian genesis; the constant changes of the layers in the soil texture – from fine sand to coarse and very coarse sand – show that the parent material formation is determined by varying intensity of aeolian processes.

Soil sequence

The discussed soil profiles illustrate the Lithuanian seaside aeolian relief soil formation evolution conditions, which depend on the terrain, slope orientation, dynamic processes and soil moisture regime. The catena is reflected in the morphology of the soil profile, changes in the chemical and physical properties depending on human activities (e.g. afforestation), the intensity of aeolian processes, air humidity and hydromorphic moisture regime in soil.

Arenosol (profile 1) is located in the upper part of the eastern slope of the great coastal dune ridge. Primarily (before drifting) such **Arenosols** were probably **Podzols**. The present-day **Arenosols** have suffered strong aeolian effects. This is reflected in their parent material texture with dominant 0.5–0.25 mm (38–40%) and 0.25–0.1 mm (50–55%) grain size fractions. There is also a 1–0.5 mm (4–8%) sand fraction. The finer sand fractions are drifted and coarser are accumulated. The presence of the AE horizon indicates that the soil is evolving into a **Podzol**. It is likely that in the long term it will have features very similar to soil profiles 2 or 4. At present, this profile represents the re-naturalization of the soil after the anthropogenic transformation of the landscape of the Curonian Spit from forest to sands and meadows, and back.

Podzols (profiles 2–4) developed in redistributed aeolian deposits that dominate in the upper part of the great coastal dune ridge. This is evidenced by the prevailing in these soils (75–86%) of fine sand 0.25–0.1 mm and very small amount (10–17%) of coarser sand fractions. Since these soils are formed in acid parent material under (mature) old-growth forest, they are evolving as **Podzols**. These automorphic **Podzols** are characteristic in natural coniferous forest of the Curonian Spit landscape.

Deflated negative forms of the relief, developed under the alternate erosion–deposition conditions of the drifting sand material, represents the **Podzol** over the (buried) **Gleysol** (profile 3). The abrupt textural change and soil moisture regime changes from automorphic to hydromorphic indicate the sand drifting processes. Deflation is visible in soil horizons (2Cr3 and 2Cr4) as the amount of 1–0.5 mm coarse sand fraction increases.

The influence of the relief and moisture regime on the soil formation processes in the catena is manifested through the E horizon thickness and the amount of organic carbon (OC) in the accumulative zone of the soil profile. The young soil (profile 1) ***Dystric*** **Arenosol**, in which the podzolic processes are at the early stage, is characterized by the AE horizon, in which the OC amount is 0.29 mg kg^{-1}. *Podzol* (profile 4) with automorphic soil moisture regime is characterized by about 10 cm E horizon, and 0.9 g kg^{-1} OC in the AE horizon. With intensification of the hydromorphic soil regime (profile 2), the thickness of the E horizon increases (it reaches about 15 cm) and OC – 2.15 g kg^{-1} in the AE horizon. The maximum thickness of the E horizon is characterized the **Podzol** (profile 3) which has been developed in the hydromorphic soil moisture regime. Here's the E horizon of 20 cm in thickness, and the OC amount in the A horizon – 4.31 g kg^{-1}.

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Regular topographically-induced variation of soils on inland dunes in the Toruń Basin (N Poland)

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The study area is located in the middle part of the Toruń Basin in northern Poland, which is one of the largest inland dune fields within the European sand belt (Mrózek, 1958; Zeeberg, 1998). The studied dunes were formed in periglacial conditions during the Dryas phases of the Late Glacial (Wisła/Würm glaciation decline) (Jankowski, 2000, 2012).

Fig. 1. Location

Lithology and topography

The Toruń Basin is part of the Toruń-Eberswalde ice-marginal valley. The Basin is 90 km long and on average 20 km wide and it is bordered both from north and south by morainic plateaux composed of loamy materials of the last glaciation. Contrary to surrounding areas, the Toruń Basin is built of glaciofluvial and fluvial sands with thickness varying from a few to approximately 10 m (Niewiarowski and Weckwerth, 2006). These sand deposits constituted the primary material for the dune-forming process.

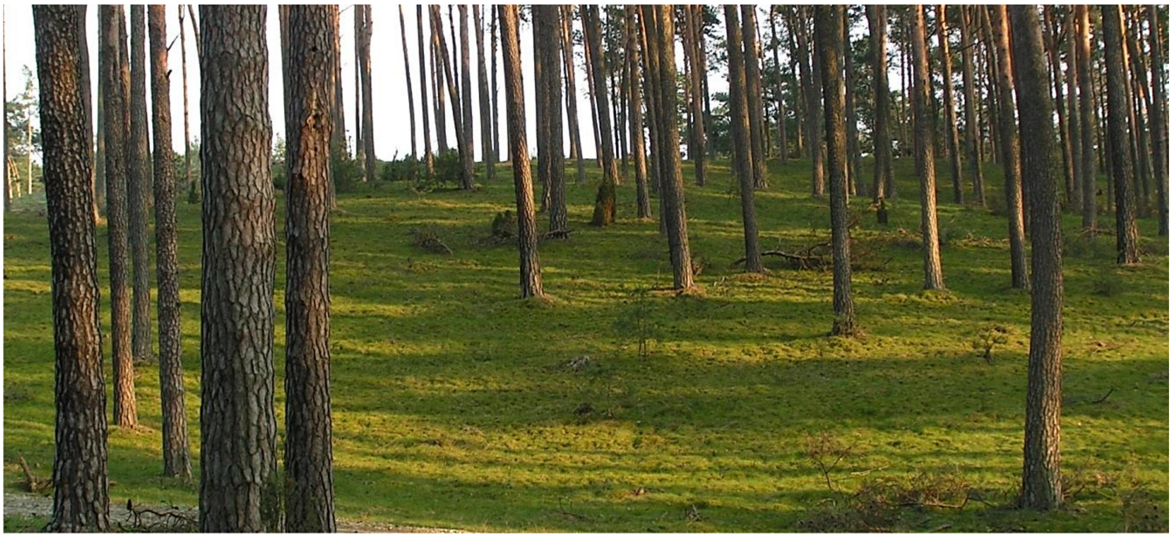
Along with post-glacial climate warming, the dunes in the Toruń Basin were gradually stabilized by encroaching vegetation, first by tundra (in Bölling, 14.6–14.1 ka BP), and subsequently by taiga forest (in Alleröd, 14.0–12.7 ka BP) and temperate forest (in Holocene, since 11.7 ka BP; Starkel, 1990; Niewiarowski and Weckwerth, 2006). The dunes of the study area are of different shapes. There are bow-shaped, parabolic, longitudinal and irregular forms. The main relative height of the dunes is 10–25 m with the highest dune reaching 44.7 m (115.9 a.s.l.). Inclination of dune slopes depends strictly on the aspect. Eastern (distal) slopes are usually more steep (5–32˚) than western (proximal) ones (3–20˚; Mrózek, 1958; Niewiarowski and Weckwerth, 2006). The mineral substrate of the dunes is very homogeneous, which applies both to texture (medium and fine sand) and mineralogical composition being clearly dominated (85-99%) by quartz (Jankowski, 2010; Sewerniak et al., 2017).

Land use

Due to low moisture as well as low fertility of soils, inland dunes of the Toruń Basin are almost entirely covered with Scots pine (*Pinus sylvestris*) forests. Although they constitute the potential natural vegetation of the study area (Chojnacka et al., 2010), they are currently mostly forest plantations. The only large-scale dune area that is not covered with pine production stands is the inner part of an artillery training ground situated south of Toruń. Since the 19th century, this military area has been gradually deforested to expose the terrain for shootings and observation. After the deforestation, the area has been gradually overgrown with psammophilous vegetation representing natural secondary succession (grasslands and heathlands), which is occasionally destroyed by fires (Jankowski, 2010; Sewerniak and Mendyk, 2015).

Profile 1 – Albic **Podzol** (Arenic)

Localization: North-facing dune slope, inclination 10°, 135 years old pine forest, 59 m a.s.l., **N** 52°55'37.9" **E** 18°42'9.9"



Morphology:

Oi – 8–5.5 cm, slightly decomposed organic material;

Oe – 5.5–2.5 cm, moderately decomposed organic material;

Oa – 2.5–0 cm, highly decomposed organic material;

AE – 0–8 cm, humus horizon with features of eluviation, fine sand, dark brown (10YR 4/2, 10YR 3/3), slightly moist, single grain structure, many roots, single fine charcoals, clear and wavy boundary;

Bhs – 8–18 cm, *spodic* horizon, fine sand, brown (10YR 5/6, 7.5YR 4/4), slightly moist, single grain structure, common fine roots, single fine charcoals, gradual and smooth boundary;

Bs – 18–30 cm, illuvial horizon, fine sand, strong brown (10YR 6/8, 7.5YR 5/6), slightly moist, single grain structure, few fine roots, single fine charcoals, diffuse and smooth boundary;

BC – 30–65 cm, transitional horizon, fine sand, reddish yellow (10YR 7/6, 7.5YR 6/6), slightly moist, single grain structure, very few fine roots, single fine charcoals, diffuse and smooth boundary;

C – 65–(115) cm, parent material, fine sand, light yellowish brown (10YR 7/6, 10YR 6/4), slightly moist, single grain structure, very few roots;

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
AE	0–8	0	1	2	11	73	11	2	0	0	0	S
Bhs	8–18	0	1	1	8	78	11	1	0	0	0	S
Bs	18–30	0	0	1	7	78	14	0	0	0	0	S
BC	30–65	0	0	1	7	79	13	0	0	0	0	S
C	65– (115)	0	0	1	13	76	10	0	0	0	0	S

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH	
					H_2O	KCl
Oi	8–5.5	491	17.8	28	4.4	3.7
Oe	5.5–2.5	461	15.7	29	4.0	3.0
Oa	2.5–0	334	11.7	29	3.7	2.8
AE	0–8	13.7	0.47	29	3.7	3.2
Bhs	8–18	13.3	0.58	23	4.6	4.1
Bs	18–30	2.9	0.20	15	4.8	4.5
BC	30–65	-	-	-	5.1	4.5
C	65–(115)	-	-	-	5.1	4.5

Table 3. Contents of different forms of iron and aluminium

Horizon	Depth [cm]	Fe_t	Fe_d	Fe_o	Fe_t -Fe_d	Fe_d -Fe_o	Al_t	Al_o
		[g·kg^{-1}]						
AE	0–8	1.58	0.69	0.26	0.89	0.43	14.3	0.34
Bhs	8–18	3.85	3.21	2.31	0.64	0.90	16.2	0.31
Bs	18–30	2.42	1.31	0.67	1.11	0.63	16.2	1.49
BC	30–65	2.20	0.70	0.25	1.50	0.44	15.9	0.85
C	65–(115)	1.90	0.64	0.19	1.26	0.45	14.6	0.51

Profile 2 – Dystric Albic **Arenosol** (Ochric)

Localization: South-facing dune slope, inclination 11°, 135 years old pine forest, 59 m a.s.l., **N** 52°55'35.2" **E** 18°42'10.9"

Morphology:

Oi – 6–4 cm, slightly decomposed organic material;

Oe – 4–3 cm, moderately decomposed organic material;

Oa – 3–0 cm, highly decomposed organic material;

AE – 0–5(7) cm, humus horizon with features of eluviation, fine sand, very dark grayish brown (10YR 5/2, 10YR 3/2), slightly moist, single grain structure, many roots, single fine charcoals, clear and wavy boundary;

Bhs – 5(7)–12 cm, illuvial horizon, fine sand, brown (10YR 5/4, 10YR 4/3), slightly moist, single grain structure, common roots, single fine charcoals, gradual and smooth boundary;

Bs – 12–30 cm, illuvial horizon, fine sand, yellowish brown (10YR 6/6, 10YR 5/4), slightly moist, single grain structure, few roots, single fine charcoals, diffuse and smooth boundary;

BC – 30–65 cm, transitional horizon, fine sand, dark yellowish brown (10YR 7/6, 10YR 4/6), slightly moist, single grain structure, very few fine roots, single fine charcoals, diffuse and smooth boundary;

C – 65–(120) cm, parent material, fine sand, light yellowish brown (10YR 7/4, 10YR 5/6), slightly moist, single grain structure, very few roots;

Table 4. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
AE	0–5(7)	0	1	1	9	78	9	2	0	0	0	S
Bhs	5(7) –12	0	0	0	8	78	13	1	0	0	0	S
Bs	12–30	0	0	0	8	78	13	0	0	0	0	S
BC	30–65	0	0	0	7	80	13	0	0	0	0	S
C	65–(120)	0	0	0	5	87	8	0	0	0	0	S

Table 5. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [$g \cdot kg^{-1}$]	Nt [$g \cdot kg^{-1}$]	C/N	pH	
					H_2O	KCl
Oi	6–4	441	14.6	30	4.3	3.4
Oe	4–3	390	13.7	28	4.1	3.2
Oa	3–0	352	12.4	28	4.0	3.0
AE	0–5(7)	10.1	0.35	29	4.1	3.4
Bhs	5(7)–12	7.1	0.33	21	4.5	3.8
Bs	12–30	3.2	0.20	16	4.8	4.1
BC	30–65	-	-	-	4.9	4.5
C	65– (120)	-	-	-	5.1	4.6

Table 6. Contents of different forms of iron and aluminium

Horizon	Depth [cm]	Fe_t	Fe_d	Fe_o	Fe_t -Fe_d	Fe_d -Fe_o	Al_t	Al_o
		[$g \cdot kg^{-1}$]						
AE	0–5(7)	2.13	0.88	0.53	1.25	0.35	14.6	0.28
Bhs	5(7)–12	2.30	1.15	0.84	1.15	0.31	14.8	0.47
Bs	12–30	2.71	1.26	0.99	1.45	0.27	15.7	0.77
BC	30–65	2.46	0.81	0.65	1.65	0.16	15.6	0.80
C	65– (120)	1.88	0.47	0.18	1.41	0.29	15.0	0.42

Profile 3 – Entic **Podzol** (Arenic, Aric)
Localization: Intra-dune depression, 135 years old pine forest, 49 m a.s.l.,
N 52°55'34.2" **E** 18°42'11.6"

Morphology:

Oi – 5–3 cm, slightly decomposed organic material;

Oe – 3–0 cm, moderately decomposed organic material;

A(E) – 0–3 cm, humus horizon with features of eluviation, fine sand, black (10YR 3/2, 10YR 2/1), slightly moist, single grain structure, many roots, single fine charcoals, clear and smooth boundary;

ABp – 3–29 cm, plough humus horizon, fine sand, very dark brown (10YR 4/2, 10YR 2/2), slightly moist, single grain structure, many fine roots, single fine charcoals, abrupt and wavy boundary;

Bhs – 29–42 cm, *spodic* horizon, fine sand, very dark brown (2.5Y 4/4, 10YR 2/3), slightly moist, single grain structure, many fine roots, single fine charcoals, clear and wavy boundary;

CB – 42–70 cm, transitional horizon, fine sand, dark yellowish brown (10YR 7/4, 10YR 4/4), slightly moist, single grain structure, few fine roots, single fine charcoals, gradual and smooth boundary;

C – 70–(120) cm, parent material, fine sand, light yellowish brown (10YR 6/4, 10YR 5/6), slightly moist, single grain structure, few roots;

Table 7. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
A(E)	0–3	0	0	0	14	77	7	2	0	0	0	S
ABp	3–29	0	0	0	7	82	8	3	0	0	0	S
Bhs	29–42	0	0	1	6	80	11	2	0	0	0	S
CB	42–70	0	0	0	6	72	20	2	0	0	0	S
C	70– (120)	0	0	0	5	88	5	2	0	0	0	S

Table 8. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [$g \cdot kg^{-1}$]	Nt [$g \cdot kg^{-1}$]	C/N	pH	
					H_2O	KCl
Oi	5–3	387	18.6	21	4.4	3.7
Oe	3–0	373	18.1	21	3.9	3.3
A(E)	0–3	47.9	2.65	18	4.1	3.4
ABp	3–29	15.5	0.88	18	5.5	4.5
Bhs	29–42	5.6	0.64	9	6.0	4.9
CB	42–70	-	-	-	5.1	4.9
C	70–(120)	-	-	-	6.1	5.7

Table 9. Contents of different forms of iron and aluminium

Horizon	Depth [cm]	Fe_t	Fe_d	Fe_o	Fe_t -Fe_d	Fe_d -Fe_o	Al_t	Al_o
		[$g \cdot kg^{-1}$]						
A(E)	0–3	5.92	3.16	2.05	2.76	1.11	13.6	1.13
ABp	3–29	6.60	3.23	2.07	3.37	1.16	15.5	1.68
Bhs	29–42	6.38	2.79	1.90	3.59	0.89	15.0	1.72
CB	42–70	4.24	1.06	0.65	3.18	0.41	12.8	0.84
C	70–(120)	4.62	0.80	0.44	3.82	0.36	13.0	1.13

Profile 4 – Albic **Podzol** (Arenic)

Localization: North-facing dune slope, inclination 10°, heathland with admixture of birches and pines, 67 m a.s.l., **N** 52°56'12.4" **E** 18°39'3.3"

Morphology:

Oie – 4–3 cm, slightly and moderately decomposed organic material;

Oa – 3–0 cm, highly decomposed organic material;

AE – 0–10 cm, humus horizon with features of eluviation, fine sand, very dark grey (7.5YR 5/2, 10YR 3/1), slightly moist, single grain structure, many roots of a heather, single fine charcoals, clear and smooth boundary;

Bhs – 10–20 cm, *spodic* horizon, fine sand, dark brown (10YR 5/3, 7.5YR 3/3), slightly moist, single grain structure, few fine roots, single fine charcoals, gradual and smooth boundary;

Bs – 20–32 cm, illuvial horizon, fine sand, brown (10YR 6/4, 7.5YR 4/4), slightly moist, single grain structure, very few fine roots, single fine charcoals, diffuse and smooth boundary;

BC – 32–100 cm, transitional horizon, fine sand, strong brown (10YR 7/4, 7.5YR 5/6), slightly moist, single grain structure, very few fine roots, single fine charcoals, diffuse and smooth boundary;

C – 100–(130) cm, parent material, fine sand, brownish yellow (10YR 7/4, 10YR 6/6), slightly moist, single grain structure;

Table 10. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
AE	0-10	0	0	1	19	78	1	1	0	0	0	S
Bhs	10-20	0	0	1	17	79	2	1	0	0	0	S
Bs	20-32	0	0	0	18	77	5	0	0	0	0	S
BC	32-100	0	0	1	21	73	5	0	0	0	0	S
C	100-(130)	0	0	0	6	89	5	0	0	0	0	S

Table 11. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [$g\cdot kg^{-1}$]	Nt [$g\cdot kg^{-1}$]	C/N	pH	
					H_2O	KCl
Oie	4-3	418	16.4	26	4.3	3.6
Oa	3-0	239	11.2	21	4.3	3.2
AE	0-10	14.3	1.12	13	4.4	3.5
Bhs	10-20	6.6	0.50	13	4.7	4.5
Bs	20-32	3.6	0.49	7	4.8	4.6
BC	32-100	-	-	-	4.7	4.7
C	100-(130)	-	-	-	6.0	4.8

Table 12. Contents of different forms of iron and aluminium

Horizon	Depth [cm]	Fe_t	Fe_d	Fe_o	Fe_t -Fe_d	Fe_d -Fe_o	Al_t	Al_o
		[$g\cdot kg^{-1}$]						
AE	0-10	2.90	0.92	0.53	1.98	0.39	13.8	0.81
Bhs	10-20	3.57	1.54	1.15	2.03	0.39	13.6	0.86
Bs	20-32	4.00	1.42	0.81	2.58	0.61	14.3	0.76
BC	32-100	3.56	1.21	0.53	2.35	0.68	15.3	0.86
C	100-(130)	2.65	0.61	0.17	2.04	0.44	13.7	1.00

Profile 5 – Dystric **Arenosol** (Ochric)

Localization: South-facing dune slope, inclination 10°, grassland with single birches and pines, 67 m a.s.l., N 52°56'10.3" E 18°39'3.3"

Morphology:

(A) – 0–6 cm, initial humus horizon, fine sand, very dark grayish brown (10YR 5/2, 10YR 3/2), dry, single grain structure, few fine roots of grasses, single fine charcoals, clear and smooth boundary;

Bs(A) – 6–12 cm, illuvial horizon, fine sand, brown (10YR 6/3, 10YR 4/3), dry, single grain structure, few fine roots of grasses, single fine charcoals, gradual and smooth boundary;

BC – 12–30 cm, transitional horizon, fine sand, yellowish brown (10YR 6/4, 10YR 5/6), dry, single grain structure, single fine charcoals, diffuse and smooth boundary;

C – 30–(100) cm, parent material, fine sand, brownish yellow (10YR 7/4, 10YR 6/6), slightly moist, single grain structure, single fine charcoals;

Table 13. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
(A)	0–6	0	0	1	11	76	11	1	0	0	0	S
Bs(A)	6–12	0	0	0	10	75	14	1	0	0	0	S
BC	12–30	0	0	0	8	83	9	0	0	0	0	S
C	30–(100)	0	0	0	6	92	2	0	0	0	0	S

Table 14. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH	
					H_2O	KCl
(A)	0–6	6.7	0.83	8	4.5	4.4
Bs(A)	6–12	4.6	0.54	8	4.6	4.1
BC	12–30	2.8	0.40	7	4.5	4.5
C	30–(100)	-	-	-	4.8	4.6

Table 15. Contents of different forms of iron and aluminium

Horizon	Depth [cm]	Fe_t	Fe_d	Fe_o	Fe_t -Fe_d	Fe_d -Fe_o	Al_t	Al_o
		[g·kg^{-1}]						
(A)	0–6	4.79	1.19	0.55	3.60	0.64	14.7	1.45
Bs(A)	6–12	4.58	1.15	0.64	3.43	0.51	15.9	1.57
BC	12–30	5.02	1.26	0.66	3.76	0.60	15.3	0.85
C	30–(100)	4.16	0.65	0.24	3.51	0.41	16.1	0.72

Profile 6 – Entic **Podzol** (Arenic)
Localization: Intra-dune depression, grassland, 58 m a.s.l.
N 52°56'8.1" E 18°39'3.2"

Morphology:

Oie – 2.5–0 cm, slightly and moderately decomposed organic material;

AB – 0–17 cm, humus horizon, fine sand, very dark brown (10YR 3/3, 7.5YR 2/2), slightly moist, single grain structure, many roots of grasses, single fine charcoals, clear and smooth boundary;

Bh – 17–39 cm, *spodic* horizon, fine sand, dark brown (10YR 3/4, 7.5YR 3/2), slightly moist, single grain structure, many roots of grasses, single fine charcoals, gradual and smooth boundary;

BC – 39–49 cm, transitional horizon, fine sand, dark brown (10YR 5/4, 7.5YR 3/4), slightly moist, single grain structure, few roots, single fine charcoals, clear and wave boundary;

CB – 49–70 cm, transitional horizon, fine sand, yellowish brown (10YR 6/4, 10YR 5/6), slightly moist, single grain structure, very few roots, single fine charcoals, gradual and smooth boundary;

C – 70–(120) cm, parent material, fine sand, brownish yellow (10YR 7/3, 10YR 6/6), slightly moist, single grain structure;

Table 16. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0-1.0	1.0-0.5	0.5-0.25	0.25-0.1	0.1-0.05	0.05-0.02	0.02-0.005	0.005-0.002	< 0.002	
AB	0–17	0	0	1	25	68	4	2	0	0	0	S
Bhs	17–39	0	0	1	26	70	2	1	0	0	0	S
BC	39–49	0	0	2	32	64	1	1	0	0	0	S
CB	49–70	0	0	3	36	57	3	1	0	0	0	S
C	70–(120)	0	0	0	40	58	2	0	0	0	0	S

Table 17. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH	
					H_2O	KCl
Oie	2.5–0	134	7.83	17	5.0	4.5
AB	0–17	17.6	1.20	15	5.5	4.5
Bhs	17–39	6.9	0.52	13	6.7	5.3
BC	39–49	2.3	0.37	6	6.5	5.3
CB	49–70	-	-	-	6.4	5.3
C	70–(120)	-	-	-	6.3	5.2

Table 18. Contents of different forms of iron and aluminium

Horizon	Depth [cm]	Fe_t	Fe_d	Fe_o	Fe_t -Fe_d	Fe_d -Fe_o	Al_t	Al_o
		[g·kg^{-1}]						
AB	0–17	7.91	4.56	2.01	3.35	2.55	20.9	1.16
Bhs	17–39	8.18	4.86	2.00	3.32	2.86	20.9	0.56
BC	39–49	4.83	2.07	1.15	2.76	0.92	15.8	0.48
CB	49–70	3.96	1.15	0.51	2.81	0.64	13.3	0.73
C	70–(120)	2.53	0.45	0.17	2.08	0.28	12.6	0.50

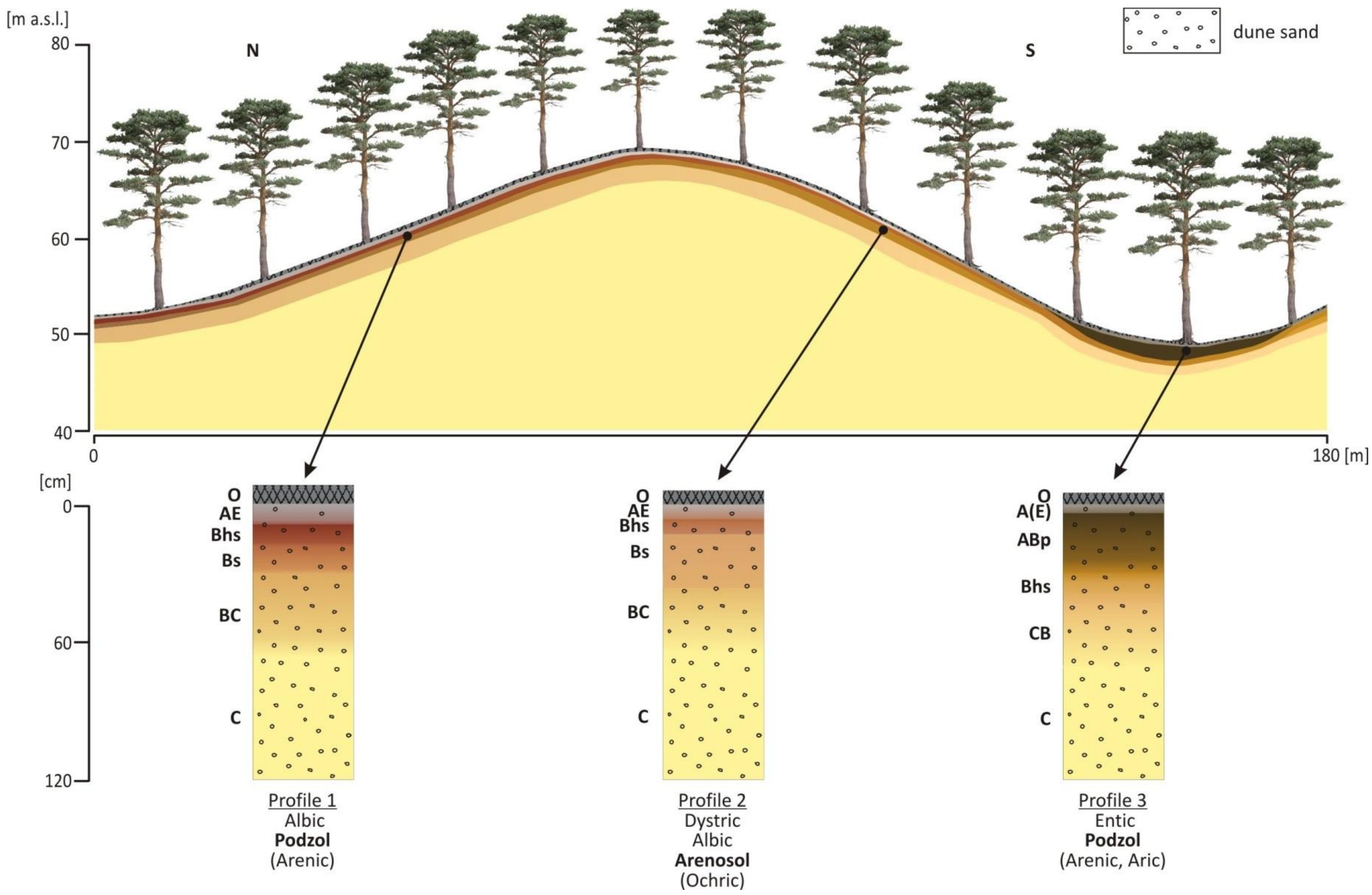


Fig. 2. Toposequence of soils on inland dunes in the 135 years old production pine forest

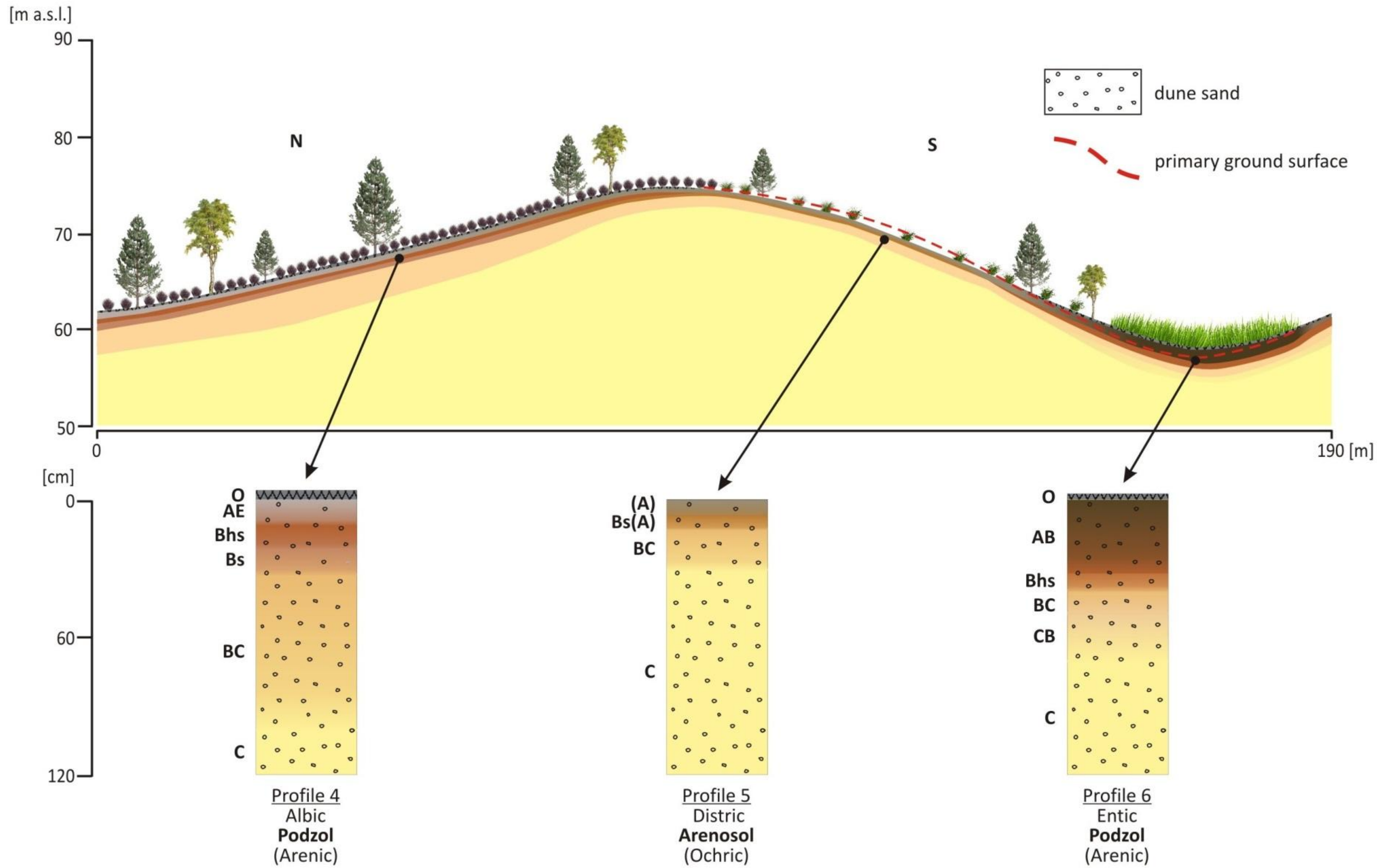


Fig. 3. Toposequence of soils on inland dunes in the deforested area which has been subsequently revegetated by natural succesion

Climate

The investigated dune area is located in the fully humid zone with temperate and warm summer (Kottek et al., 2006). The average annual temperature is 7.9˚C, with July being the warmest (18.1˚C) and January the coldest (–2.2˚C) month. The average annual precipitation is low compared to other parts of Central Europe. It amounts to 520 mm, with July being the wettest (82.6 mm) and February the driest (23.8 mm) month (Wójcik and Marciniak, 2006).

Soil genesis and systematic position

All the studied soils have been formed from highly sorted aeolian sand. This means that the soils are almost identical with reference to the texture of parent material, in which the total contribution of medium (0.5–0.25 mm), fine (0.25–0.1 mm) and very fine sand (0.1–0.05 mm) usually exceeds 95% of all grains. This textural homogeneity as well as ca. 85–90% dominance of quartz in mineral composition of dune sand (Jankowski, 2012) result in the fact that the natural vegetation of the study area is relatively species-poor, subcontinental, fresh Scots pine forest of *Peucedano-Pinetum* (Chojnacka et al., 2010; Gugnacka-Fiedor and Adamska, 2010). This forest overgrows the analyzed toposequence located in the external zone of the artillery training ground (soil profiles 1–3), where forest stands have been subjected to standard treatments used in forest management (cuttings, thinning etc.). Due to low moisture as well as low content of nutrients in soils on dune slopes in the Toruń Basin (Sewerniak et al., 2017), broadleaved tree species are scarce and forest stands are usually single-storeyed and highly dominated by Scots pine. Such ecological conditions make the podzolization the main soil-forming process on inland dunes of the Toruń Basin (Jankowski 2003; Bednarek and Jankowski, 2006). However, the process intensity and the degree of advancement is spatially differentiated by such factors as topography (Jankowski, 2003, 2010; Sewerniak et al. 2011, 2017), deforestation (Jankowski and Bednarek, 2000; Jankowski, 2010; Sewerniak et al., 2017) and soil preparation before planting (Jankowski et al., 2013). As a result, not all soils situated on the studied dunes meet the criteria of **Podzols** according to WRB (IUSS Working Group WRB, 2015). Among the investigated pedons, only those located on north-facing slopes (profiles 1 and 4) and in depressions between dunes (profiles 3 and 6) have illuvial horizons meeting the criteria of the **Spodic** horizon and thus can be classified as **Podzols**.

Sandy texture of the studied **Podzols** has been highlighted by the ***Arenic*** supplementary qualifier. Pedons situated on south-facing exposures (profiles 2 and 5) do not have horizons meeting the criteria of the **Spodic** horizon (e.g. color, OC content, $Al_o+1/2Fe_o$ content) and they are classified as **Arenosols** (Sewerniak et al., 2017). For both **Arenosol** profiles, strongly acid reaction evidencing low base saturation allows to use the ***Dystric*** principal qualifier. Accumulation of organic carbon ≥ 0.2% in the top 10 cm of the mineral soil is marked with the ***Ochric*** supplementary qualifier.

Following the occurrence of the ***Albic material*** in both studied north-facing soils as well as in a south-facing soil located in the 135 year old pine stand (profile 2), the ***Albic*** principal qualifier was ordered to WRB names of these pedons. The ***Albic material*** is lacking in both soils located in depressions between dunes, so the ***Entic*** principal qualifier was added to the description of both pedons (profiles 3 and 6). In these soils, criteria of the **Spodic** horizon are met also by the surface mineral horizons (AB), evidencing illuvial accumulation of OC, Al and Fe in the entire solum. This is a result of lateral podzolization, which was initially described for granite and sandstone areas of the Scharzwald Mountains in Germany (Sommer et al., 2000, 2001). With reference to inland dunes, this process has been recently recognized by Jankowski (2001, 2014). In profile 3, clear traces of former ploughing (ABp horizon) have been marked with the ***Aric*** supplementary qualifier.

In addition to pedons of ***Entic* Podzols** situated in depressions, the ***Albic material*** is also lacking in soil of a south-facing slope in a deforested area where forest vegetation has been subsequently encroached by natural secondary succession (profile 5). This lack has been caused by truncation of the former Podzol topsoil by denudation processes, initiated after deforestation which was carried out for military purposes in the study area at the turn of the 1940s and 1950s. Soils of south-facing slopes are the driest among all the studied topographic positions and the differences in soil moisture between the positions clearly increased after deforestation (Sewerniak et al., 2017). Following the removal of vegetation cover and occurrence of seasonally extremely low moisture of soils, south-facing slopes of the deforested area become very susceptible to wind erosion, which was indicated as the most important denudation process in dry sandy areas (Funk and Reuter, 2006). The secondary factor of soil truncation in the studied dune area is the colluvial process. Due to the blowing out of the rinsed material just after it becomes dry, the colluvial process usually does not induce the formation of deep colluvial soils in depressions between dunes (Sewerniak et al., 2017). Sometimes, however, the denudation increases the depth of a solum in ***Entic* Podzols** up to 1.2–1.4 m (Jankowski, 2014). This appears to be particularly the case at clearcutting sites in production forests, where blowing out of colluvial deposits is hampered by the occurrence of nearby forest stands surrounding a clearcutting site.

Soil sequence

Topography is one of the key factors in soil-forming processes (Jenny, 1941), because of its obvious effect on the amount of solar radiation intercepted by the ground surface and the correlation between land relief and soil erosion. The toposequence located in a production old-growth pine stand (profiles 1–3) shows the primary morphology of soils in the studied dune area. Soils of north-facing slopes are characterized by lower insolation and consequently lower losses of rainwater with evapotranspiration as well as distinctly higher moisture than pedons situated on sunny slopes (Sewerniak et al., 2017). Therefore, following the more intensive leaching of north-facing soils, the pedons are finally more podzolized and consequently meet the criteria of ***Albic* Podzols,** contrary to soils located on south-facing slopes. Higher moisture pools of northern slopes involve more effective soil leaching with organic acids which are produced in O horizons. Consequently, soils of north-facing slopes are usually characterized by lower pH than pedons located on southern exposures. This regularity was observed both for aeolian landforms (Kuźnicki et al., 1974, Sewerniak et al., 2011, 2017) as well as for deposits of other genesis (Egli et al., 2006, Seibert et al., 2007). In addition, it was reported that soils of north-facing slopes were characterized by higher content of carbon and nitrogen compared to pedons from southern exposures (Rezaei and Gilkes, 2005, Pueyo et al., 2007, Sewerniak et al., 2017).

Soils occurring in depressions between dunes (***Entic* Podzols**) are visibly enriched with organic matter, iron and manganese when compared to pedons of dune slopes (Jankowski, 2001, 2014; Sewerniak et al., 2017). The content of organic matter is crucial for water sorption as well as nutrients' pools in dry sandy soils (Prusinkiewicz, 1961, Elgersma, 1998). This means that pedons of depressions between dunes are "hot spots" of distinctly higher moisture and fertility in otherwise dry and nutrient-poor inland dune areas (Sewerniak et al., 2017). This outstanding ecological value of dune ***Entic* Podzols** has consequences for vegetation, i.e. despite their small areas (usually 200-1000 m^2, Jankowski, 2014), much higher biodiversity (Sewerniak and Jankowski, 2017) as well as higher productivity of pine stands (Sewerniak, 2016) was determined for the soils in depressions than for dune slopes.

The described effect of topography on dune soils is altered after deforestation, mainly by such factors as: (i) opening of soil mineral surface for denudation processes and (ii) disruption of alimentation of acidic pine litterfall to O horizons (Sewerniak et al., 2017). With regard to soil morphology, however, the effect is clearly related to the location in the relief, i.e. after deforestation, soils of depressions and of north-facing slopes stay wet enough to be constantly overgrown with ground vegetation which protects them against denudation processes. While soils of south-facing dune slopes, when covered with scarce vegetation, are highly exposed to insolation. They periodically highly desiccate and warm up in growing seasons (Sewerniak and Stelter, 2016) and thus form suitable conditions for the occurrence of scarce xerothermic vegetation only. This type of plant cover inadequately protects soil from denudation factors and finally pedons located on south-facing slopes become truncated (Fig. 3). In the studied deforested area, the truncation of south-facing dune slopes was estimated for ca. 25 cm (to the depth of the Bs horizon, Sewerniak et al., 2017). The occurrence of the topographically-induced soil differentiation in the studied deforested dune area results in the clear pattern of vegetation: northern slopes are overgrown with *Calluna vulgaris*, south-facing with *Corynephorus canescens*, while depressions between dunes with *Calamagrostis epigejos* mainly (Jankowski, 2010; Sewerniak and Jankowski, 2017). These relations are, however, mutually interacted because soils and vegetation constantly affect each other to create a dynamic equilibrium.

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Chronosequence of dune soils on Barrier islands at the North Sea coast – exemplified at Spiekeroog, Northwest Germany

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Chains of Dunes, separated by mostly near–groundwater slacks, are typical features of the barrier islands at the North Sea coast (Pott, 1995). Like a rope of elongated pearls, barrier islands are located offshore the mainland parallel to the coast and separate small parts of sea from the open sea. They occur from the island of Texel in the Netherlands via the East and West Frisian Islands in Germany to the island of Fanø in Denmark. The exemplified study island Spiekeroog belongs to the East Frisian Islands, located between the inlets of the rivers Ems and Weser (Fig. 1). The barrier islands are very young Holocene formations approximately 2000 years old (Streif, 1990). They are still however partly developing, through forces such as waves, water currents and wind. The required geo–hydro–morphological conditions for their formation are shallow coasts, sufficient sediment supply and adequate tidal amplitudes, the latter of which accounts for about 2.5 m for Spiekeroog. According to Barckhausen (1969) the formation process of a barrier island starts with the accumulation of sediment initially below mean high tide level, leading to periodically flooded shelves with partly dry beaches, which steadily rise to final dry dune islands.

Fig. 1. Location

Lithology and topography

Dunes, of up to 25 m height, are epilittoral characteristic geomorphological features of Spiekeroog. They comprise of loose, permeable, very poor, well–sorted aeolian sands. The oldest dunes (up to approx. 350 years), referred to as brown dunes, in the centre of the island are surrounded by younger dune chains comprised of so–called gray dunes and the most recently formed white dunes (Sindowski, 1970; Streif, 1990). Dune slacks form depressions between dune ridges. They are mostly saturated with groundwater and therefore tend to peat formation. Due to successive formation and very homogenous parent material; the dune complex represents a soil chronosequence. North of the dune complex wide sublittoral and eulittoral beach zones adjoin the open sea. Southwards of the dune complex are sublittoral and eulittoral marshes, tidal flats and the Wadden Sea.

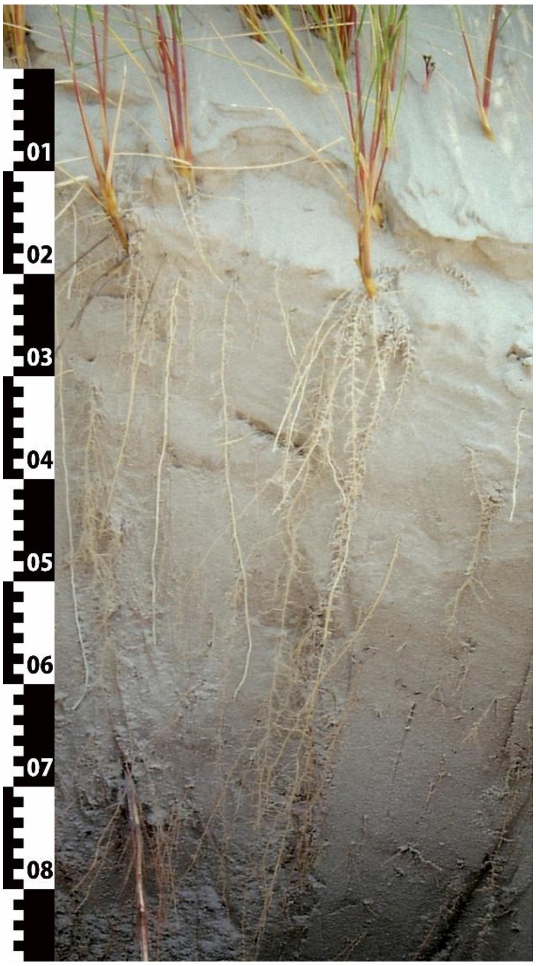
Land use

Except for a small afforested area, the dunes are not used, and thus bear natural vegetation. Beach grass (*Ammophila arenaria*) is characteristic for the white dunes. The gray dunes are covered with dominantly sand sedge (*Carex arenaria*), gray hairgrass (*Corynephorus canescens*), seabuckthorn (*Hippophaë rhamnoides)* and beach rose (*Rosa rugosa*). The brown dunes show a distinct vegetation zoning with crowberry (*Empetrum nigrum*) and common polypody (*Polypodium vulgare*) at the north

Profile 1 – Eutric Protic **Arenosol** (Aeolic)

Localization: First dune chain south of the beach, north slope, inclination 30°, white dune covered with beach grass (*Ammophila arenaria*), 8 m a.s.l., **N** 53°46'30.7'' **E** 7°43'10.9''

Time of dune formation: still active



Morphology:

C – 0–(87) cm, parent material, sand, light brownish gray (2.5Y 8/1, 2.5Y 6/2), dry, single grain structure, many fine roots, few medium roots;

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]				Textural class
		> 2.0	2.0–0.63	0.63–0.2	0.2–0.125	
C	0–(87)	0	34.6	61.9	3.5	FS

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH KCl	$CaCO_3$ [g·kg^{-1}]
C	0–(87)	1.2	0.20	6	6.8	0.3

Table 3. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	TEB	CEC	BS [%]
		[cmol(+)·kg^{-1}]						
C	0–(87)	0.654	0.288	0.136	0.187	1.265	1.265	100

Profile 2 – Eutric **Arenosol** (Aeolic, Hydrophobic, Nechic, Ochric)

Localization: Second dune chain south of the beach, north slope, inclination 30°, gray dune dominantly covered with sand sedge (*Carex arenaria*), gray hairgrass (*Corynephorus canescens*), seabuckthorn (*Hippophaë rhamnoides*) and moos species, 8 m a.s.l., **N** 53°46’28.9’’ **E** 7°43’9.6’’

Time of dune formation: < 60 years ago

Morphology:

Ah – 0–6 cm, humus horizon, sand, very dark brown (10YR 3/2, 10YR 2/2), dry, single grain structure, many very fine roots, clear and smooth boundary;

C – 6–(100) cm, parent material, sand, brown (10YR 5/3, 10YR 4/3), dry, single grain structure, many medium roots in the upper part, few fine roots in the lower part;

Table 4. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]					Textural class
		> 2.0	2.0–0.63	0.63–0.2	0.2–0.125	<0,063	
Ah	0–6	0.3	40.4	55.6	3.4	0.3	FS
C	6–(100)	0.1	41.5	55.9	2.3	0.2	FS

Table 5. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH KCl	$CaCO_3$ [g·kg^{-1}]
Ah	0–6	7.25	0.5	14.5	5.4	0
C	6–(100)	1.90	0.2	9.5	5.4	0

Table 6. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	TEB	CEC	BS [%]
		[cmol(+)·kg^{-1}]						
Ah	0–6	1.138	0.510	0.269	0.370	2.287	2.570	89
C	6–(100)	0.512	0.247	0.129	0.170	1.058	1.579	67

Profile 3 – Dystric Brunic Folic **Arenosol** (Aeolic, Hydrophobic, Nechic, Ochric)
Localization: Brown dune, north slope, inclination 30°, dominantly covered with crowberry (*Empetrum nigrum*), 8 m a.s.l., **N** 53°46'27.0'' **E** 7°43'8.8''
Time of dune formation: 60–160 years ago

Morphology:

Oi – 5–0 cm, slightly decomposed *organic* material, reddish brown (5YR 6/3, 5YR 5/4), dry, clear and smooth boundary;

AE – 0–4 cm, humus horizon with *albic* material, sand, light brownish gray (10YR 7/2, 10YR 6/2), dry, single grain structure, very few roots, clear and wavy boundary;

Bw – 4–25 cm, braunified horizon, sand, brown (7.5YR 6/4, 7.5YR 5/4), dry, single grain structure, very few roots, clear and smooth boundary;

C – 25–(90) cm, parent material sand, very pale brown (10YR 7/3, 10YR 8/3), dry, single grain structure, very few roots;

Table 7. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]					Textural class
		> 2.0	2.0–0.63	0.63–0.2	0.2–0.125	<0,063	
Oi	5–0	–	–	–	–	–	–
AE	0–4	0.2	30.5	65.1	3.8	0.4	FS
Bw	4–25	0.1	35.4	61.2	3.1	0.2	FS
C	25–(90)	0.0	34.7	62.2	3.0	0.1	FS

Table 8. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH KCl	$CaCO_3$ [g·kg^{-1}]
Oi	5–0	–	–	–	–	–
AE	0–4	4.6	0.2	23.0	3.5	0
Bw	4–25	3.0	0.3	10.0	3.8	0
C	25–(90)	–	–	–	4.2	0

Table 9. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	CEC	BS
		[cmol(+)·kg^{-1}]						[%]
Oi	5–0	–	–	–	–	–	–	–
AE	0–4	0.190	0.148	0.159	0.278	0.775	2.499	31
Bw	4–25	0.180	0.173	0.082	0.196	0.631	1.661	38
C	25–(90)	0.215	0.214	0.105	0.178	0.712	1.779	40

Profile 4 – Histic **Gleysol** (Arenic)
Localization: Dune slack between brown dunes, dominantly covered with moor birch (*Betula pubescens*)
2 m a.s.l., **N** 53°46’8.4’’ **E** 7°43’4.1’’
Time of dune formation: 160–270 years ago

Morphology:

Oi – 4–0 cm, slightly decomposed *organic* material, black (5YR 2.5/1), moist, abrupt and smooth boundary;

H – 0–17 cm, *histic* horizon, black (5YR 2.5/1), moist, coarse roots, clear and wavy boundary;

Cl – 17–55 cm, parent material, sand, light brownish gray (10YR 6/2), moist, single grain structure, redoximorphic features (mottling), few roots, clear and wavy boundary;

Cr – 55–(65) cm, beneath groundwater level, parent material, sand, light gray (2.5Y 7/1), wet, *reductive* conditions, single grain structure, clear and smooth boundary;

Table 10. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]					Textural class
		> 2.0	2.0–0.63	0.63–0.2	0.2–0.125	<0,063	
Oi	4–0	–	–	–	–	–	–
H	0–17	–	–	–	–	–	–
Cl	17–55	0	35.4	61.3	3.2	0.1	FS
Cr	55–(65)	0	24.5	73.1	2.4	0.0	FS

Table 11. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH KCl	$CaCO_3$ [g·kg^{-1}]
Oi	4–0	–	–	–	–	–
H	0–17	347.4	19.3	18	3.0	0
Cl	17–55	1.2	–	–	3.8	0
Cr	55–(65)	–	–	–	4.0	0

Table 12. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	TEB
		[cmol(+)·kg^{-1}]				
Oi	4–0	–	–	–	–	–
H	0–17	4.087	4.567	3.018	8.961	20.633
Cl	17–55	0.791	0.366	0.188	0.511	1.856
Cr	55–(65)	1.592	0.551	0.136	0.318	2.597

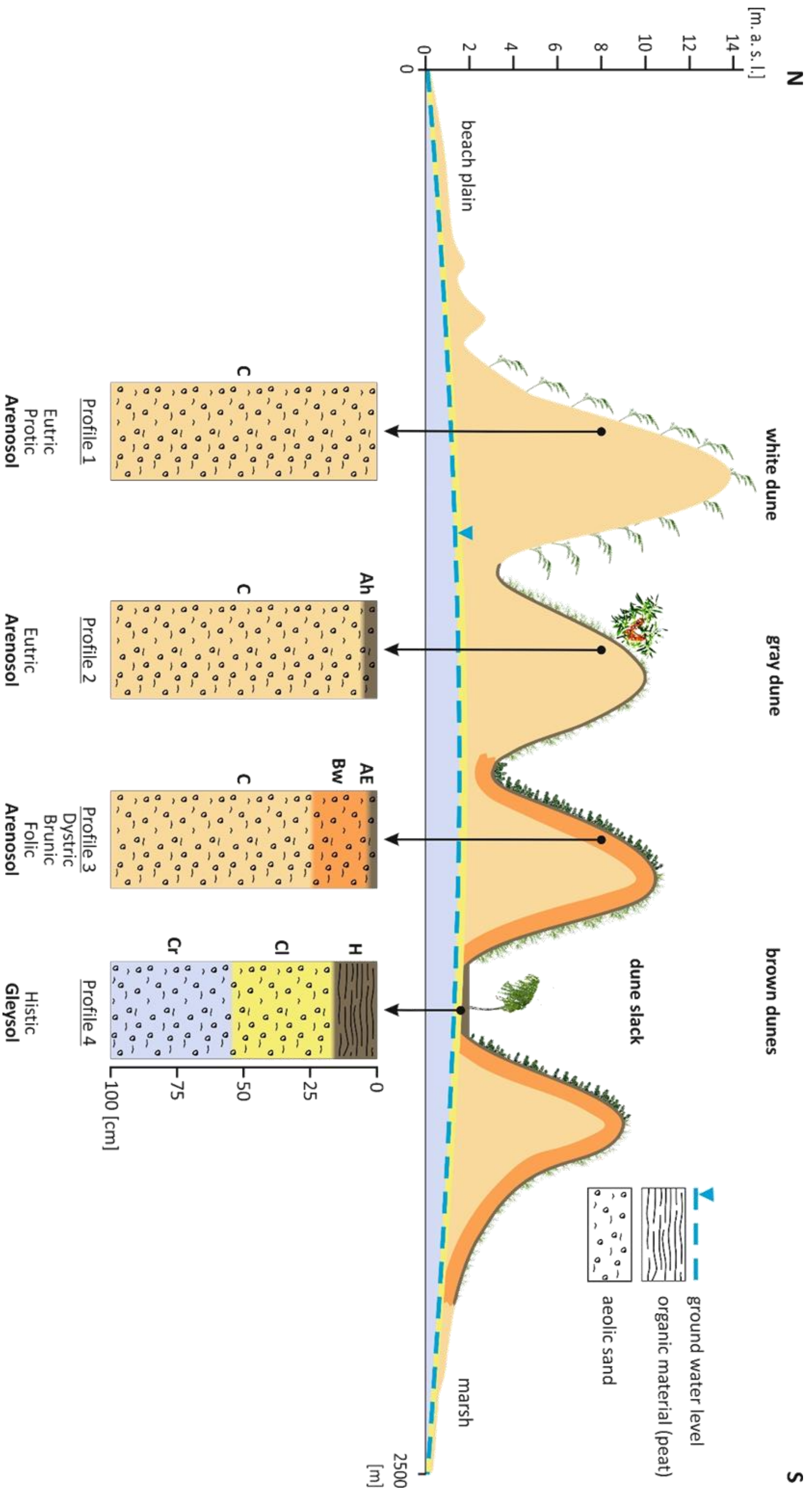


Fig. 2. Soil chronosequence within the dune complex of Spiekeroog Island

slopes and gray hairgrass accompanied by lichen species at the south slopes. Moor birch (*Betula pubescens*) is typical in the wet dune slacks. The beaches are mostly without any vegetation and the marshes are covered with halophytes (Pott, 1995).

Climate

The climate is temperate oceanic (Köppen–Geiger Cfb type) (Geiger, 1961). The average annual air temperature is 8.8 °C (de.climate–data.org/location/890092). The warmest months are July and August (18 °C) and the coldest January and February (2 °C). The average annual precipitation is 795 mm with a maximum in August (80 mm).

Soil genesis and classification

Profile 1 represents the youngest soil of the studied sequence. It is located on the north slope of the first white dune chain adjoining the beach plain. The dune chain is covered with beach grass (*Ammophila arenaria*) which allows for intensive vertical growth of dunes by trapping the windblown sand. Its vertical root growth keeps pace with over–sedimentation and the trapped sand becomes fixed in a dense root network (Ranwell, 1972). The profile consisted of a single C horizon comprised of carbonatic sandy parent material, showing neutral soil reaction (Table 1 and 2). The ongoing over–sedimentation with sand inhibits soil formation and consequently the development of pedogenetic features. Since no other horizon existed the classifier ***Protic*** was applicable. The sand consisted mainly of quartz (~ 96 wt%) and, to a minor extend, of feldspar, plagioclase and heavy minerals. The majority of quartz exhibited a low CEC. The base saturation was 100 % by which the criteria of a ***Eutric*** qualifier was fulfilled (Table 3). Due to the aeolian origin of the parent material, the supplementary qualifier ***Aeolic*** was added. Since the soil lacked a diagnostic horizon and had a texture class coarser than loamy sand (Table 1), it was classified as a ***Eutric Protic*** **Arenosol** (***Aeolic***) (IUSS Working Group WRB, 2015).

Profile 2 is located on a gray dune belonging to the second dune chain south of the beach and formed after 1960 (Sindowski, 1970). Because of the greater distance to the beach and the sheltering effect of the white dune chain, sand movement was prevented which resulted in the profile having a fixed surface. This allowed for an increase in plant species diversity and biomass production (Isermann, 2011). The dominant vegetation consists of sand sedge (*Carex arenaria*), gray hairgrass (*Corynephorus canescens*), seabuckthorn (*Hippophaë rhamnoides*) and mooses. Humifaction of organic material, such as plant residues and dead roots, led to the formation of a humus enriched topsoil horizon (Table 5). Within this horizon, white uncoated sand grains stand out from the very dark brown matrix. These features justified the use of the supplementary qualifier ***Nechic***. The supplementary qualifier ***Ochric*** was added since the weighted average of OC in the soil was higher than 0.2 % to a depth of 10 cm, but insufficient to fulfill the criteria of the ***Humic*** qualifier. The dry soil surface showed strong water repellency, which is typical for sandy dune soils on islands along the North Sea coast (Dekker et al., 2000). Therefore, the supplementary qualifier ***Hydrophobic*** was added. The profile was free of carbonates throughout and soil acidification was marked by a decrease in pH of 1.4 units compared to profile 1 (Table 5). The CEC in the subsoil was similar to profile 1 and slightly higher in the topsoil due to additional sorption capacity provided by the humified organic material. The BS in the topsoil was high (89 %) and decreased towards the parent material (67 %) (Table 6). Since the BS exceeded 50 % throughout the profile and due to the aeolic origin of the parent material, the qualifier ***Eutric*** and the supplementary qualifier ***Aeolic*** was applied, respectively. Since no diagnostic horizon was detected and the texture class of the soil was coarser than loamy sand

(Table 4), the soil was classified as a ***Eutric*** **Arenosol** (***Aeolic, Hydrophobic, Nechic, Ochric***) (IUSS Working Group WRB, 2015).

Profile 3 is located in one of the older parts of the dune complex which developed approximately 60 to 160 years ago (Sindowski, 1970) comprising brown dunes. The north slopes of the brown dunes are mainly covered with crowberry (*Empetrum nigrum*), the occurrence of which is favored by a colder and more humid microclimate compared to the south slopes which receive more solar radiation (Isermann, 2011). The litter of crowberry is very acidic and has a wide C/N–ratio and is therefore slowly decomposed (Gerlach et al., 1994), which led to the formation of a 5 cm thick layer of slightly decomposed *organic* material (***Folic*** qualifier) on top of the mineral soil surface. Advanced leaching of carbonates and other readily weathered minerals in combination with the input of organic acids from the *organic* material layer on top of the mineral surface caused a decrease of pH to very acidic conditions throughout the profile (Table 8). Incipient podzolization of the topsoil was marked by the occurrence of *albic* material and unexceptionally uncoated sand grains (***Nechic*** supplementary qualifier) within the AE horizon, where mobilization and eluvial removal of iron is promoted by the iron complexing effect of the organic acids in the soil solution (Sauer et al., 2007). The overall low pH favored the weathering of iron bearing primary minerals. Through the process of braunification, iron became liberated from the crystalline mineral structure and oxidized on the grain surfaces, where it formed brown oxidic coatings. This process was morphologically expressed by a brown colored Bw horizon. The texture of the Bw horizon was too coarse to fulfill the criteria of a *cambic* horizon (Table 7). Moreover, a *spodic* horizon was precluded due to insufficiently high OC content (Table 8) and optical density of the oxalate extract (ODOE) (0.06). However, the color was 2.5 units redder than the underlying parent material, which allowed the designation of ***Brunic*** qualifier. The overall low pH and leaching of base cations resulted in a low BS (< 50 %) throughout the profile, which is expressed by the ***Dystric*** qualifier (Table 9). Since the average OC content down to a depth of 10 cm was over 0.2 % but less than 1 % within the depth of 50 cm, the supplementary qualifier ***Ochric*** was added. The parent material was of aeolic origin (***Aeolic*** supplementary qualifier) and similar to profile 2 the soil was strongly water repellent (***Hydrophobic*** supplementary qualifier). Similar to profile 1 and 2, the soil lacked a diagnostic horizon and had a texture class coarser than loamy sand. It was therefore classified as a ***Dystric Brunic Folic*** **Arenosol** (***Aeolic, Hydrophobic, Nechic, Ochric***) (IUSS Working Group WRB, 2015).

Profile 4 represents a soil in a dune slack influenced by high groundwater level. The dune slack is located between brown dunes, which are approximately 160 to 270 years old (Sindowski, 1970), and is covered by a small stock of moor birches (*Betula pubescens*). The litter of the trees has accumulated in a 4 cm thick layer of slightly decomposed *organic* material on the surface of a peat sediment high in OC content, which forms a *histic* horizon (Table 11). The accumulation of litter and the formation of peat is the result of a mostly high groundwater level that causes prolonged water saturation in the entire profile and frequent occurrence of surface water. Moreover, an overall low pH hinders litter decomposition (Table 11). Underneath the *histic* horizon, a Cl horizon followed. This horizon is effected by changing oxic and anoxic conditions caused by alternations in the groundwater level. The changing conditions cause iron oxides to form and concentrate mainly around or within coarse pores during oxic conditions, which leads to *mottling* features. The iron enters the Cl horizon in ferrous form with the capillary fringe water and forms in the Cr horizon below, in which continuous *reductive* conditions resulted in soil colours, allowing for the designation of *gleyic* properties. Since the Cr horizon was thicker than 25 cm and began within 40 cm from the mineral surface and all mineral horizons had a sandy texture (***Arenic*** supplementary qualifier), the soil was classified as a ***Histic*** **Gleysol** (***Arenic***) (IUSS Working Group WRB, 2015).

Soil sequence

The studied soils represent a soil chronosequence characterized by quick acidification typical for dune soils on barrier islands comprising quartz–rich and carbonate–poor parent material (Gorham, 1958; Gerlach et al., 1994) (Fig.2). Other characteristic pedogenetic processes involved are humus accumulation, carbonate loss, base saturation decrease, braunification and incipient podzolization (Giani and Buhmann, 2004). While the ***Eutric Protic*** **Arenosol** (profile 1) shows neutral soil reaction and high content of base cations due to continuous supply of fresh, carbonatic sand; the ***Eutric*** **Arenosol** on the older gray dune (profile 2) is characterized by a loss of carbonates and base cations which results in a decrease in pH and BS. Low sand movement allowed for higher plant species diversity, higher biomass production, and in turn for the formation of a humus enriched topsoil. The ***Dystric Brunic Folic*** **Arenosol** (profile 3) on an approximately 60 to 160 year old brown dune (Sindowski, 1970) shows very acidic soil reactions and low BS. It displays advanced soil formation, evinced by pedogenetic features caused by braunification (***Brunic*** qualifier) and incipient podzolization (*albic* material; ***Nechic*** supplementary qualifier). The early occurrence of incipient podzolization within decades is in accordance with findings from other dunes at the North Sea coast (Stützer, 1998). The ***Histic*** **Gleysol** (profile 4) has formed in a dune slack between brown dunes, which are approximately 160 to 270 years old (Sindowski, 1970). Within a maximum 270 years a 17 cm thick peat layer (***Histic*** qualifier) has formed under the influence of a mostly high groundwater level, which led to *gleyic* properties and *reductive* conditions in the soil.

In general, the soil chronosequence illustrates fast soil formation within dunes at the North Sea coast. At a small–scale (< 3 km), it covers unaffected carbonatic parent material, a braunified and incipiently podzolized acidic soil and peat formation within a time range of maximal 270 years.

Acknowledgement

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Soils of hilly loess region in Ždánice Forest, south–east Czechia

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The study area comprises slope systems that are typical of the undulating landscape in the dry and warm region in south-east Czechia. The area is characterized by loess covers over cretaceous sediments and belongs to regions with the longest tradition of agriculture. The archaeological findings of the first Neolithic cultures, which used the area for agriculture production, are dated back to 5500 B.C. It makes this area one of the oldest agriculturally-used regions in Central Europe.

Fig. 1. Location

Lithology and topography

The area is formed by the upper Eocene molasse facies (sandstones, conglomerates and marls) and Oligocene sandstones covered by a Pleistocene loess layer with a variable depth ranging from several meters to several tens of meters (Chlupáč et al., 2002). The soil sequence characterizes a typical agricultural plot forming a complex slope system with different types of landforms (side valley, toe-slope, plateau and back-slope). The plot is characterized by a flat upper part (slope 0–0.5°), while the middle part, formed by a back slope and a tributary valley, is steeper (up to 23°). The mean slope of the plot is 12.7°. The tributary valley represents a major line of the concentrated runoff emptying into a colluvial fan at the concave base-slope.

Land use

The region ranks among the earliest human settlements in Central Europe and has been under uninterrupted agricultural use since the mid-Holocene (Bogaard, 2002). The early Neolithic farmers, represented by the Linear Bandkeramik culture (broadly dated to 5700 BC–5000 BC; Zvelebil and Pettitt, 2013), likely preserved the prevailing steppe nature of the area, so that the climax stage of oak-elm forests has never fully developed in the region (Eckmeier et al., 2007; Neühauslová, 1998). During the Middle Ages, the area underwent several oscillations in erosional intensity according to historical changes in human settlement and climatic conditions. Strip farming was the main cultivation method adopted from the High Middle Ages until the late 1950s (Beranová and Kubačák, 2010). Despite the small size of the plots, soil erosion was significant, as the majority of fields were down-slope oriented and tens to several hundred meters long (Fig. 1). Extremely intensive erosion took place after political changes in the 1950s, which implicated forced collectivization of agricultural land resulting in spatial enlargement of fields to the extent of several hundred hectares and the destruction of landscape elements with an anti-erosional effect (Zádorová et al., 2013).

Profile 1 – Calcic Pachic **Chernozem** (Aric, Siltic)
Localization: Upper plateau – inclination 2°, arable field, 220 m a.s.l.,
N 48°57'47.7" **E** 16°52'57.9"

Morphology:

Ap – 0–30 cm, ploughed part of *chernic* horizon, colour very dark grayish brown (10YR 3/2), slightly moist, strong medium (2–5 mm) granular structure, texture silt loam, none rock fragments, slightly calcareous – no visible carbonates, firm consistency, common roots and earthworms channels, abrupt (0–2 cm) horizon boundary;

Ac – 30–60 cm, *chernic* horizon; colour very dark brown (10YR 2/2), slightly moist, strong medium (2–5 mm) granular structure, texture silt loam, none rock fragments, slightly calcareous – secondary carbonates in form of pseudomycelia, firm consistency, common roots and earthworms channels diffuse (>15 cm) horizon boundary;

Ck – 60–(100) cm, calcic horizon; colour light yellowish brown (10YR 6/4), slightly moist, weak very coarse (>50 mm) blocky structure, texture silt loam, none rock fragments, strongly calcareous – secondary carbonates in form of pseudomycelia, firm consistency, few roots channels and earthworms channels;

Table 1. Chemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	pH		$CaCO_3$ [g·kg^{-1}]
			H_2O	KCl	
Ap	0–30	13.5	7.0	6.7	0.1
Ac	30–60	16.5	7.1	6.8	0.1
Ck	60–100	0.5	7.6	7.1	18.0

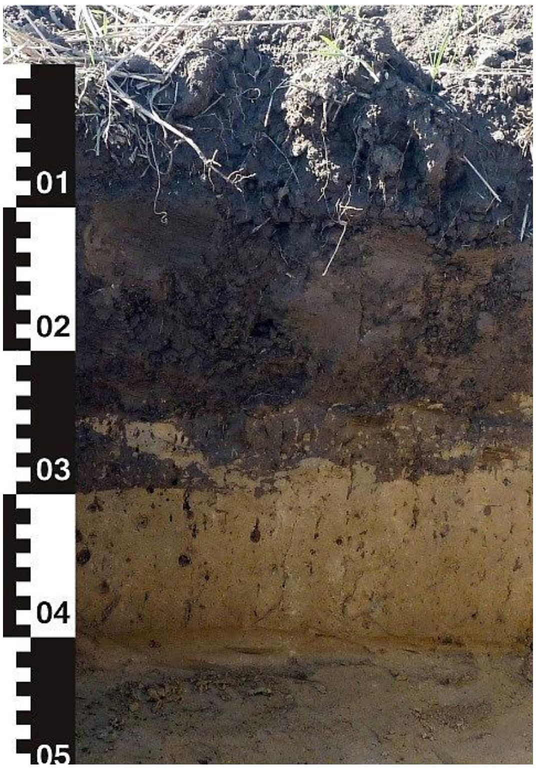
Table 2. Soil texture

Horizon	Depth [cm]	Percentage share of fraction [mm]					Textural class
		> 2.0	2.0–0.1	0.1–0.05	0.05–0.002	< 0.002	
Ap	0–30	0	15.3	6.5	55.4	22.8	SiL
Ac	30–60	0	17.3	6.7	54.1	21.9	SiL
Ck	60–100	0	16.5	7.4	53.8	22.3	SiL

Table 3. Soil sorption, nutrition and contaminants content

Horizon	Depth [cm]	CEC [cmol(+)·kg^{-1}]	BS [%]	P	K	DDT	Pb	Cd
				[mg·kg^{-1}]				
Ap	0–30	16.4	94	20	168	0.11	9.6	0.19
Ac	30–60	17.5	97	24	77	0.05	5.3	0.11
Ck	60–100	12.1	100	0	55	0	5.1	0.09

Profile 2 – Calcic **Chernozem** (Aric, Siltic)
Localization: Upper slope – inclination 6°, arable field, 205 m a.s.l.,
N 48°57'54.5" **E** 16°53'00.9"



Morphology:

Ap – 0–30 cm, ploughed *chernic* horizon, colour very dark grayish brown (10YR 3/2), slightly moist, strong medium (2–5 mm) granular structure, texture silt loam, none rock fragments, slightly calcareous – no visible carbonates, firm consistency, common roots and earthworms channels, abrupt (0–2 cm) horizon boundary;

Ck – 30–(100) cm, *calcic* horizon; colour light yellowish brown (10YR 6/4), slightly moist, weak very coarse (>50 mm) blocky structure, texture silt loam, strongly calcareous – secondary carbonates in form of pseudomycelia, firm consistency, common roots channels and earthworms channels;

Table 4. Chemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	pH		$CaCO_3$ [g·kg^{-1}]
			H_2O	KCl	
Ap	0–30	11.6	7.2	6.9	2.0
Ck	30–(100)	0.9	7.8	7.4	18.0

Table 5. Soil texture

Horizon	Depth [cm]	Percentage share of fraction [mm]					Textural class
		> 2.0	2.0–0.1	0.1–0.05	0.05–0.002	< 0.002	
Ap	0–30	0	16.4	7.0	53.8	22.8	SiL
Ck	30–(100)	0	16.0	6.8	54.9	22.3	SiL

Table 6. Soil sorption, nutrition and contaminants content

Horizon	Depth [cm]	CEC [cmol(+)·kg^{-1}]	BS [%]	P	K	DDT	Pb	Cd
				[mg·kg^{-1}]				
Ap	0–30	14.7	100	18	157	0.09	7.8	0.13
Ck	30–(100)	11.6	100	0	51	0	5.0	0.03

Profile 3 – Haplic **Calcisol** (Aric, Siltic)
Localization: Middle slope – inclination 2°, arable field, 185 m a.s.l.,
N 48°58'01.5" **E** 16°53'04.2"

Morphology:

Ap – 0–25 cm, ploughed *mollic* horizon, colour very dark grayish brown (10YR 3/3), slightly moist, strong medium (2–5 mm) granular structure, texture silt loam, none rock fragments, slightly calcareous – no visible carbonates, firm consistency, common roots and earthworms channels, abrupt (0–2 cm) horizon boundary;

Ck – 25–(100) cm, *calcic* horizon; colour light yellowish brown (10YR 6/4), slightly moist, weak very coarse (>50 mm) blocky structure, texture silt loam, strongly calcareous – secondary carbonates in form of pseudomycelia, firm consistency, few roots channels and earthworms channels.

Table 7. Chemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	pH		$CaCO_3$ [g·kg^{-1}]
			H_2O	KCl	
Ap	0–25	6.9	8.1	7.7	15.6
Ck	25–(100)	1.0	8.4	7.9	18.0

Table 8. Soil texture

Horizon	Depth [cm]	Percentage share of fraction [mm]					Textural class
		> 2.0	2.0–0.1	0.1–0.05	0.05–0.002	< 0.002	
Ap	0–25	0	16.4	7.0	52.7	23.9	SiL
Ck	25– (100)	0	13.2	5.6	56.1	25.1	SiL

Table 9. Soil sorption, nutrition and contaminants content

Horizon	Depth [cm]	CEC [cmol(+)·kg^{-1}]	BS [%]	P	K	DDT	Pb	Cd
				[mg·kg^{-1}]				
Ap	0–25	14.3	100	10	73	0.12	5.6	0.12
Ck	25–(100)	11.8	100	0	50	0.06	4.0	0.02

Profile 4 – Eutric Colluvic **Regosol** (Bathyhumic, Panthosiltic)
Localization: Foot slope – inclination 2°, arable field, 170 m a.s.l.
N 48°58'06.5" **E** 16°53'07.6"

Morphology:

Ap – 0–30 cm, colour dark yellowish brown (10YR 4/4) slightly moist, weak granular structure, texture silt loam, none rock fragments, moderately calcareous – no secondary carbonates visible, friable consistency, common roots, abrupt (0–2 cm) horizon boundary, colluvial material;

Ah1 – 30–90 cm, colour dark yellowish brown (10YR 4/4) slightly moist, weak coarse (>50 mm)ranular structure, texture silt loam, few rock fragments, moderately calcareous, friable consistency, common roots and earthworm channels, diffuse (>15 cm) horizon boundary, colluvial material with no stratification features;

Ah2 – 90–150 cm, colour dark yellowish brown (10YR 4/4) slightly moist, weak coarse (>50 mm) granular structure, texture silt loam, none rock fragments, moderately calcareous, in some depth intervals visible secondary carbonates (lublinite), friable consistency, common roots and earthworm channels, diffuse (>15 cm) horizon boundary, colluvial material with no stratification features;

Ah3 – 150–200 cm, colour very dark brown (10YR 3/3), moist, structure not observed, texture silt loam, none rock fragments, slightly calcareous – no visible concentrations, gradual (5–15 cm) horizon boundary, colluvial material with no stratification features;

Acb – 200–(260) cm, buried *chernic* horizon, colour black (10YR 2/1), moist, structure not observed, texture silt loam, none rock fragments, slightly calcareous – no visible concentrations, firm consistency;

Table 10. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	pH		$CaCO_3$ [g·kg^{-1}]
			H_2O	KCl	
Ap	0–30	8.5	7.4	6.7	7.2
Ah1	30–90	6.5	7.3	6.8	5.4
Ah2	90–150	7.9	7.5	7.1	2.5
Ah3	150–200	12.1	7.6	7.3	2.1
Acb	200–(260)	20.5	7.6	7.2	0.9

Table 11. Soil texture

Horizon	Depth [cm]	Percentage share of fraction [mm]					Textural class
		> 2.0	2.0–0.1	0.1–0.05	0.05–0.002	< 0.002	
Ap	0–30	0	15.5	9.5	51.6	23.4	SiL
Ah1	30–90	0	16.3	7.4	54.2	22.1	SiL
Ah2	90–150	0	16.1	7.8	53.7	22.4	SiL
Ah3	150–200	0	16.4	7.6	54.6	21.4	SiL
Acb	200–(260)	0	17.1	2.6	57.1	23.2	SiL

Table 11. Soil sorption, nutrition and contaminants content

Horizon	Depth [cm]	CEC [cmol(+)·kg^{-1}]	BS [%]	P	K	DDT	Pb	Cd
				[mg·kg^{-1}]				
Ap	0–30	12.1	100	27	113	0	6.5	0.21
Ah1	30–90	11.7	100	40	85	0.54	7.1	0.27
Ah2	90–150	12.9	100	14	75	0.21	6.2	0.18
Ah3	150–200	14.2	100	7	67	0.02	5.3	0.11
Acb	200–(260)	17.2	97	0	42	0.05	3.0	0.09

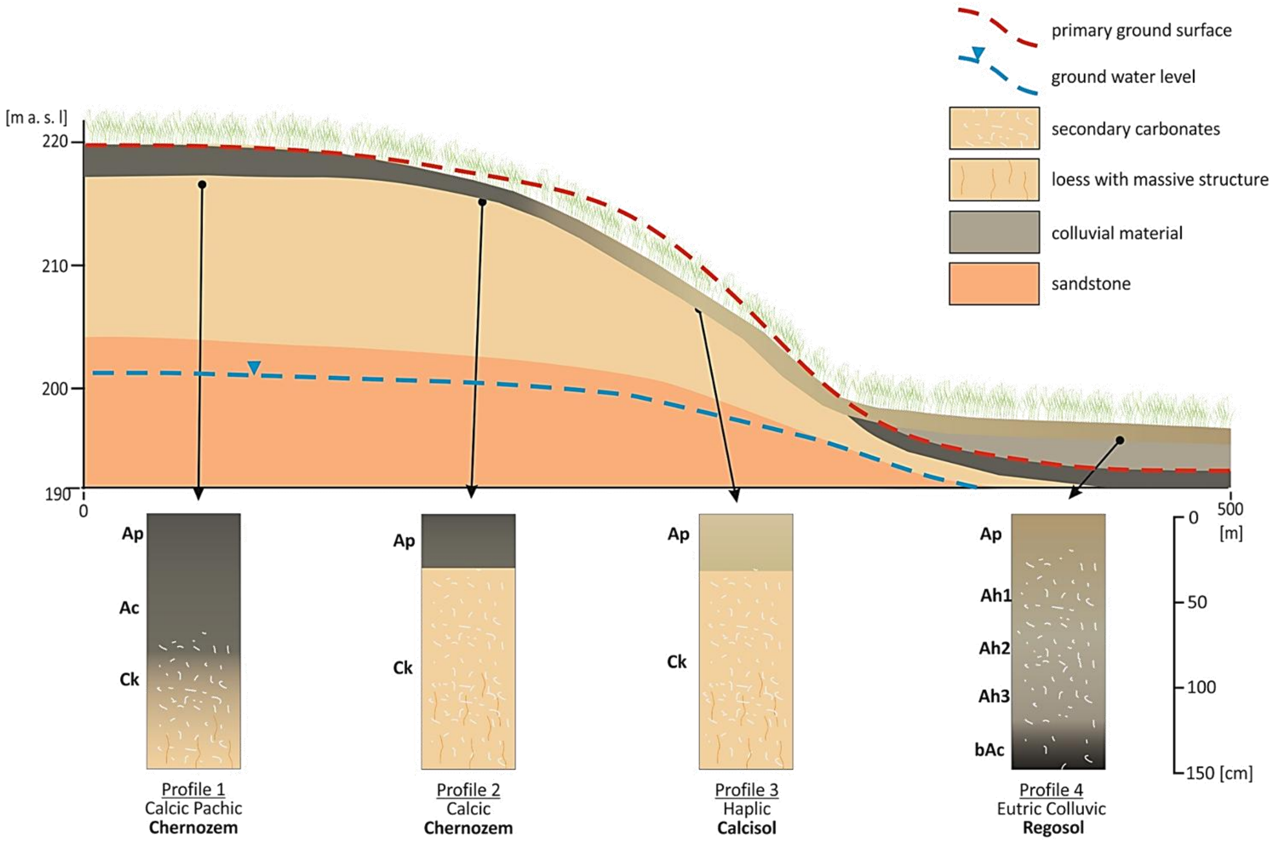


Fig. 2. Toposequence of soils in loess region in Ždánice Forest, South-east Czechia

Climate

Climate is characterized by a mean annual precipitation of 542 mm and a mean annual temperature of 8.4°C (Tolasz, 2007). According to Kottek et al. (2006), the region is located in the fully humid zone with temperate and warm summer.

Soil genesis and classification

The actual soil cover is a result of two main soil-forming processes. The first stage of the soil development can be characterized by natural development of soils from loess under the steppe vegetation that started after the last ice age. The rather dry and warm climate, high biological activity and parent material with favourable physical and chemical properties led to the development of soils with **chernic** horizon. It can be presumed that the natural erosion of the soil material was limited due to dense grass vegetation in this period. **Chernozem** dominated the typical soil cover in this period. Because of the dissected topography, it can be assumed that the thickness of the humus horizon varied within the slope system. However, the variability did not reach extreme values of tens of centimeters.

An important change of the soil cover has started with the agricultural exploitation of the landscape. The agriculture use caused an increased soil erosion and redistribution of the soil material within the landscape. Initially, during the Neolithic period, the intensity of agriculture was small due to small irregular fields and limited primitive ploughing (Beranová and Kubačák, 2010). Later, the intensity of agriculture increased. During the Middle Ages, a belt-shaped field mosaic was established. Very narrow, long (up to several hundred meters long) and down-slope oriented fields formed such a mosaic. Extremely intensive erosion took place after political changes in the 1950s, which implicated forced collectivization of agricultural land resulting in spatial enlargement of fields to the extent of several hundred hectares and the destruction of landscape elements with an anti-erosional effect. The volume of the erosion at that time increased rapidly and resulted in the final differentiation of the soil cover.

The upper plateau of the study plot is formed by ***Calcic Pachic*** **Chernozems** (***Aric, Siltic***). These soils represent undisturbed soils with no or very low impact of soil erosion. They are characterized by a deep humus horizon (for this reason, ***Pachic*** qualifier is used) with relatively high humus content, high base saturation, well-developed granular structure and signs of high biological activity (Table 1). Based on these properties, the horizon meets the ***Chernic*** criteria. The upper 30 cm of the *chernic* horizon is ploughed and for that reason the ***Aric*** qualifier is applied (as in all soils in the study area). Loess with enriched amount of secondary carbonates, partially leached from the chernic horizon, is present underneath the chernic horizon. Due to a large amount of secondary carbonates (Table 1) in the form of pseudomycelia, this material meets the criteria of the *calcic* horizon.

Moving downslope, the thickness of the *chernic* horizon decreases. This is due to the removal of the topsoil material as a result of soil erosion. The *chernic* horizon is limited by a depth of ploughing, which is evident from the abrupt transition between Ac and Ck horizons. Since the soils still have a very dark, humus-rich horizon, they are classified as ***Calcic*** **Chernozems** (***Aric, Siltic***).

Further down, where the slope is steeper, the original *chernic* horizon is washed out and the plough horizon is characterized by lower content of humus and high content of carbonates. The content of humus does not meet the criteria for the *chernic* horizon, but it is sufficient for the ***Mollic*** horizon (Table 7). Such soils are classified as ***Haplic*** **Kastanozems** (***Aric, Siltic***). The extremely eroded parts of the landscapes at convex steep slopes are covered with soil of light color and very low humus content that decreases below 0.6% of soil organic carbon and does not meet criteria for the *mollic* horizon. Due to the presence of a large amount of carbonates, these soils should be classified as ***Haplic*** **Calcisols** (***Aric, Siltic***).

At lower parts of the landscape, such as back slopes and toe slopes, the eroded material sedimented and formed thick layers of eroded topsoil. In case of extreme events, when gully erosion takes place, the loess material is admixed in significant amounts. These soils are generally called colluvial soils. The total depth of these colluvial soils reaches several meters (1–4 m) in the area. In WRB 2014, the soils are classified as ***Eutric Colluvic*** **Regosols** (***Bathyhumic, Panthosiltic***). Buried original **Chernozems** occur underneath these recent soils. In fact, the profile mirrors the stratigraphy and the sequence of soil properties of the parental soil. The highest humus content in the buried soil is observed in the Ab horizon; it decreases with the increasing depth toward the C material (Ckb). The recent colluvial layers (qualifier ***Colluvic***), covering the original soils and forming the new soil profile, record the highest humus content at the contact with the buried soil (Ah3). The oldest sediments, originated in the Neolithic period, were formed only by humus-rich eroded material from the topsoil of original **Chernozems**. With the progressive erosion, the redistributed material consisted of a mixture of eroded **Chernozem** topsoil and **Kastanozem** topsoil with lower humus content (Ah2). The most recently sedimented material (Ap and Ah1), corresponding to the last several decades, has the lowest humus content, because it originates from widely spread **Kastanozems** and **Calcisols**. Due to the fact that humus content changes with the depth, only the ***Bathyhumic*** qualifier can be used to indicate the relatively high humus content of the colluvial material and the criteria for ***Humic*** (SOC > 1.0%) are met below 100 cm (Table 10). The relationship between the sedimentation of soil horizons and the above-mentioned periods has been documented by the stratification of chemical properties. The Ah1 horizon has significantly higher content of chemicals (DDT) used in the 1950s and the 1970s so its origin can be assigned to that period. Similarly, the increased content of nutrients (P, K) throughout the Ap to Ah2 horizons corresponds to the use of mineral fertilizers (Table 12).

Soil sequence

The presented soil sequence is typical of the landscape degraded due to the long-term intensive agriculture influencing the region since the Neolithic times. The original landscape covered with **Chernozems** with varying thicknesses of chernic horizons has been greatly changed. The original **Chemnozems** are preserved only at flat plateaux; in other places, the erosion changed the soils to such an extent that they now belong to different classification units. This process, when mature and developed soils are transformed into soils at the initial stage of their development, is called a retrograde soil development. Two resulting soil units can be distinguished. On the one hand, soils with truncated soil profiles with decreased humus content (**Kastanozems** and **Calcisols**) occur at exposed sloping parts of the landscapes. On the other hand, soils formed by deep, recent soil sediments (***Colluvic* Regosols**) develop at concave slope locations (backslopes and toeslopes).

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Culti–sequence of village garden soils on the Great Hungarian Plain

Tibor József Novák, Tamás Mester, Dániel Balla, György Szabó

The study area comprises the Nagy-Sárrét microregion (620 km^2) in Eastern Hungary, which is a recent alluvial plain interspersed with alkaline lands and flood-free areas (Fig. 1). The characteristic landforms (natural levees, abandoned river beds) of the microregion have fluvio-aeolian origin (Dövényi 2010).

Fig. 1. Location

Lithology and topography

The average elevation of the Nagy-Sárrét is typically 84–100 m a.s.l. and the region can be classified as a flat plain, the mean relative relief is < 1.5 m·km^{-2}. Most of the surface is covered with fluvial silt and clay mixed with aeolian dust at higher elevated locations. The source of fluvial material is predominantly the catchment of the Berettyó river. In addition to the silt and sand layers, we can often find clay layers in the upper 10 m sequence, which leads to stagnic conditions in many places (Dövényi 2010). The groundwater level is close to the surface, with a typical seasonal variation in depth between 1 and 2 m; consequently, the soils frequently show the influence of shallow groundwater (Michéli et al. 2006). In the study area, the most common soils are Solonetzs, Vertisols, Kastenozems, and Chernozems, and in residential areas – accumulation of artefacts and human transported materials is observed as a result of soil sealing – Technosols and Anthrosols (Novák &Tóth 2016, Balla et al. 2017).

Land use

The microregion has been significantly altered by anthropogenic effects, starting from their cultivation in the Neolithic. Over the time, not only the cultivated areas have been expanded, but there has also been an increase in the intensification of cultivation. In 75% of the microregion area, predominantly wheat, corn and sunflower are cultivated, with an increase in rape in the recent years. The deeper areas, which are influenced by shallow groundwater or stagnic conditions because of the low permeability of soils, are typically used as pastures and meadows, accounting for 16% of the area. The objective of our study was to describe and classify the soils of intensively used gardens covering 3.6% of the microregion, located partially around settlements, partially interspersed between residential areas around houses and other buildings. Since the first agricultural settlement, the pattern of residential and garden areas has been repeatedly reorganized in space, recently the built-up areas constitute 4% of the microregion area (Dövényi 2010).

Climate

The microregion has moderately warm and dry climate. The annual average of sunshine duration is between 1960 and 2000 hours, the annual mean temperature is 10.2°C and the mean temperature of the growing season is 17.3°C. The mean temperature of the coldest and the warmest month is –1.6°C and 20.7°C. The total annual amount of precipitation is 530 mm, its distribution is uneven with frequent periods of draught. Of the annual amount, 310–320 mm falls during the growing season (Dövényi 2010).

Profile 1 – Luvic Calcic **Chernozem** (Aric, Epiloamic, Clayic, Pachic)

Localization: fluvial silt, infusion loess, inclination < 3° garden: annual crops, vegetables, 91 m a.s.l., **N** 47°17'29.3" **E** 21°15'01.1"

Morphology:

Ap – 0–20 cm, black (10YR 2/1), loam, fine granular structure, many fine roots, ploughed horizon, artefacts (fine brick fragments, <2%);

Ah – 20–35 cm, Very dark gray (10YR 2/1), clay loam, lenticular, strongly compacted structure, many fine roots, humus coatings;

2ABt – 35–55 cm, Very dark grayish brown (10YR 2/1), fine to medium size strong prismatic structure, clay, strong humus coatings;

2Btg – 55–70 cm, Very dark gray (2.5Y 3/1), clay, prismatic structure, moderately carbonates, very fine soft iron concentrations, clay accumulation;

2BCk – 70–110 cm, Very dark grayish brown (2.5Y 3/2), weak structure, clay, strongly carbonated, weak humus–clay coatings;

2BCk2 – 110–130 cm, Light olive brown (2.5Y 4/3), weak structure, clay, strongly carbonated, hard calcretes;

2Ck – 130–160 cm, Light olive brown (2.5Y 5/4) clay loam, strongly carbonated, very fine iron–manganese concentrations;

2C – 160– (180) cm, Light olive brown (2.5Y 5/4) clay loam, weakly carbonated;

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]			Textural class
		> 0.05	0.05–0.002	< 0.002	
Ap	0–20	29.1	34.6	26.3	L
Ah	20–35	27.2	34.5	38.3	CL
2ABt	35–55	22.8	32.5	44.7	C
2Btg	55–70	20.5	34.3	45.2	C
2BCk	70–110	20.6	34.2	45.2	C
2BCk2	110–130	20.1	38.8	41.1	C
2Ck	130–160	24.5	35.8	39.7	CL
2C	160–(180)	26.0	38.4	35.6	CL

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [$g \cdot kg^{-1}$]	EC_{SE} [dS/m]	pH [H_2O]	Exchangeable cations [$cmol(+) \cdot kg^{-1}$]		$CaCO_3$ [$g \cdot kg^{-1}$]
					Ca^+	Na^+	
Ap	0–20	17	0.97	6.94	6.94	<0.02	1
Ah	20–35	15	0.75	7.63	7.63	<0.02	6
2ABt	35–55	11	1.22	7.74	7.74	<0.02	1
2Btg	55–70	7	0.93	8.10	8.10	<0.02	11
2BCk	70–110	3	0.42	8.58	8.58	<0.02	174
2BCk2	110–130	2	0.39	8.76	8.76	<0.02	161
2Ck	130–160	2	0.39	8.75	8.75	0.1	117
2C	160–	2	0.42	8.74	8.74	0.34	85

Profile 2 – Hortic **Chernozem** (Protoclacic, Loamic, Pachic, Prototechnic)
Localization: fluvial silt, infusion loess, inclination < 3°, garden, orchard, 92 m a.s.l.,
N 47°28'74.4" **E** 21°23'89.9"

Morphology:

Ah1 – 0–40 cm, *hortic horizon, part of chernic horizon,* accumulation of organic matter, silt loam, very dark brown (10YR 2/2), slightly moist, medium moderate granular structure, very fine and common roots, animal pores <25%, gradual and smooth boundary; artefacts < 5%

Ah2 – 40–80 cm, *chernic horizon*, accumulation of organic matter, silt clay loam, brownish black (10YR 3/2), slightly moist, fine subangular blocky structure, fine and few roots, artefacts 2–5%, gradual and smooth boundary;

ABh – 80–100 cm, clay loam, black (10YR 2/1), slightly moist, subangular blocky structure, fine and common roots, artefacts 2–5%, gradual and smooth boundary;

B – 100–120 cm, silt loam, very dark gray (10 YR 3/1), subangular blocky structure, fine and few roots, artefacts < 2%;

BCk – 120–(140) cm, *protocalcic properties* grayish brown (10 YR 5/2), silt loam;

Table 3. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0–1.0	1.0–0.5	0.5–0.25	0.25–0.1	0.1–0.05	0.05–0.02	0.02–0.005	0.005–0.002	< 0.002	
Ah1	0–40	–	–	–	–	1	4	25	35	15	20	SL
Ah2	40–80	–	–	–	–	1	3	24	29	12	31	SiCL
ABh	80–100	–	–	–	–	2	3	25	28	12	30	SiCL
B	100– 120	–	–	–	–	1	4	24	30	14	27	SL
BCk	120–(140)	–	–	–	–	2	5	22	29	13	29	SL

Table 4. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	P_2O_5 [g·kg^{-1}]	NO_3^- [g·kg^{-1}]	EC_{SE} µS/cm	pH		$CaCO_3$ [g·kg^{-1}]
						H_2O	KCl	
Ah1	0–40	25	0.1825	0.0088	192	7.8	7.5	70
Ah2	40–80	18	0.0707	0.0087	138	8.0	7.5	56
ABh	80–100	13	0.0377	0.0062	2250	7.9	7.7	50
B	100– 120	9	0.0150	0.0085	1563	8.1	7.9	124
BCk	120–(140)	9	0.0149	0.0062	2820	8.3	8.0	182

Profile 3 – Hortic **Anthrosol** (Loamic, Protocalcic)

Localization: fluvial loess (uf), inclination < 3°, residential area, kitchen garden, 92 m a.s.l., **N** 47°28'19.5" **E** 21°23'94.2"

Morphology:

Ap1 – 0–20 cm, plough *mollic* horizon, *hortic* horizon, silt loam, very dark grayish brown (10YR 3/2), subangular blocky structure, animal pores >25%, artefacts (fine brick fragments, <2%), gradual and smooth boundary;

Ap2 – 20–55 cm, plough *mollic* horizon, *hortic* horizon, silt loam, black (10YR 2/1), subangular blocky structure, animal pores >25%, artefacts <2%, bones, gradual and irregular boundary;

Ah1 – 55–85 cm, silt loam, black (10YR 2/1), granular structure, common soft concretions and pseudomycelium of secondary carbonates, animal pores <25%;

Ah2 – 85–120 cm, black (10YR 2/1), granular structure, common soft concretions and pseudomycelium of secondary carbonates;

ACl – 120–150, grayish brown (10 YR 5/2), transitional horizon, silt loam, fine to medium subangular blocky structure, common soft concretions and pseudomycelium of secondary carbonates protocalcic properties;

Clk – 150–(160) cm, silt loam, grayish brown (10 YR 5/2), common secondary carbonates;

Table 5. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0–1.0	1.0–0.5	0.5–0.25	0.25–0.1	0.1–0.05	0.05–0.02	0.02–0.005	0.005–0.002	< 0.002	
Ap1	0–20	–	–	–	–	4	7	21	34	15	20	SL
Ap2	20–55	–	–	–	–	4	5	25	32	14	20	SL
Ah1	55–85	–	–	–	–	2	5	26	34	13	21	SL
Ah2	85– 120	–	–	–	–	4	5	20	32	13	26	SL
ABl	150–(160)	–	–	–	–	–	4	24	29	14	29	SL

Table 6. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	P_2O_5 [g·kg^{-1}]	NO_3^- [g·kg^{-1}]	EC_{SE} μS/cm	pH		$CaCO_3$ [g·kg^{-1}]
						H_2O	KCl	
Ap1	0–20	24	0.2163	0.0233	216	8.1	7.6	105
Ap2	20–55	23	0.1971	0.0194	249	8.0	7.5	89
Ah1	55–85	21	0.1671	0.0292	215	8.0	7.4	53
Ah2	85– 120	18	0.0713	0.1857	599	8.1	7.5	51
ABl	150–(160)	12	0.0328	0.1345	1105	8.2	7.8	128

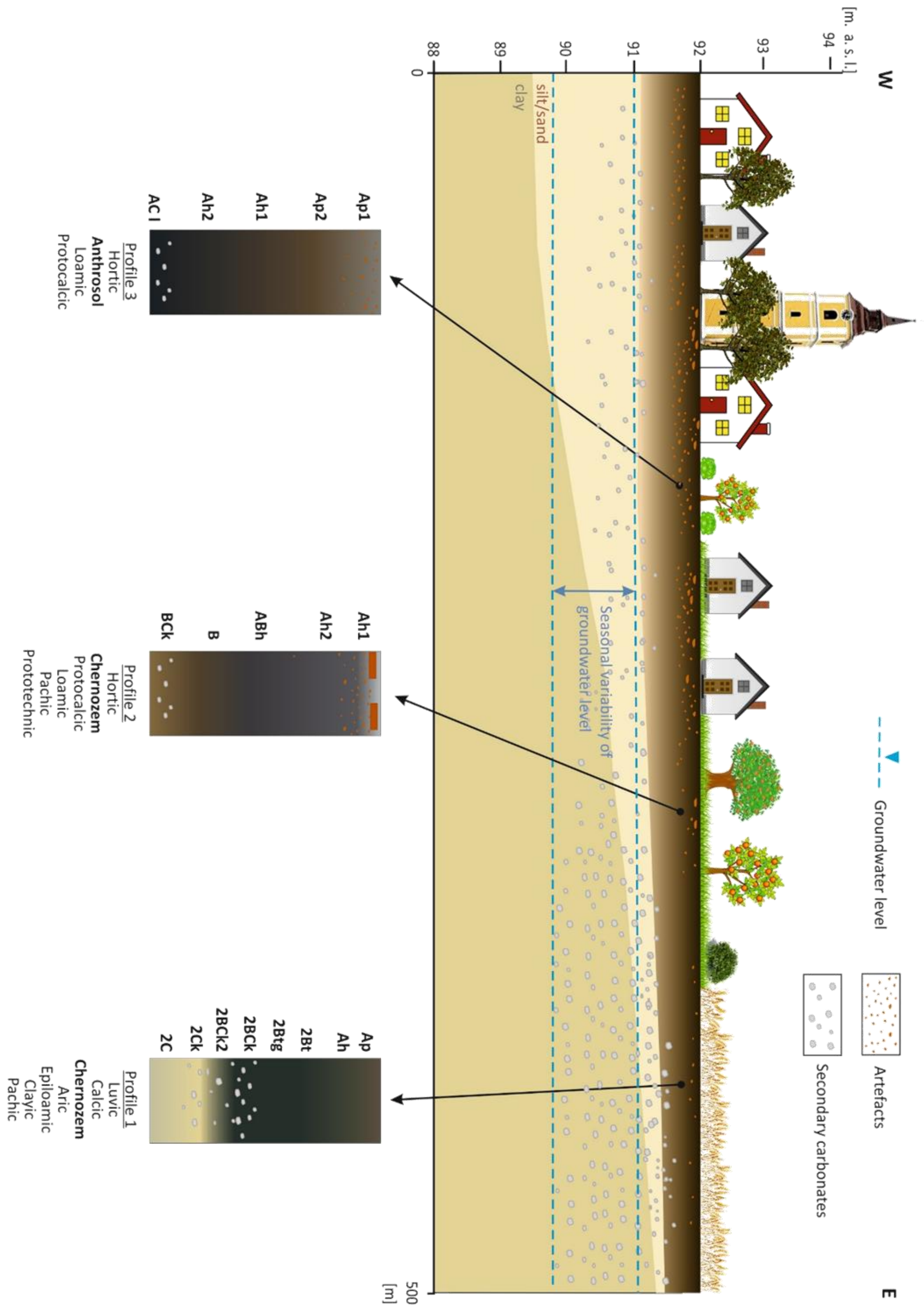

Fig. 2. Culti-sequence of village garden soils on the Great Hungarian Plain

Soil genesis and systematic position

Garden and urban soils are considered as young soils, they can develop ex situ and are often created by anthropogenic activity (Lehmann & Stahr 2007, Bulgariu et al. 2012). Garden soils are located close to inhabited areas and residential buildings, so they are exposed to strong and various anthropogenic effects (Dudal et al. 2002, Marcinek & Komisarek 2004, Hagan et al 2012). These effects are extremely mosaic and hence very large differences can occur over small areas (Greinert 2015, Charzyński et al. 2017). In this soil profile sequence, we classified soil profiles typical of rural areas on the Hungarian Great Plain, developed from natural soils during several thousand years of agricultural influence and constant human residence. The intensity and duration of anthropogenic soil transformation increases from the outskirts of villages toward the village center. Therefore, we called this sequence a culti-sequence, expressing the increasing grade of soil transformation by cultivation.

Profile 1 was classified into **Chernozem** (IUSS Working Group WRB, 2015), where the occurrence of the *calcic* horizon starting at a depth of 70 cm was highlighted by applying the ***Endocalcic*** qualifier. To express the presence of the *argic* Bt horizon, the ***Luvic*** qualifier was added to the RSG. The thickness of the A horizon was expressed by the ***Pachic*** qualifier. The place is used as an arable field, which is manifested in the ploughing character of the A horizon (***Aric***). From 35–130 cm, the texture class is clay; the ***Clayic*** qualifier was added to the RSG. The topsoil of the investigated soil profiles has developed on infusion loess with silt-rich loamy texture, therefore the ***Epiloamic*** qualifier is assigned to the profile. In each of the profiles, secondary carbonates can also be found in various amounts and at different depths (Fig. 2).

Profile 2 was classified as **Chernozem** (IUSS Working Group WRB, 2015), because the structure, the colour, the base saturation and the amount of organic carbon of the A horizon meet the criteria of the *chernic* horizon and there are *protocalcic properties* present in a soil layer starting ≤ 50 cm below the lower limit of this horizon (***Protocalcic*** suplementery qualifier). The significant thickness of the A horizon is expressed by the ***Pachic*** qualifier (≥50 cm). Because of the human influence (fertilization, application of wastes and other organic residues), the 0.5 M $NaHCO_3$ extractable P_2O_5 content in the upper 40 cm of the profile is ≥ 100 mg kg^{-1} (Table 4), therefore it is suitable to classify it as a *hortic* horizon. The presence of this horizon is the reason of adding the ***Hortic*** principal qualifier. The amount of artefacts was ≥ 5% in the upper 100 cm from the soil surface, which was expressed by adding the ***Prototechnic*** qualifier.

Profile 3 is located in the village center in a kitchen garden, impacted by anthropogenic effects to the point where it is observable at the level of Reference Soil Groups (**Anthrosol**) as it contains a *hortic* horizon >50 cm thick. The *Hortic* horizon has high content of organic matter and phosphorous, high animal activity in the form of mole burrows (≥ 25% of animal pores, coprolites), high base saturation (Table 6), resulting from long-term cultivation, fertilization and application of organic residues (*hortic* horizon). This horizon was diagnosed by adding the ***Hortic*** principal qualifier. Loess parent material occurs directly under the transitional ABl horizon. It contains primary and secondary carbonates in the form of soft concretions, which is expressed by using the ***Protocalcic*** qualifier.

Profile 1 was established east of Báránd, in an arable land where the recent land use has led to anthropogenic transformation of the topsoil manifested by a cultivated layer (***Aric*** supplementary qualifier). Profile 2 was established in a plum plantation within a settlement which is used as a garden and orchard since several hundred years. The increase of anthropogenic effects can be observed in the high density of artefacts (***Prototechnic*** supplementary qualifier) and the alteration of chemical parameters of the profile (***Hortic*** principal qualifier). In the case of three profiles, we could observe increasing anthropogenic influences from the outskirts toward the center of the settlement.

Human-made soils were often younger and shallower and contained many artefacts, higher content of coarse fraction, sand and $CaCO_3$ compared to other soils (Amossé et al. 2015). The performed laboratory test showed the transformation in the diagnostic soil properties, which were caused by anthropogenic activities. In the case of the described soil profiles the alteration of the carbonate profile could be explained by calcareous material present in Profile 3. In natural soils, with the appearance of the original soil horizons, carbonate content gradually increases toward the bedrock, or an accumulation level is formed under the influence of water (*calcic, protocalcic* horizons). This natural pattern of carbonates can be significantly modified due to anthropogenic effects, like soil improvement through calcification, mixing artefacts with the soil leading to an increase in $CaCO_3$ concentration in the cultivated layer of the topsoil. In the case of soil profile 3, it is characteristic that the $CaCO_3$ content artificially increased until the depth of cultivation, and increases again only in the deeper horizons, as a result of the influence of seasonally fluctuating groundwater rich in carbonates. The continuous cultivation (disturbance, ploughing, mixing of construction waste) of the upper layers in these garden soils leads to greater porosity, which causes increased decomposition of organic matter. The value of organic C is slightly above 2% in the case of the Ah1 horizon in Profile 2 and the Ap horizon in Profile 3, which is typical of cultivated soils. The nitrogen content of the heavily fertilized soils is typically above 60 mg/kg. In the case of values above 100 mg kg^{-1}, the possibility of wash-out significantly increases. Based on the N content in the soil profiles, it can be concluded that Profile 3, classified as **Anthrosol,** has been heavily fertilized for a longer period (Figure 5). The maximum of the N content in this soil profile (185.7 mg kg^{-1}) was measured in the Ah2 horizon, ranging from 85 to 120 cm, which indicates a significant degree of wash-out.

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Agricultural areas in the Zemgale Plain of Latvia

Aldis Karklins, Raimonds Kasparinskis, Maris Krievans

The study area comprises the southern part of the Central Latvian Lowland, which was formed during the Late Weichselian glaciation by the activation of the Zemgale Ice Lobe of the Riga Ice Stream. The Zemgale region in Latvia is located in the boreo-nemoral vegetation zone, where boreal coniferous forests are mixed with nemoral deciduous forests (Hytteborn *et al.*, 2005). The region contains a dense network of streams and rivers running into the Gulf of Riga via the Lielupe river (Zelčs, 1998). Although most of Zemgale is characterized by fertile soils that formed on granitic or metamorphic bedrock, the western part of the region includes some areas with calcareous and moderately calcareous bedrock (Zelčs, 1998).

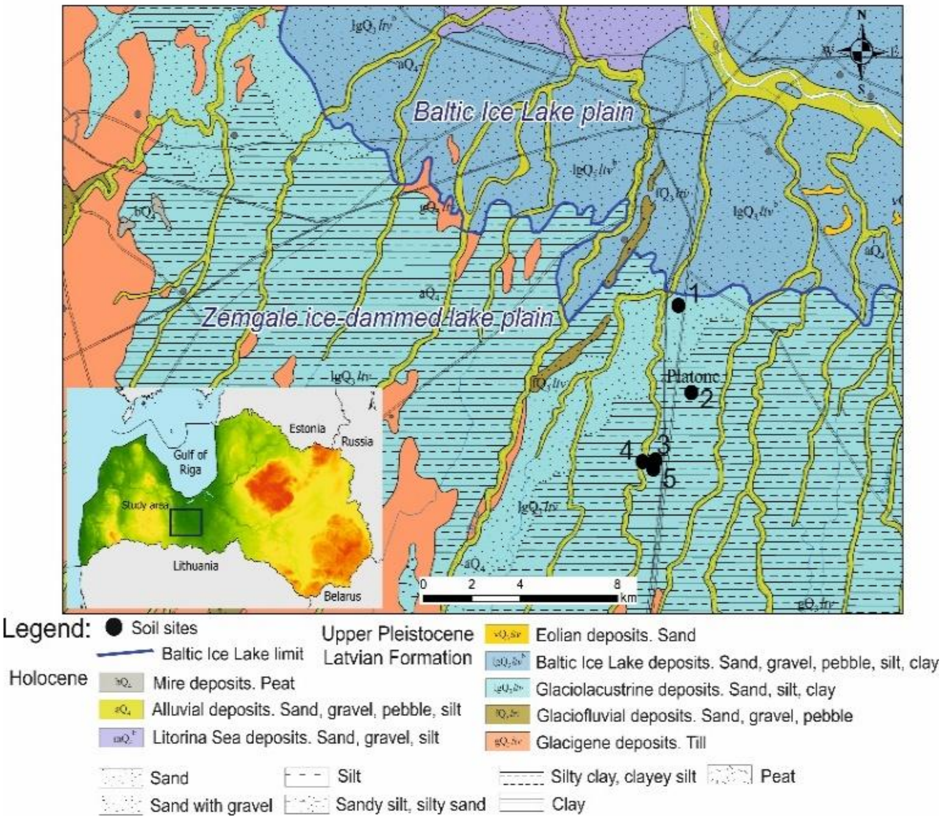


Fig. 1. Location

Lithology and topography

Soil profiles are situated in the northern part of the Zemgale Plain (further ZP) and on the edge of the Tīreļi Plain (further TP). The ZP and TP occupy the southern and central part of the Central Latvian Lowland. This glacial lowland is classified as a divergent-type lowland, because it widens in the direction of the Weichselian Scandinavian Ice Sheet movement (Zelčs, 1993; Zelčs and Markots, 2004). The glaciogenic landforms in the ZP and TP area were formed by the Zemgale Ice Lobe of the Riga Ice Stream during the oscillatory retreat of the Weichselian Scandinavian Ice Sheet in the Linkuva phase (termed after Meirons *et al.*, 1976). The above-mentioned glacial phase can be correlated to the Ottepaa/Sakala ice-marginal formation in Estonia and the North Lithuanian glacial phase in Lithuania (Zelčs *et al.*, 2011). The mean absolute age of the Linkuva glacial phase is 13 100 ±

300^{10}Be years (Rinterknecht *et al.*, 2006). The Zemgale Ice Lobe marginal position during that time is marked by the well-developed end-moraine chain in northern Lithuania (Karmaziene *et al.*, 2013) and partly in Latvia (Zelčs and Markots, 2004). Readvances of the Zemgale Ice Lobe in the ZP and TP during the Linkuva glacial phase created a subglacial bedform assemblage, consisting of drumlins (Lamsters and Zelčs, 2015).

The hypsometric position of the ZP relief surface ranges from 60–80 m a.s.l. to 10–15 m a.s.l. toward the north. The thickness of glacial sediments varies from 5 to 10 m, and exceeds 15–25 m only at the highest points of the glacial topography and buried valleys (Misāns *et al.*, 2001). The Pleistocene deposits are composed mainly of the Late Weichselian deformed till with interlayers of glacio-aquatic sediments (Straume, 1979). During the Linkuva phase, as glacial ice retreated further north, the western Latvia uplands and most of eastern Latvia became ice-free. Large ice-dammed lakes covering an area of some thousands km^2 developed in glacial lowlands. The largest part of the ZP glacial sediments is overlaid by the glaciolacustrine sediments of the Zemgale Ice-Dammed Lake. The glaciolacustrine sediments are represented by varved clays and other types of laminated and non-laminated sediments (Zelčs and Markots, 2004). The mean thickness of those sediments is 1–3 m. According to varve chronology, the Zemgale Ice-Dammed Lake existed for at least 46 years (Kuršs and Stinkule, 1966). There are no recent studies that would provide an accurate age interval of the ice-dammed lake. The thickness of the Zemgale Ice-Dammed Lake sediment reaches up to 5–8 m in its northern part, where it is covered by a thin Baltic Ice Lake sandy sediment layer (Misāns *et al.*, 2001).

In the study area, the hypsometric position of the TP relief varies from 6 to 13 m a.s.l. The thickness of glacial sediments is mainly less than 10 m. The TP glacial sediments are overlaid by the sandy glaciolacustrine sediments of the Baltic Ice Lake.

The topmost part of the pre-Quaternary sequence in the ZP and TP is composed of Upper Devonian (Famennian) sedimentary rocks: dolomite, marl, and clay (Straume, 1979). The bedrock represents a broad depression, the surface of which declines from 40–60 m a.s.l. in the southwestern part to 3–0 m b.s.l. in the northern part toward the Gulf of Riga (Misāns *et al.*, 2001).

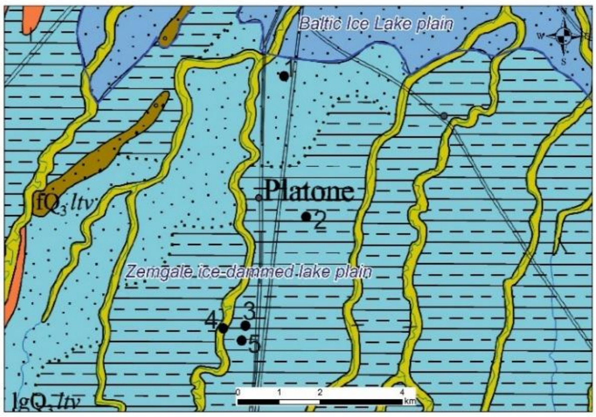


Fig. 2. Location of soil profiles.
(Quaternary surficial deposits: Q_3 – Upper Pleistocene; lg – glaciolacustrine deposits; Profile 1 – sand; Profiles 2–5 – silty clay / clayey silt.)

Land use

The natural vegetation of the Zemgale Plain is mixed broadleaf forests, which nowadays are extremely rare. At present, the dominant land-use type is agriculture with cropland as the main component.

The spatial pattern of land use in Zemgale can be explained by soils and parent material interacting with political, economic and social factors (Fescenko *et al.*, 2014). Due to intensive agricultural use of fertile soils (Penēze, 2009), the forest area in the Zemgale region makes currently only 31% of the total territory (State Forest Service, 2010).

Pollen analysis showed that about 1500 years before the intensive settlement in the Zemgale region, its fertile soils were covered with nemoral forests (Galeniece, 1959). Historical data show that despite the vast depletion of oak forests in north-eastern Latvia at the beginning of the 19th century (Von Löwis, 1824), Zemgale was still a region of oak and ash woodland until the early 20th century

(Oranovskij, 1862; Sivers, 1903). However, by the end of the 1930s, the nemoral tree species were replaced by coniferous and early successional species (Eiche, 1940).

In the past, the Zemgale region was dominated by pedunculate oak (*Quercus robur* L.), European ash (*Fraxinus excelsior* L.), and small-leaved lime (*Tilia cordata* Mill.) (Sivers, 1903). At present, however, the area of deciduous hardwood forests covers only 4% of the total area (State Forest Service, 2010), of which forest stands with the age over 100 years account for less than 0.25% (Ikauniece *et al.*, 2012a).

The forest area in the Zemgale region is now dominated by the boreal coniferous tree species: Scots pine (*Pinus silvestris* L.) and Norway spruce (*Picea abies* (L.) H. Karst.), and by the early successional tree species: silver birch (*Betula pendula* Roth.), downy birch (*B. pubescens* Ehrh.), common aspen (*Populus tremula* L.), grey alder (*Alnus incana* L. Moench), and black alder (*A. glutinosa* L. Gaertn.). Stands with the typical nemoral deciduous tree species: pedunculate oak (*Quercus robur* L.), common ash (*Fraxinus excelsior* L.), small-leaved lime (*Tilia cordata* Mill.), and Scots elm (*Ulmus glabra* Huds.) are relatively rare (Fescenko *et al.*, 2014).

The patterns of recent forest development differ among the soil trophic groups. Afforestation occurred mainly on wet and poor soils in the 19th and 20th century, while the proportion of woodland area on fertile soils typical of nemoral forests was fairly stable. Only 1% of the fertile soil area has been covered by continuous forests for more than 220 years, and only 11% of them are protected. Nemoral deciduous forests cover only 15% of their potential natural vegetation area of forested eutrophic soils (Fescenko *et al.*, 2014).

The south-central part of Zemgale is largely covered by eutrophic soils. Mesotrophic soils cover mostly a compact area in the western part of Zemgale, as well as smaller areas in the eastern and northern parts of the territory, alternating with patches of oligotrophic soils. The area of mesotrophic and oligotrophic soils is mostly covered with boreal coniferous and early successional tree species stands. The nemoral tree species woodland forms patches in the central, south-central and south-eastern parts of Zemgale (Fescenko *et al.*, 2014).

Changes in tree species distribution in relation to soils

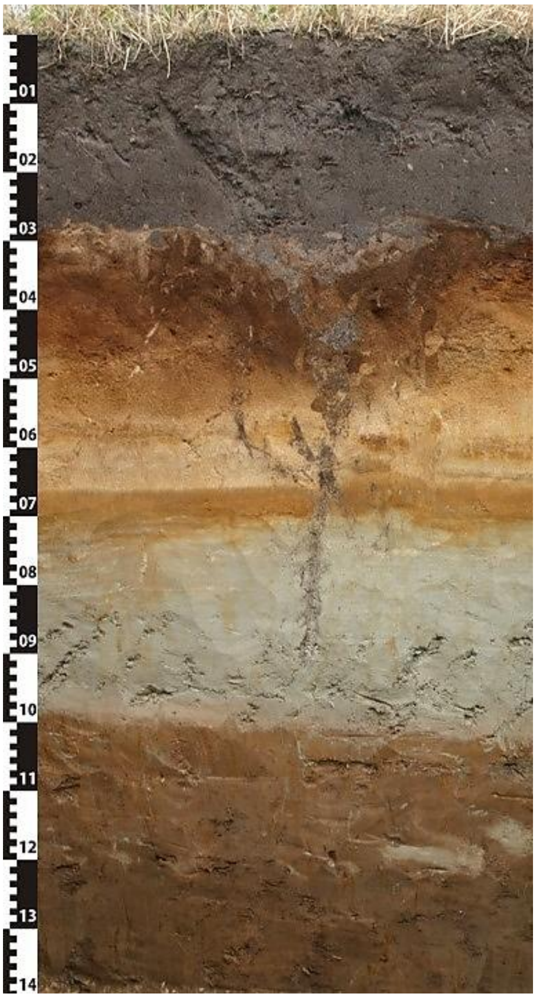
A total of 2.1% of the area of fertile eutrophic soils is covered with nemoral deciduous tree species. On forested eutrophic soils, the proportions of the area of nemoral, boreal and successional tree species are 15.0%, 24.6%, and 60.0%, respectively. Smaller relative areas of nemoral forest occur on less productive soils. As expected, the largest part of the eutrophic (86.2%) and mesotrophic (63.5%) soils is agricultural land. Early successional forests are most frequent (48% of all successional forests) on mesotrophic soils. Almost half (45.2%) of the area of poor and dry (oligotrophic) soils is covered with forests, the majority (61.5%) of which are boreal pine forests. Out of the total forest area, boreal coniferous and early successional forests (together 48%) strongly prevail; while nemoral deciduous forests cover only 4%, notwithstanding the fact that the area of fertile eutrophic and mesotrophic soils predominate in the landscape (39.7% and 36.1%, respectively) (Fescenko *et al.*, 2014).

Climate

Compared to the whole territory of Latvia, the Zemgale Plain is on average relatively warmer during the growing season and is distinguished by lower rainfall. The mean annual temperature is 5.0–5.2°C (1925–2006) (Lizuma *et al.*, 2007), and the mean annual precipitation is 670–700 mm (1925–2006) (Lizuma *et al.*, 2010). Snow cover is usually relatively thinner and, therefore, soil water resources in spring as well as water runoff are lower than the average in Latvia.

Profile 1 – Amphistagnic Endogleyic Entic **Podzol** (Abruptic, Arenic, Aric, Drainic, Endoeutric, Endoraptic, Bathycalcaric, Mollllic)

Localization: Glaciolacustrine plain – inclination 2°, arable field, 10 m a.s.l., **N** 56°34.014' **E** 23°42.558'



Morphology:

Ap – 0–32 cm, plough *mollic* horizon, medium sand, gray black (2.5Y 5/1, 2.5Y 2.5/1)[8], slightly moist, weak fine granular structure, common fine and medium roots, abrupt and smooth boundary;

Bhs – 32–49 cm, *spodic* horizon, medium sand, dark reddish brown (7.5YR 3/3, 5YR 3/4), moist, moderately cemented, medium fine granular structure, common medium rounded hard and soft sesquioxides concretions, few fine roots, gradual and wavy boundary;

Bs – 49–75 cm, medium sand, yellowish brown (10YR 8/6, 10YR 5/8), moist, weakly cemented, very weak fine subangular structure, very few fine roots, clear and wavy boundary;

Bg – 75–102 cm, silt loam, greenish gray (10GY 7/1, 5GY 6/1), wet, very weak and very fine granular structure, clear and smooth boundary;

2Bg – 102–137 cm, calcareous material, abrupt textural difference and lithic discontinuity, silty clay, brown (5YR 5/3, 7.5YR 4/3), wet, moderate medium and coarse prismatic structure, few clay coatings, very fine and very few roots, clear and smooth boundary;

2Btg – 137–(160) cm, *argic* horizon, calcareous material, silty clay, brown (7.5YR 5/4, 7.5YR 5/2), wet, moderate medium prismatic structure, many clay coatings.

[8] Hereafter – dry/moist.

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]									Textural class
		>2.0	2.0–1.0	1.0–0.5	0.5–0.25	0.25–0.10	0.10–0.05	0.05–0.02	0.02–0.002	<0.002	
Ap	0–32	0	0.5	3.5	24.3	49.8	9.0	7	5	1	MS
Bhs	32–49	0	0.6	3.3	24.8	59.4	5.0	3	1	3	MS
Bs	49–75	0	0.3	3.8	34.3	54.7	4.0	1	1	1	MS
Bg	75–102	0	0	0.3	0.8	3.0	24.0	49	16	1	SiL
2Bg	102–137	1.0	0	0.8	3.0	7.2	3.0	2	15	41	SiC
2Btg	137–(160)	1.0	0	0.8	3.0	7.2	3.0	2	15	41	SiC

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	pH		$CaCO_3$ [g·kg^{-1}]
			H_2O	KCl	
Ap	0–32	20.1	6.87	6.66	4.1
Bhs	32–49	13.7	6.60	6.52	1.3
Bs	49–75	1.7	5.96	5.60	0
Bg	75–102	0.6	7.44	6.26	1.8
2Bg	102–137	1.7	8.03	7.90	116.7
2Btg	137–(160)	3.0	7.87	7.67	163.1

Profile 2 – Epiabruptic Amphiprotostagnic Endostagnic Endoprotocalcic **Luvisol** (Aric, Amphiclayic, Cutanic, Hypereutric, Ochric)
Localization: Glaciolimnic plain, arable field, 10 m a.s.l.,
N 56°32.230' **E** 23°43.096'

Morphology:

Ap – 0–20 cm, plough horizon, silty clay loam, brown (7.5YR 6/3, 7.5YR 4/2), dry, coarse and very coarse, very strong granular structure, many very fine and fine roots, clear and wavy boundary;

AE – 20–35 cm, partly plough horizon, clay, brown (7.5YR 6/2, 7.5YR 5/3), dry, very coarse strong granular structure, many very fine and fine roots, clear and wavy boundary;

Btg1 – 35–58 cm, *argic* horizon, clay, olive brown (7.5YR 7/3, 2.5YR 4/4), dry, fine moderate subangular prismatic structure, pseudomycelium of secondary carbonates, protostagnic properties, many very fine and fine roots, clear and wavy boundary;

Btg2 – 58–92 cm, *argic* horizon, clay, olive brown (7.5YR 6/3, 2.5YR 4/4), dry, medium moderate prismatic structure, common fine soft and hard calcareous concretions, protocalcic and protostagnic properties, common very fine roots, clear and smooth boundary;

Bkg1 – 92–139 cm, silt loam, brown (7.5YR 7/3, 7.5YR 5/4), dry, coarse moderate prismatic structure, stagnic properties, very few very fine, soft manganese concretions, very few very fine roots, clear and smooth boundary;

Bkg2 – 139–(200) cm, silt loam, brown (7.5YR 7/4, 7.5YR 5/4), slightly moist, weak, coarse platy structure, stagnic properties, very few very fine soft manganese concretions;

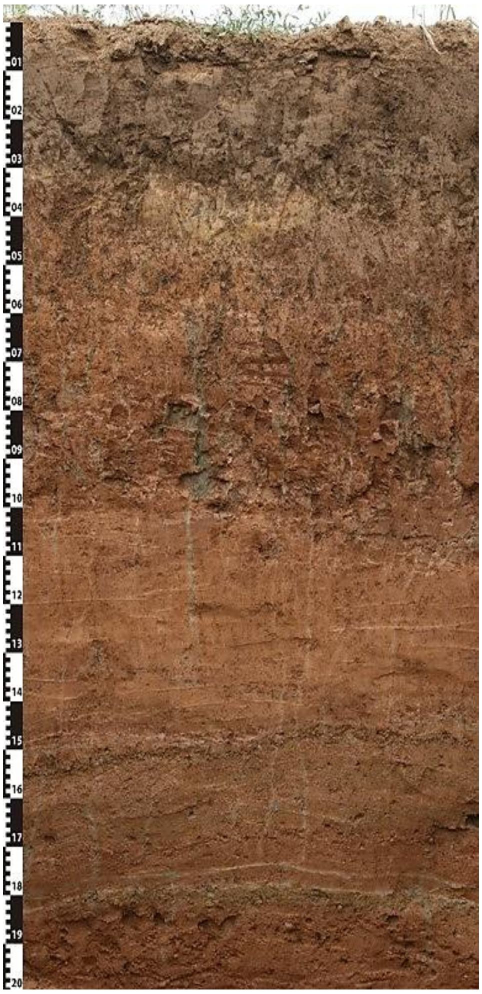
Table 3. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]									Textural class
		>2.0	2.0–1.0	1.0–0.5	0.5–0.25	0.25–0.125	0.125–0.063	0.063–0.02	0.02–0.002	<0.002	
Ap	0–20	1	0	0	1	1	7	30	29	32	SiCL
AE	20–35	0	0	0	0	1	6	14	26	52	C
Btg1	35–58	0	0	0	0	0	1	3	37	59	C
Btg2	58–92	1	0	0	1	0	0	3	29	67	C
Bkg1	92–139	0	0	0	1	2	2	5	65	26	SiL
Bkg2	139–(200)	0	0	0	0	0	0	10	65	24	SiL

Table 4. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	pH		$CaCO_3$ [g·kg^{-1}]
			H_2O	KCl	
Ap	0–20	8.9	8.11	7.38	31.6
AE	20–35	5.0	8.16	7.31	12.3
Btg1	35–58	2.3	8.45	7.47	153.2
Btg2	58–92	0.5	8.54	7.61	195.9
Bkg1	92–139	0	8.54	7.68	230.9
Bkg2	139–(200)	0	8.45	7.88	287.3

Profile 3 – Cambic **Calcisol** (Aric, Endohypocalcic, Ochric, Endoraptic, Episiltic, Protostagnic, Bathyluvic)
Localization: Glaciolimnic plain, arable field, 20 m a.s.l.,
N 56˚30.845' **E** 23˚41.664'



Morphology:

Ap – 0–42 cm, plough horizon, silty clay loam, grayish brown (10YR 6/3, 10YR 5/2), dry, strong fine subangular prismatic structure, common very fine and medium roots, abrupt and smooth boundary;

Bg1 – 42–62 cm, *cambic* horizon, silty clay, brown (7.5YR 7/3, 7.5YR 5/3), dry, medium strong subangular and angular blocky structure, few clay coatings, very few fine hard calcareous concretions, very fine and medium common roots, abrupt and smooth boundary;

Bg2 – 62–88 cm, silt loam, strong brown (10YR 7/4, 7.5YR 5/6), slightly moist, medium weak granular structure, few clay coatings, few fine hard and soft manganese concretions, common very fine and medium roots, clear and wavy boundary;

Bkg – 88–121 cm, *calcic* horizon, clay, reddish brown (7.5YR 6/4, 5YR 4/4), moist, strong fine subangular blocky structure, few clay coatings, many medium soft and hard calcareous concretions, pseudomycelium of secondary carbonates, very fine and very few roots, gradual and wavy boundary;

2Btg – 121–152 cm, *argic* horizon, silty clay loam, very few coarse fragments, reddish brown (7.5YR 8/5, 7.5YR 5/4), wet, weak fine subangular prismatic structure, very few clay coatings, layered, very few hard concretions of carbonates, very fine and very few roots, gradual and wavy boundary;

3Bkg1 – 152–181 cm, *calcaric* material, loam, many coarse gravel and stones, light yellowish brown (7.5YR 8/2, 10YR 6/4), wet, weak fine subangular blocky structure, layered, common soft concretions of secondary carbonates, gradual and wavy boundary;

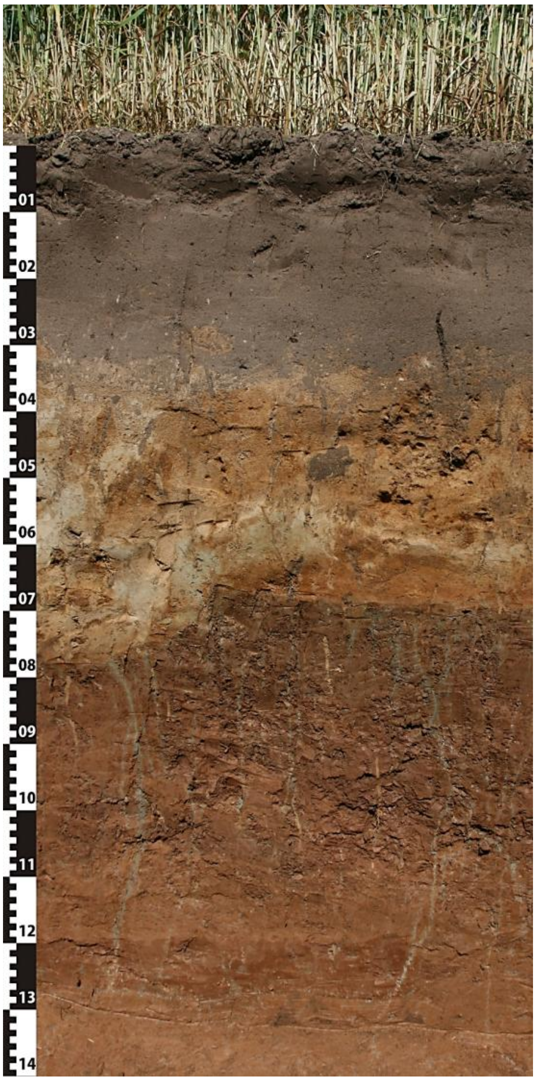
Table 5. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]									Textural class
		>2.0	2.0–1.0	1.0–0.5	0.5–0.25	0.25–0.125	0.125–0.063	0.063–0.02	0.02–0.002	<0.002	
Ap	0–42	1	0	1	1	1	6	27	31	32	SiCL
Bg1	42–62	0	0	0	0	1	1	9	45	44	SiC
Bg2	62–88	0	0	0	0	1	9	43	22	25	SiL
Bkg	88–121	3	0	0	0	0	0	9	27	63	C
2Btg	121–152	2	0	0	1	1	1	11	56	31	SiCL
3Bkg1	152–181	11	2	3	10	15	17	13	19	21	L
3Bkg2	181–187	9	1	4	14	16	15	14	19	17	L
3Ck	187–205	13	2	5	12	22	22	13	11	14	FSL
3Ck	205–(265)	9	2	4	11	20	21	13	13	17	FSL

Table 6. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	pH		$CaCO_3$ [g·kg^{-1}]
			H_2O	KCl	
Ap	0–42	10.6	7.54	7.00	4.6
Bg1	42–62	3.2	7.68	6.67	4.3
Bg2	62–88	2.4	8.02	7.07	11.6
Bkg	88–121	2.9	8.43	7.40	160.3
2Btg	121–152	2.3	8.45	7.71	273.9
3Bkg1	152–181	2.5	8.60	7.92	267.8
3Bkg2	181–187	1.0	8.67	8.02	249.8
3Ck	187–205	0.7	8.75	8.29	268.8
3Ck	205–(265)	0.6	8.74	8.24	301.0

Profile 4 – Hypereutric Endoluvic Endoalbic **Planosol** (Aric, Endoclayic, Drainic, Epiloamic, Endoraptic)
Localization: Glaciolimnic plain, arable field, 16 m a.s.l.,
N 56°30.811' **E** 23°41.139'



Morphology:

Ap – 0–34 cm, plough horizon, sandy loam, brown (7.5YR 5/2, 7.5YR 4/2), slightly moist, medium moderate granular structure, common very fine and fine roots, gradual and smooth boundary;

Eg/A – 34–51 cm, transitional horizon, loamy sand, light brown (7.5YR 6/3, 10YR 6/3), slightly moist, moderate fine granular structure, few very fine and fine roots, gradual and wavy boundary;

Eg/B – 51–59 cm, transitional horizon, sandy loam, light yellowish brown (10YR 7/3, 10YR 6/4), slightly moist, fine and medium weak granular structure, very few fine roots, gradual and smooth boundary;

Bg – 59–65 cm, fine sandy loam, strong brown (7.5YR 6/4, 7.5YR 5/6), moist, fine and medium weak granular structure, very few fine roots, gradual and smooth boundary;

2Btg1 – 65–111 cm, *argic* horizon, silty clay, dark reddish gray (5YR 6/4, 5YR 4/2), moist, fine and medium weak granular structure, very few fine roots, gradual and smooth boundary;

2Btg2 – 111–158 cm, *argic* horizon, silty clay, reddish brown (5YR 7/4, 5YR 5/3), moist, fine and medium weak granular structure, very few fine roots, gradual and smooth boundary;

2Bt – 158–(265) cm, *argic* horizon, silt loam, brown (5YR 7/3, 7.5YR 5/4), moist, fine and medium weak granular structure, very few fine roots;

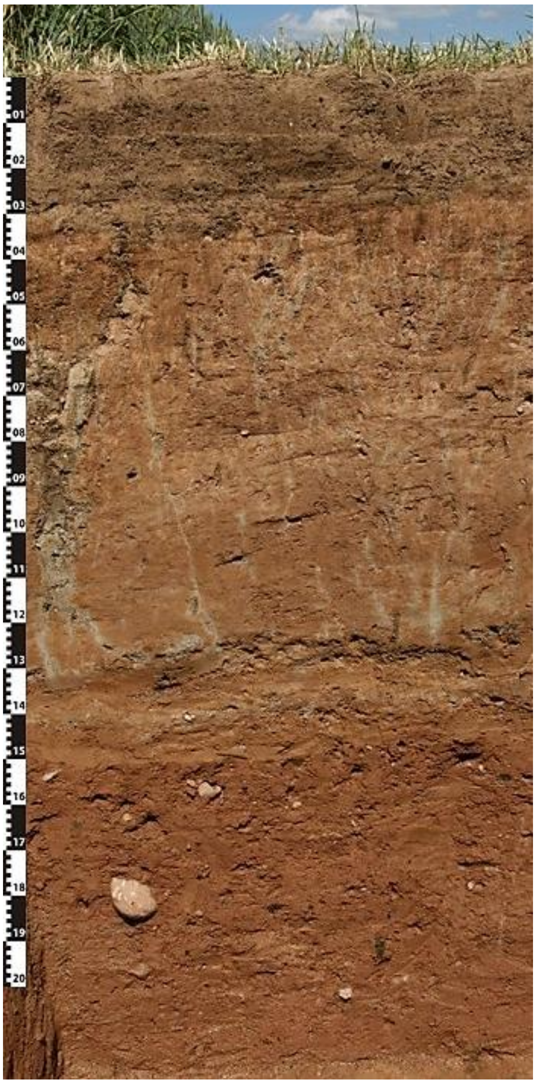
Table 7. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]									Textural class
		>2.0	2.0–1.0	1.0–0.5	0.5–0.25	0.25–0.125	0.125–0.063	0.063–0.02	0.02–0.002	<0.002	
Ap	0–34	0	0	2	20	34	19	8	9	8	SL
Eg/A	34–51	0	1	3	28	36	16	6	5	5	LS
Eg/B	51–59	0	1	9	14	20	23	21	5	7	SL
Bg	59–65	0	0	2	16	28	21	21	9	2	FSL
2Btg1	65–111	0	0	0	1	2	1	8	37	50	SiC
2Btg2	111–158	0	0	0	0	1	1	5	51	43	SiC
2Bt	158–(265)	9	0	0	1	2	2	17	57	21	SiL

Table 8. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	pH		$CaCO_3$ [g·kg^{-1}]
			H_2O	KCl	
Ap	0–34	11.2	6.81	6.33	3.3
Eg/A	34–51	3.1	7.17	6.50	4.5
Eg/B	51–59	2.2	7.10	6.47	2.4
Bg	59–65	2.0	7.38	6.39	2.8
2Btg1	65–111	2.8	7.94	7.16	91.4
2Btg2	111–158	2.2	8.20	7.40	226.6
2Bt	158–(265)	2.1	8.29	7.63	279.2

Profile 5 – Cambic **Calcisol** (Aric, Ochric, Anosiltic, Katoprotostagnic, Bathyluvic)
Localization: Glaciolimnic plain, arable field, 20 m a.s.l.,
N 56°30.658' **E** 23°41.580'



Morphology:

Ap – 0–33 cm, plough horizon, silt loam, brown (10YR 7/3, 10YR 4/3), slightly moist, medium moderate granular structure, common very fine roots, clear and smooth boundary;

Bwk – 33–46 cm, *calcic* horizon, silt loam, brown (10YR 8/3, 7.5YR 5/3), dry, medium moderate granular structure, few fine roots, gradual and smooth boundary;

Bkg1 – 46–77 cm, *calcic* horizon, silt loam, light brown (10YR 8/2, 7.5YR 6/3), slightly moist, medium weak granular structure, very few fine and medium roots, gradual and smooth boundary;

Bkg2 – 77–116 cm, *calcic* horizon, loam, brown (10YR 8/2, 7.5YR 5/3), slightly moist, medium weak granular structure, very few fine roots, diffuse and smooth boundary;

2Bk – 116–124 cm, *calcic* horizon, medium sand, brown (10YR 8/3, 7.5YR 5/4), slightly moist, medium weak granular structure, very few fine roots, illuvial lamellae, gradual and smooth boundary;

3Bkg – 124–138 cm, *calcic* horizon, loam, brown (10YR 8/2, 7.5YR 5/3), moist, medium moderate granular structure, very few coarse and fine roots;

3Ck1 – 138–151 cm, calcareous parent material, loamy sand, light yellowish brown (7.5YR 8/3, 10YR 6/4), slightly moist, medium weak granular structure, very few fine and medium roots, gradual and smooth boundary;

3Ck2 – 151–(235) cm, calcareous parent material, fine sandy loam, brown (7.5YR 7/3, 7.5YR 5/4), slightly moist, medium weak granular structure, very few fine and medium roots;

Table 9. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]									Textural class
		>2.0	2.0–1.0	1.0–0.5	0.5–0.25	0.25–0.125	0.125–0.063	0.063–0.02	0.02–0.002	<0.002	
Ap	0–33	1	0	1	2	5	7	26	38	20	SiL
Bw	33–46	1	0	0	2	7	11	20	39	22	SiL
Bkg1	46–77	1	0	0	3	10	12	15	36	24	SiL
Bkg2	77–116	0	0	0	3	12	16	13	29	26	L
2Bk	116–124	18	2	6	25	34	21	5	3	4	MS
3Bkg	124–138	3	0	1	5	16	23	14	29	11	L
3Ck1	138–151	9	1	3	10	37	36	3	4	7	LS
3Ck2	151–(235)	7	1	4	11	20	26	9	12	18	FSL

Table 10. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	pH		$CaCO_3$ [g·kg^{-1}]
			H_2O	KCl	
Ap	0–33	9.8	7.98	7.33	20.4
Bw	33–46	6.4	8.40	7.60	313.5
Bkg1	46–77	0.7	8.59	7.79	364.2
Bkg2	77–116	0	8.54	7.82	363.9
2Bk	116–124	0	8.75	8.49	164.7
3Bkg	124–138	0	8.63	7.93	323.4
3Ck1	138–151	0	8.78	8.59	203.2
3Ck2	151–(235)	0	8.69	8.11	290.7

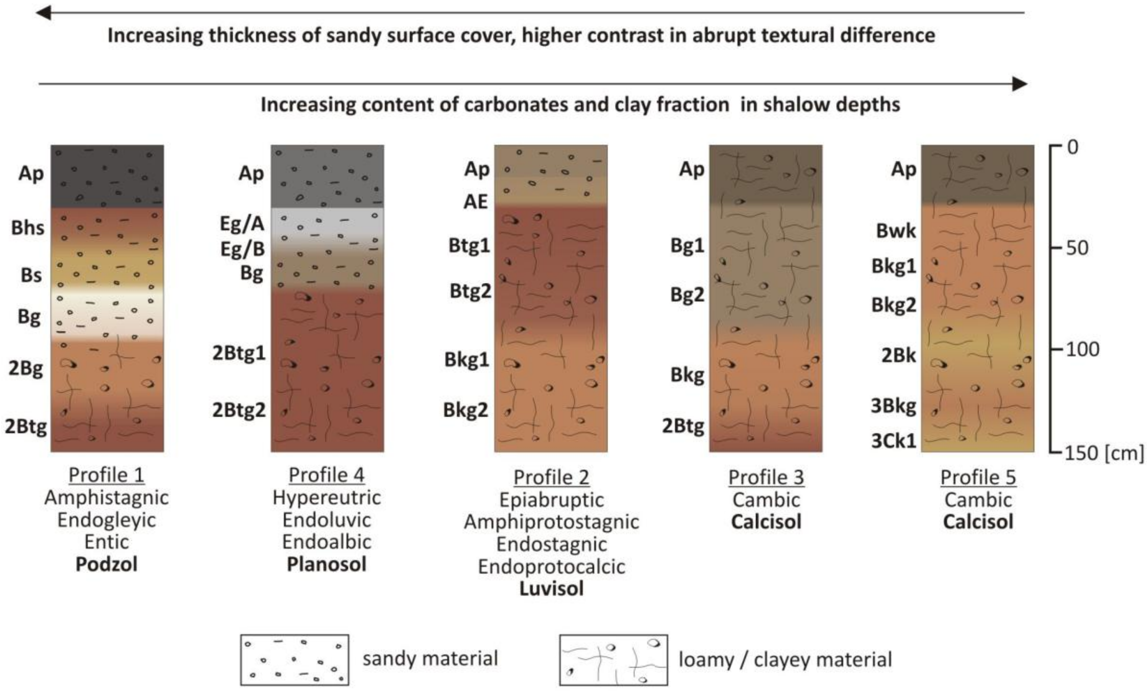


Fig. 3. Lithosequence of soils developed from glaciolacustrine deposits

Soil genesis and systematic position

The investigated soil profiles exhibit a diversity of soil cover within the Zemgale Plain south to the Jelgava town. Profile No. 1 is located at the edge of the Baltic Ice Lake sand deposits having sharp boundary from the Baltic Ice Lake Plain in the north and the Zemgale Ice-Dammed Plain in the south (Figs 1 and 2). It represents the soil developed from glaciolacustrine deposits with distinct change of soil texture due to the lithic discontinuity (***Abruptic*** and ***Endoraptic*** supplementary qualifiers) (Table 1). The represented area is characterized by a great diversity of soil types depending on the thickness of the sandy material above the loamy one. In some places where the loamy and calcareous materials are closer to the land surface and acidification has had a significant impact on soil profile development, **Planosols**, **Phaeozems** or **Luvisols** may occur. The characteristic feature of the soils in the Zemgale Plain is stagnation of surface waters if the soils are not artificially drained.

Local development of **Podzols** from the sandy material overlaying heavier textured silty loams and clays is a characteristic feature under natural forest vegetation and also after afforestation of agricultural land. The represented soil profile (No. 1) located at about 50 m from the current forest area is like a marginal classification category and does not represent very typical features of **Podzols**, because some initial soil properties (e.g., soil pH in topsoil) are changed due to agricultural activities as well as lack of a bleached E horizon in the soil. Still, some weakly cemented soil layers and ortstein grains are presented in the subsoil, as well as uncoated sand grains – in the topsoil, which are characteristic features of Podzols.

The discussed soil profile contains three diagnostic horizons: *mollic* (0–32 cm), *spodic* (32–49 cm), and *argic* (below 137 cm). Only the *spodic* diagnostic horizon is important for the classification, classifying the soil to the **Podzol** WRB Reference group (IUSS Working Group WRB, 2015). The *mollic* horizon is not a typical feature in such a situation and is feasible only in the case when soil is altered by cultivation. Therefore, respective qualifiers are not foreseen in the classification key. The *argic* diagnostic horizon is located too deep to make any influence on the soil name, and also the presence of *spodic* is used as priority. The main qualifier characterizing this particular soil is ***Entic*** – showing that the *spodic* horizon is loose and does not have a layer with *albic* material. Therefore, it is young, weakly developed **Podzol**, and the process of podsolization is not very pronounced because of the heavy textured and calcareous subsoil. The ***Amphistagnic*** qualifier indicates that soil is water-saturated for some time of a year in the layer above and below 50 cm but not deeper than 100 cm from the soil surface. This is, of course, a limitation for agricultural activities if the soil is not drained.

Profile No. 2 is located already inside the former Zemgale Ice-Dammed Lake and has developed from glaciolacustrine sediments rich in calcareous silt-size particles (Tables 3–4). Glacigenic deposits (till) start below 300 cm from the soil surface. The soil has a well-expressed *argic* diagnostic horizon (35–92 cm) as well as pseudomycelium and soft calcareous concretions of secondary carbonates. *Protocalcic* properties could be identified within the 58–92 cm soil layer. This classifies the soil to ***Endoprotocalcic*** **Luvisol** as a WRB soil name. Additionally, the soil has an abrupt textural difference from 20 cm and *stagnic* properties. From 35 to 92 cm, stagnation of the surface water has made morphological features weaker, therefore the ***Amphiprotostagnic*** qualifier was applied; whereas from 92 cm, the morphological features are made stronger, which allows using the ***Endostagnic*** qualifier. In this particular location, the presence of secondary carbonates can be argued. Their distribution can differ within a rather short distance, and in places where secondary carbonate accumulation is more distinct, the *calcic* horizon will be identified. In such a situation, the soil will be classified as **Calcisol** instead of **Luvisol**. The number of supplementary qualifiers suggests that soil is cultivated deeper than 20 cm (***Aric***); it is heavy textured between 20–92 cm (***Amphiclayic***), the presence of clay coatings (***Cutanic***) and a high base saturation (***Hypereutric***) is found, as well as the soil color for topsoil is not dark enough to classify it as a *mollic* horizon (***Ochric*** qualifier).

Next profile (No. 3) is located more to the south. It is also developed from glaciolacustrine sediments rich in calcareous silt-size particles (Tables 5–6), but glacigenic deposits (till) start already from 152 cm. The soil profile has distinct layering. On the top (0–100 cm), there are glaciolacustrine deposits, followed by glaciofluvial ones (100–150 cm), which end with thin (about 1–2 cm) lamellae composed of a material rich in fine and medium grade (less than 10 mm in diameter) gravel. Similar lamellae occur again at a depth of 187 cm in the layer of till. The soil has the *cambic* diagnostic horizon (42–62 cm), the *calcic* diagnostic horizon (88–121 cm), and the *argic* horizon (121–152 cm). Protostagnic properties start from 42 cm, but an abrupt textural difference starts from 88 cm. The presence of the *calcic* horizon leads to the **Calcisol** reference soil group with the principal qualifier – ***Cambic***. As the *argic* diagnostic horizon is deeper than 100 cm, the ***Luvic*** qualifier can be used only with the prefix ***Baty***- and placed at the very end of the soil name. In the list of supplementary qualifiers, ***Endohypocalcaric*** means that the *calcaric* horizon is rather weakly expressed, contains less than 250 g kg^{-1} of calcium carbonate equivalent (Table 6), and starts deeper than 50 cm from the mineral soil surface.

Profile No. 4 is located closer to a small stream – the Platone river; however, still at the same elevation as Profiles No. 3 and No. 5. Glacigenic deposits (till) start deeper, at a depth of 265 cm. *Lithic discontinuity* was identified also at a depth of 65 cm, where sandy material was changed by silty clay. At this particular depth, an abrupt textural difference was also observed by a sharp increase in clay content – from 2% to 50% (Table 7). This leads to the formation of *stagnic* properties and seasonal reducing conditions in the layer above that line. Additionally, the soil has discontinuous *albic* materials (51–59 cm) and the *argic* diagnostic horizon (from 65 cm downwards). Clay cutans were observed even at a depth of 265 cm. *Calcaric* materials start from a depth of 65 cm with a gradual increase in calcium carbonate equivalent (Table 8). The well-expressed abrupt textural difference (at a depth of 65 cm) with *stagnic* properties and reducing conditions for some time during the years classifies this soil to the **Planosol** reference group. In the case when the abrupt textural difference is not so pronounced and *stagnic* properties on the border of these two soil layers are very distinct, the soil will be classified as **Luvisol**. Three principal qualifiers are possible to be used for **Planosol**: ***Endoalbic*** – due to *albic* materials, and ***Luvic*** – due to *argic* horizon, both below 51 cm from the soil surface. The ***Hypereutric*** qualifier shows a high base saturation – more than 50% throughout the soil profile and more than 80% in some parts of the soil profile, e.g., from 65 to 100 cm. Supplementary qualifiers show human influence (***Aric*** and ***Drainic***) as well as soil texture pattern (***Epilomic*** and ***Endoclayic***) and lithic discontinuity (***Endoraptic***) in different soil layers.

Profile No. 5 is represented by two diagnostic horizons: *cambic* (from 33 to 116 cm) and *calcic* (from 33 to 138 cm). *Lithic* discontinuity was identified at a depth of 116 cm, where glaciolacustrine deposits were changed to glacigenic deposits (till). Protostagnic properties were evident from 46 to 151 cm ***(Katoprotostagnic*** qualifier), and secondary carbonates – from 33 to 138 cm. High silt content is up to 77 cm from the soil surface (Table 9), which justifies the use of the ***Anosiltic*** qualifier. A characteristic feature of a particular soil profile is the distribution of carbonates within the soil layers (Table 10). From 33 to 138 cm, the content of carbonates is higher compared to the soil parent material. This shows accumulation of secondary carbonates in the upper soil layer formed from the upward soil solution movement. Similarly to Profile No. 3, this soil is classified as ***Cambic*** **Calcisol** with the ***Bathyluvic*** supplementary qualifier, because clay illuviation was observed below the 100 cm depth. This particular soil has a surface horizon with properties (colors) very close to be *mollic*. If so, the soil will be keyed in as **Phaeozem**, which could be a case when the accumulation of organic matter is slightly higher, e.g., in small depressions or as a result of cultivation.

Soil sequence

The above-described transect shows significant differences in the soil cover due to the distribution of glaciolacustrine deposits in the former basin of the Zemgale Ice-Dammed Lake. The distance from Profile No. 1 (farthermost north) to Profile No. 5 (farthermost south) is only 6.4 km by airline. Glaciolacustrine deposits covering glacigenic deposits (till) are very variable. For Profile No. 2, located already inside the former Zemgale Ice-Dammed Lake, glaciogenic deposits were found at a depth of 300 cm from the soil surface. For Profile No. 5, located only 3.2 km from Profile No. 2 toward the south, glaciogenic deposits were found at a depth of 116 cm.

Profile No. 1 represents the peculiarities of soils formed from the Baltic Ice Lake sand deposits covering heavier-textured glaciolacustrine deposits. In both situations, outside or inside the former Zemgale Ice-Dammed Lake, the thickness and properties of the superficial glaciolacustrine deposits are variable. For example, comparison of the description and data of Profile No. 4 and Profiles No. 3 and No. 5 located only 400 m from one another shows significant differences in topsoil properties. The redistribution of glaciolacustrine deposits was not homogeneous – more sandy material or more silty/clayey material may cover the glaciogenic deposits; therefore, a variety of soils is feasible in this particular area.

Taking into consideration the WRB classification rules, **Planosols** will come first if *stagnic* properties and reducing conditions will be observed at the border of an abrupt textural difference, which is very possible if the textural difference is more pronounced.

The next Reference soil group, very relevant to this situation, is **Phaeozems**, especially in places where due to the soil management or under natural grasslands, the soil organic carbon content is higher and provides respective colors for the identification of the *mollic* diagnostic horizon.

Soils are rich in carbonates and clayey deposits reduce the leaching, therefore the accumulation of secondary carbonates may reach the amount necessary for the identification of the *calcic* diagnostic horizon. In such a case, **Calcisols** will be identified.

The next possibility if the previous ones were not met, is **Luvisols**, having the *argic* horizon starting within 100 cm from the soil surface. Clay illuviation is a widespread feature for these soils. If the *argic* horizon is lacking, the last choice is the **Cambisols** Reference soil group.

The depth of the water table inside the research area is deep during the growing season – from 230 to 265 cm from the soil surface. Usually, the heavy textured material has abundant cracks providing a relatively good internal drainage. Therefore, the development of **Stagnosols** has low probability but not excluded.

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Soils of slope niches in the Toruń–Eberswalde ice–marginal valley

Marcin Świtoniak, Piotr Hulisz, Tomasz Jaworski, Damian Pietrzak, Sylwia Pindral

The study area comprises the northern slopes of the Toruń-Eberswalde ice-marginal valley, which was formed during the youngest Pomeranian phase of the Weichselian glaciation (16–17 kyr BP; Fig.1; Roszko, 1968; Marks, 2012). It represents young glacial landscape, specific to this region. According to Kondracki (2002), the studied soil sequence is located in two mesoregions: Toruń Basin and Kraina Morainic Plateau, near the town of Nakło on the Noteć River.

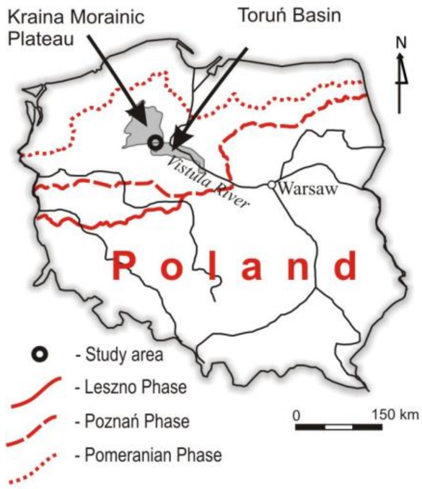


Fig. 1. Location

Lithology and topography

The Toruń-Eberswalde ice-marginal valley near Nakło is a vast form of 3 to 8 km width and E-W orientation, clearly cut in the morainic plateau. The valley drained water from proglacial streams of Pomeranian outwashes and extraglacial areas from the south (Galon, 1961; Roszko, 1968; Weckwerth, 2010). Nowadays, the bottom of the valley is fed by waters of the Noteć river. The thickness of the bottom, organic (peat and gyttja) and mineral (deluvial sands) sediments reaches an average of 5-7 m.

In the north, the valley borders on the Kraina Morainic Plateau (90–105 m a.s.l.). This plain is built of glacial tills which are locally covered with sands and gravels. It is situated several dozen meters above the bottom of the valley (62–65 m a.s.l.). The edge of the valley is characterized by high (35–40 m) and steep slopes reaching 30–35°. Those features were conducive to the development of numerous denuded forms (both flat and concave) as a result of sheet erosion and congeliflucton (Churska, 1965; Jahn, 1975). The slope niches, known solely from the contemporaneous periglacial areas (French, 2007), show specific shapes: they are short, deep, with wide flat floors. These forms are steep-sided, both at their rear face and their sides. Most frequently, the niches start directly from the flat plateau surface.

Land use

The vegetation of the northern slopes of the Toruń-Eberswalde ice-marginal valley is very unique in Poland. There is the Skarpy Ślesińskie nature reserve (13.2 ha) established to protect the xerothermic grassland with species such as *Stipa joannis* Čelak., *Adonis vernalis*, *Skorzonera purpura*, *Pulsatilla pretensis*, *Aster amellus* and *Anemone silvestris* (Marcysiak, 2004). The morainic plateau is occupied by arable land, while the bottom of the valley is dominated by meadows, pastures and wasteland.

Climate

The study area belongs to the Eastern Great Poland (*Wielkopolska*) region (Woś, 2010). According to Kottek et al. (2006), the region is located in the fully humid zone with temperate and warm summer. The average annual temperature is 8°C. The average temperature of the coldest month (January) is –3.5°C, while the warmest month is July (17.5°C. The average annual precipitation is one of the lowest in Poland – 520 mm. The February is the driest month (26 mm), while the highest precipitation is recorded in July (80 mm) (Woś, 2010).

Profile 1 – Endocalcaric **Luvisol** (Aric, Cutanic, Epieutric, Loamic, Ochric)
Localization: Undulating morainic plateau, summit – inclination 3°, arable field, 95 m a.s.l.,
N 53°09'20.6" **E** 17°39'42.9"

Morphology:

Ap – 0–20 cm, plough humus horizon, sandy loam, dark yellowish brown (10YR 4/4, 10YR 3/4), slightly moist, medium moderate granular structure, very fine and few roots, abrupt and smooth boundary;

Ap2 – 20–32 cm, plough humus horizon, sandy loam, dark yellowish brown (10YR 4/6, 10YR 3/6), slightly moist, medium moderate granular structure, fine and few roots, abrupt and smooth boundary;

Bt – 32–45 cm, *argic* horizon, loam, brown (7.5YR 5/6, 7.5YR 4/4), slightly moist, coarse strong angular structure, many clay coatings, fine and very few roots, clear and wavy boundary;

Ck – 45–(70) cm, *calcaric* parent material, sandy loam, dark yellowish brown (2.5 Y 5/4, 2.5 Y 4/4), dry, massive structure, common soft concretions of secondary carbonates;

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0–1.0	1.0–0.5	0.5–0.25	0.25–0.1	0.1–0.05	0.05–0.02	0.02–0.005	0.005–0.002	< 0.002	
Ap	0–20	2	4	6	6	25	17	10	8	9	15	SL
Ap2	20–32	3	5	4	7	24	20	9	8	9	14	SL
Bt	32–45	2	1	4	8	22	14	8	6	14	23	L
Ck	45–(70)	2	3	3	8	27	17	9	7	11	15	SL

Table 2. Chemical and physicochemical properties

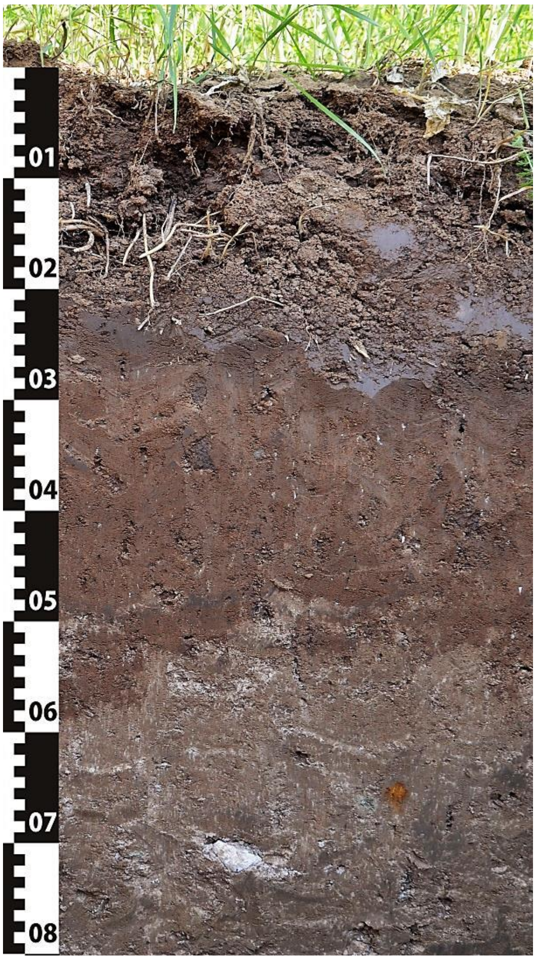
Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Ap	0–20	7.4	0.68	11	6.7	5.4	3
Ap2	20–32	6.9	0.52	13	6.9	6.0	2
Bt	32–45	–	–	–	6.8	6.1	2
Ck	45–(70)	–	–	–	7.3	6.8	67

Table 3. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	HA	CEC	CEC_{clay}	BS
		[cmol(+)·kg^{-1}]								[%]
Ap	0–20	5.48	0.06	0.12	0.05	5.70	3.77	9.48	45.9	60
Ap2	20–32	3.23	0.06	0.09	0.05	3.44	3.21	6.65	30.2	52
Bt	32–45	6.28	0.42	0.27	0.10	7.07	1.50	8.57	37.2	82
Ck	45–(70)	22.4	0.98	0.35	0.11	23.8	0.0	23.8	159	100

Profile 2 – Calcic **Kastanozem** (Aric, Loamic, Pachic)

Localization: Undulating morainic plateau, upper slope – inclination 15°, grass vegetation on edge of arable field, 94 m a.s.l., **N** 53°09'19.5" **E** 17°39'41.4"



Morphology:

Ap – 0–30 cm, plough *mollic* horizon, sandy clay loam, very dark grayish brown (10YR 4/3, 10YR 3/2), slightly moist, fine moderate subangular structure, very fine and fine common roots, abrupt and smooth boundary;

Ap2 – 30–50 cm, plough *mollic* horizon, sandy clay loam, dark brown (10YR 5/4, 10YR 3/3), slightly moist, medium strong subangular structure, fine and few roots, abrupt and irregular boundary;

Ck – 50–(90) cm, *calcic* horizon, sandy loam, yellowish brown (10YR 7/3, 10YR 5/4), slightly moist, medium weak angular structure, common soft concretions and pseudomycelium of secondary carbonates;

Table 4. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0–1.0	1.0–0.5	0.5–0.25	0.25–0.1	0.1–0.05	0.05–0.02	0.02–0.005	0.005–0.002	< 0.002	
Ap	0–30	0	0	4	9	28	15	11	7	6	20	SCL
Ap2	30–50	0	0	4	10	27	14	11	8	4	22	SCL
2Ck	50–(90)	4	0	7	10	24	12	10	10	10	17	SL

Table 5. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Ap	0–30	8.4	0.85	10	7.9	7.5	17
Ap2	30–50	6.3	0.67	9	8.0	7.5	34
2Ck	50–(90)	–	–	–	8.4	7.7	151

Profile 3 – Anocalcaric Endocalcic Luvic **Phaeozem** (Aric, Loamic, Raptic)
Localization: Niche, upper slope – inclination 15°, grass vegetation, 86 m a.s.l.,
N 53˚09'18.0'' **E** 17˚39'39,9''

Morphology:

Ak(p) – 0–20 cm, *mollic* horizon plough in the past, sandy loam, very dark grayish brown (10YR 5/3, 10YR 3/2), slightly moist, medium moderate granular structure, very fine and common roots, abrupt and smooth boundary;

Ak(p)2 – 20–30 cm, humus horizon plough in the past, sandy loam, dark grayish brown (10YR 5/4, 2.5YR 4/2), slightly moist, coarse strong angular structure, fine and few roots, abrupt and smooth boundary;

Bt – 30–50 cm, *argic* horizon, sandy loam, brown (10YR 5/3, 10YR 4/3), slightly moist, coarse moderate angular structure, many clay coatings, fine and very few roots, clear and wavy boundary;

BC – 50–80 cm, transitional horizon, sandy loam, dark yellowish brown (10YR 6/6, 10YR 4/6), slightly moist, medium weak subangular structure, gradual and wavy boundary;

2Ck – 80–140 cm, *calcaric* parent material, silty loam, light yellowish brown (10YR 7/3, 10YR 6/4), slightly moist, fine weak subangular structure, layered, common soft concretions of secondary carbonates;

2Ck2 – 140–(150) cm, *calcaric* parent material, silty loam, pale brown (10YR 8/2, 10YR 6/3), slightly moist, fine weak subangular structure, layered, common soft concretions of secondary carbonates;

Table 6. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0–1.0	1.0–0.5	0.5–0.25	0.25–0.1	0.1–0.05	0.05–0.02	0.02–0.005	0.005–0.002	< 0.002	
Ak(p)	0–20	2	0	4	8	25	20	7	6	14	16	SL
Ak(p)2	20–30	1	0	5	10	25	21	5	8	11	15	SL
Bt	30–50	4	0	5	8	30	18	10	7	5	17	SL
BC	50–80	3	0	6	10	27	20	10	8	5	14	SL
2Ck	80–140	0	0	1	5	10	10	23	28	7	16	L
2Ck2	140–(150)	0	0	3	2	2	7	23	40	10	13	SiL

Table 7. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [$g \cdot kg^{-1}$]	Nt [$g \cdot kg^{-1}$]	C/N	pH		$CaCO_3$ [$g \cdot kg^{-1}$]
					H_2O	KCl	
Ak(p)	0–20	9.6	0.90	10	8.2	7.7	50
Ak(p)2	20–30	6.1	0.60	10	8.2	7.5	49
Bt	30–50	2.9	0.30	9	8.5	7.7	38
BC	50–80	3.0	0.20	12	8.4	7.9	97
2Ck	80–140	–	–	–	8.9	8.2	195
2Ck2	140–(150)	–	–	–	8.6	8.0	179

Profile 4 – Haplic **Phaeozem** (Colluvic, Loamic, Lamellic)

Localization: Niche, medium slope – inclination 13°, grass vegetation, slope 78 m a.s.l., **N** 53°09'17.8" **E** 17°39'40.1"

Morphology:

A – 0–25 cm, *mollic* horizon, sandy loam, very dark grayish brown (10YR 5/3, 10YR 3/2), slightly moist, medium moderate granular structure, very fine and common roots, clear and smooth boundary;

A2 – 25–40 cm, horizon, colluvic material, sandy loam, dark brown (10YR 6/3, 10YR 3/3), dry, medium moderate granular structure, fine few roots, gradual and smooth boundary;

A3 – 40–80 cm, humus horizon, colluvic material, sandy loam, very dark grayish brown (10YR 5/2, 10YR 3/2), slightly moist, medium weak granular structure, fine and medium very few roots, gradual and smooth boundary;

A4 – 80–100 cm, humus horizon, colluvic material, sandy loam, dark yellowish brown (10YR 7/4, 10YR 4/4), slightly moist, medium weak granular structure, fine very few roots, illuvial lamellae, diffuse and smooth boundary;

A5 – 100–140 cm, humus horizon, colluvic material, sandy loam, dark grayish brown (10YR 6/2, 10YR 4/2), slightly moist, medium weak granular structure, fine very few roots, illuvial lamellae, gradual and smooth boundary;

A6 – 140–(200) cm, humus horizon, colluvic material, sandy loam, dark grayish brown (10YR 3/2, 10YR 2/1), moist, medium moderate granular structure, coarse and fine very few roots;

Table 8. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0–1.0	1.0–0.5	0.5–0.25	0.25–0.1	0.1–0.05	0.05–0.02	0.02–0.005	0.005–0.002	< 0.002	
A	0–25	5	0	3	8	30	18	12	8	4	17	SL
A2	25–40	0	0	5	10	29	20	12	7	4	13	SL
A3	40–80	1	0	5	10	30	23	12	8	3	9	SL
A4	80–100	1	0	5	10	31	25	12	7	3	7	SL
A5	100–140	1	0	5	10	34	24	13	7	1	6	SL
A6	140–(200)	0	0	5	10	31	21	9	8	3	13	SL

Table 9. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [$g \cdot kg^{-1}$]	Nt [$g \cdot kg^{-1}$]	C/N	pH		$CaCO_3$ [$g \cdot kg^{-1}$]
					H_2O	KCl	
A	0–25	8.7	0.8	10	8.3	7.7	9
A2	25–40	7.2	0.7	10	8.2	7.5	7
A3	40–80	6.3	0.5	11	8.5	7.9	7
A4	80–100	2.3	0.2	12	8.4	7.7	2
A5	100–140	2.8	0.1	17	8.4	7.5	2
A6	140–(200)	6.5	0.5	13	8.0	6.9	1

Profile 5 – Haplic **Phaeozem** (Colluvic, Katoarenic, Epiloamic)
Localization: Niche, foot slope – inclination 13°, grass vegetation, 72 m a.s.l.,
N 53°09'16.8" **E** 17°39'39.7"

Morphology:

A – 0–10 cm, *mollic* horizon, sandy loam, very dark gray (10YR 5/2, 10YR 3/3), slightly moist, medium moderate granular structure, very fine and fine common roots, gradual and smooth boundary;

A2 – 10–30 cm, *mollic* horizon, colluvial material, sandy loam, dark brown (10YR 4/3, 10YR 3/3), slightly moist, fine moderate granular structure, very fine and fine few roots, gradual and wave boundary;

A3 – 30–105 cm, humus horizon, colluvic material, loamy sand, dark yellowish brown (10YR 6/4, 10YR 4/3), slightly moist, fine and medium weak granular structure, fine very few roots, gradual and smooth boundary;

A4 – 105–130 cm, humus horizon, colluvic material, sandy loam, dark grayish brown (10YR 6/1, 10YR 4/2), moist, fine and medium weak granular structure, fine very few roots, gradual and smooth boundary;

A5 – 130–(160) cm, humus horizon, colluvic material, sandy loam, dark grayish brown (10YR 7/2, 10YR 4/2), moist, fine and medium weak granular structure, fine very few roots;

Table 10. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0–1.0	1.0–0.5	0.5–0.25	0.25–0.1	0.1–0.05	0.05–0.02	0.02–0.005	0.005–0.002	< 0.002	
A	0–10	0	0	5	9	33	20	13	7	4	9	SL
A2	10–30	0	0	5	10	38	20	11	6	2	8	SL
A3	30–105	0	0	6	11	42	23	7	4	5	2	LFS
A4	105–130	0	0	4	9	39	22	12	7	3	4	SL
A5	130–(160)	0	0	5	10	39	21	13	5	4	3	LFS

Table 11. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
A	0–10	13.6	1.3	11	7.2	6.7	2
A2	10–30	5.5	0.5	9	8.4	7.9	14
A3	30–105	1.1	0.1	6	8.3	7.8	1
A4	105–130	4.3	0.3	11	8.1	7.3	1
A5	130–(160)	2.3	0.2	13	8.2	7.6	1

Profile 6 – Eutric Murshic Episapric Katohemic **Histosol**

Localization: Bottom of the marginal valley – flat 1°, grass vegetation, 66 m a.s.l., **N** 53°09'13.0" **E** 17°39'33.2"

Morphology:

Ha – 0–25 cm, drained highly decomposed *histic* horizon, very dark grayish brown (10YR 4/3, 2.5Y 3/2), moist, coarse granular moderate structure, fine common roots, gradual and smooth boundary;

Ha2 – 25–40 cm, highly decomposed *histic* horizon, olive brown (2.5Y 5/3, 2.5Y 4/3), moist, layered structure, fine few roots, gradual and smooth boundary;

He – 40–(100) cm, moderately decomposed *histic* horizon; very dark grayish brown (10YR 4/3, 2.5Y 3/2), wet, layered structure, fine few roots.

Table 10. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	pH		$CaCO_3$ [g·kg^{-1}]
					H_2O	KCl	
Ha	0–25	357	29.6	12	6.4	5.7	–
Ha2	25–40	229	18.4	12	7.2	6.3	176
He	40–(100)	441	35.2	13	7.0	6.4	32

Table 11. Sorption properties

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	TEB	HA	CEC	CEC_{clay}	BS
		[cmol(+)·kg^{-1}]								[%]
Ha	0–25	65.1	3.98	0.155	0.039	69.3	17.7	87.0	–	80
Ha2	25–40	104	11.5	0.395	0.150	266	14.2	280	–	95
He	40– (100)	75.1	6.31	0.148	0.082	81.6	22.7	104.3	–	78

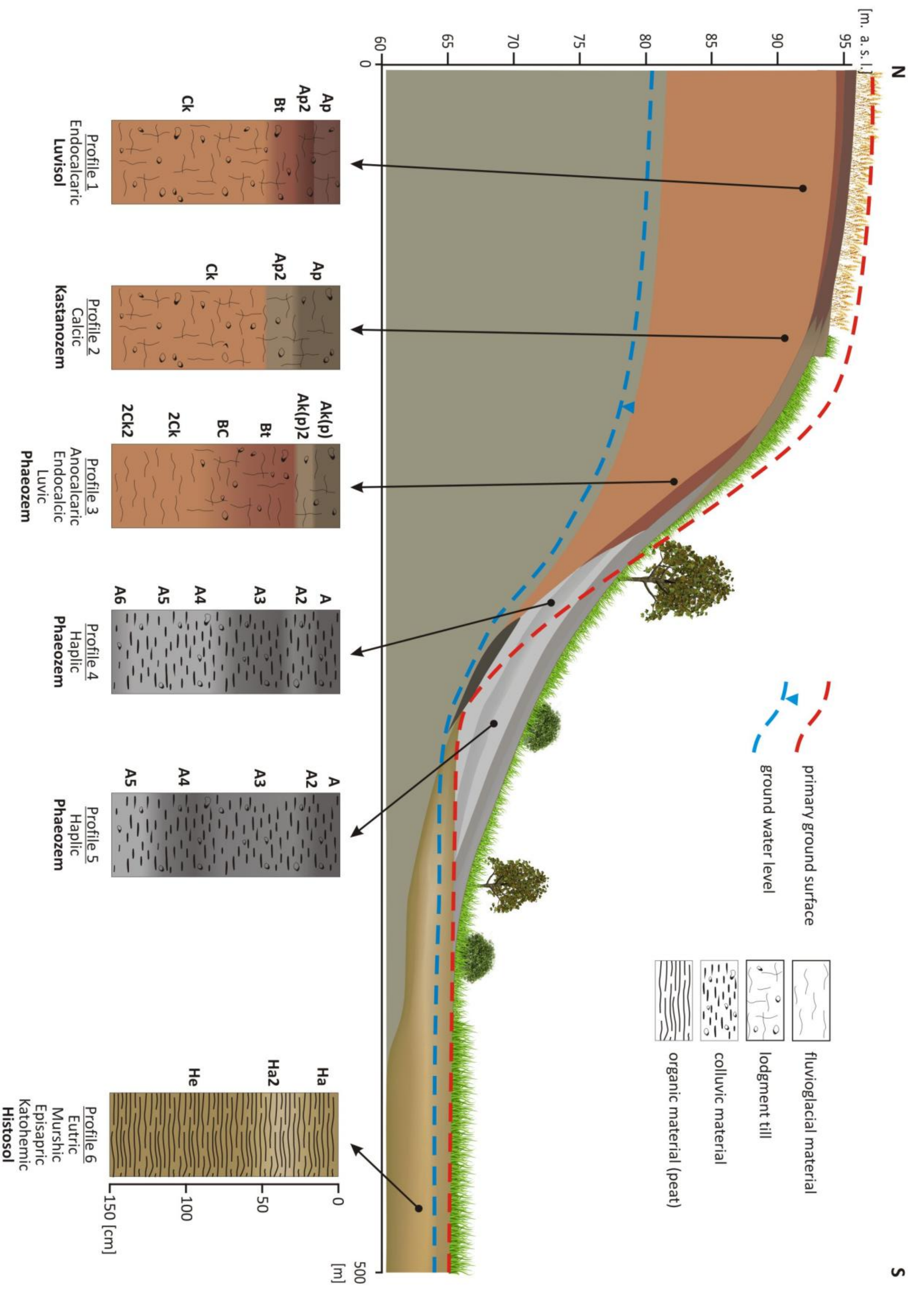


Fig. 2. Hydrolithotoposequence of soils within northern slopes of the Toruń- Eberswalde ice-marginal valley near Nakło

Soil genesis and systematic position

The investigated soil profiles exhibit high diversity of soil cover within the slopes of the Toruń-Eberswalde ice-marginal valley and its vicinity. Profile 1 is located on the upper part of the slope, which also is a marginal part of the gently sloping morainic plateau (Fig. 2). It represents soil developed from glacial morainic deposits with loamy texture (***Loamic*** supplementary qualifier) (Table 1). The only diagnostic horizon in the discussed soil is *argic* Bt. The main and most important feature of this horizon is the presence of clay coatings on the surface of soil aggregates. These illuvial films are the result of downward transport of clay particles in humid climate which favours the *lessivage* process in young morainic loamy deposits (Quénard et al., 2011). The mean annual effective rainfall (precipitation minus evapotranspiration) is approximately 300 mm (Merot et al., 2003) and stimulates the development of clay eluviation (Arkley, 1967). The abundant presence of clay illuvial forms was expressed by adding the ***Cutanic*** qualifier. The CEC in whole Bt is higher than 24 $cmol{\cdot}kg^{-1}$ of clay and the base saturation is high (Table 3) which, combined with the lack of other important features (e.g. *stagnic, retic* properties), allowed to classify Profile 1 as **Luvisol** (IUSS Working Group WRB, 2015). The common occurrence of Luvisols in young morainic landscapes has already been described by several researchers (Dąbkowska-Naskręt and Jaworska, 1994a, b; Frielinghaus and Vahrson, 1998; Jankauskas and Fullen, 2002; Kühn, 2003). Unlike the described case, **Luvisols** usually have a very well-developed eluvial zone above the Bt horizons, from which the clay fraction has been partially removed. Lack of the eluvial horizon in Porfile 1 should be interpreted as a result of the partial truncation of this soil. The area of the Kraina Morainic Plateau has been used for agricultural purposes for many centuries and therefore has been exposed to strong erosion processes. Exposure of the argic horizon on the soil surface or it appearance just under the Ap horizon as a consequence of human-induced erosion was previously observed in many agricultural young morainic areas in Poland (e.g. Sinkiewicz, 1998; Marcinek and Komisarek, 2004; Kobierski, 2013; Podlasiński, 2013; Świtoniak, 2014; Świtoniak et al., 2016). Due to the horizon sequence A-B-C, these soils were in the past often described and designated on maps as **Cambisols** (e.g. Cieśla, 1968; Cieśla et al., 1978; Pindral and Świtoniak, 2017). Directly under the Bt horizon, the morainic parent material occurs, containing primary and secondary carbonates in the form of soft concretions (***Endocalcaric*** qualifier). The surface humus horizon cannot be treated as diagnostic – the amount of organic carbon (Table 2), structure, base saturation and thickness meet criteria of *mollic* but the color is not dark enough. To mark the presence of a "weakly developed" A horizon, the qualifier ***Ochric*** was used. The properties of this horizon are strongly influenced by agricultural treatments. It is divided into two subhorizons as a result of ploughing into different depths in the past (20 and 32 cm). Each subhorizon is highly homogenized with an abrupt lower boundary. The depth of tillage is enough to use the ***Aric*** qualifier. High pH values and base saturation of the humus horizon are probably associated with the addition of mineral fertilizers (***Epieutric***). Not fertilized **Luvisols** under forests are definitely more acidic in upper parts of profiles (Świtoniak 2014).

The upper and the most convex part of the slope is covered with **Kastanozem** (IUSS Working Group WRB, 2015). This soil is built from glacial deposits (Fig. 2, Profile 2). The texture in the entire soil profile is typical of bottom glacial sediments; these are mainly loams (***Loamic***). The solum of the discussed soils is limited to a well-developed humus ploughing horizon (***Aric***) divided into two parts – Ap and Ap2. The amount of organic carbon, structure and color of this horizon is suitable to classify it as *mollic*. The significant thickness (50 cm) of the A horizon is expressed by the ***Pachic*** qualifier and partly results from accumulation of slope sediments (Fig. 2). Profile 2 is located on the edge between arable land and meadow, where the upper boundary of grass vegetation acts as a sediment trap. Directly below the plough layer, there is the *calcic* horizon Ck with calcium carbonate content slightly above 15% (***Calcic*** qualifier). Secondary carbonates in the form of soft concretions and pseudomycelium represent a significant part of the total content of $CaCO_3$. Moreover, some carbonates are present also in the Ap horizon. The absence of any other genetic horizons common to typical soils of morainic plateaux indicates strong truncation of the original profile and intensive slope processes in the past (e.g. Podlasiński, 2013; Świtoniak, 2014). Studies conducted in other regions with similar geomorphological settings suggest that upper parts of ice-marginal valleys' slopes were primarily covered by soils with *argic* horizons – **Luvisols** or **Retisols** (Świtoniak et al., 2015).

Profile 3 is developed from loamy (***Loamic***) glacial deposits covering the material of fluvioglacial origin characterized by distinct layers and high contribution of silt fraction (Table 6). The occurrence of *lithic discontinuity* is marked by the ***Raptic*** supplementary qualifier. The sequence of genetic horizons and the degree of soil truncation in Profile 3 is very similar to the first pedon. The *Argic* Bt horizon with common clay illuvial coatings and infillings occurs directly under the A horizon. The main difference in the systematic position of these two soils arises from the nature of the humus horizon and the content of calcium carbonate. In Profile 3, the horizon A meets the criteria of the *mollic* horizon. Moreover, the *calcic* horizon can be distinguished based on the large amount of $CaCO_3$ with clear secondary forms in the material at a depth ≥ 80 cm. The vertical distance between these two horizons is too high (more than 50 cm) to classify this soil as Kastanozem. It was included into **Phaeozem** where deep occurrence of the *calcic* horizon was highlighted by the ***Endocalcic*** qualifier and the presence of the *argic* Bt horizon by the ***Luvic*** qualifier. Dark color of the humus horizon and relatively higher content of carbon (Table 7) is probably connected with contemporary influence of grass vegetation. Soils located on similar slopes but in more natural conditions covered with forests, or even transformed into arable lands, have less developed humus horizons which do not meet the criteria of *mollic* (Świtoniak et al., 2015). The fact that the place was used in the past as an arable field is proved by the ploughing nature of the A horizon (***Aric***) and a significant degree of profile truncation (lack of the eluvial zone). In addition, the whole profile above the *calcic* horizon contains calcium carbonate (***Anocalcaric***), the origin of which can be connected with the accumulation of slope sediments on the soil surface derived from eroded calcareous glacial deposits in the past (see horizon Ck in Profile 2) and leaching carbonates from these surface deposits into the soil. Due to the presence of the *argic* Bt horizon, it should be assumed that the studied pedon met the criteria of Luvisol or Retisol before the anthropogenic introduction of grass vegetation.

Profiles 4 and 5 represent relatively young soils developed as a consequence of *colluvic material* accumulation (***Colluvic*** supplementary qualifier). This material has been transported as a result of sheet wash during the period when the slope was used as arable land in the past (Orzechowski, 2008; Smólczyński and Orzechowski 2010; Sowiński, 2014). The texture of the slope deposits is mainly loam (***Loamic*** – Profile 4, Table 8; ***Epiloamic*** – Profile 5, Table 10) or loamy sand (***Katoarenic*** – Profile 5, Table 10). *Colluvic material* is humic throughout its thickness, which is connected with the fact that the uppermost A horizons of higher-located soils were mostly exposed to erosion. During the accumulation of *colluvium*, certain periods of stabilization and slowing down of erosion processes were noted. It is reflected in deeper lying darker horizons, containing more organic carbon (A3, A6 – Profile 4, Table 9; A4 – Profile 5, Table 11). Also contemporary surface horizons of these soils are enriched with humus by decomposition of grass roots, which makes them darker and improves their structure. Their properties meet the criteria of *mollic* horizons. Due to the lack of other diagnostic features, these soils were classified as **Phaeozems**. Some deeper horizons are too light or have not enough organic carbon (e.g. A2, A4, A5 – Profile 4, Table 9; A3, A4 – Profile 5, Table 11), and cannot be designated as the diagnostic horizon in question. For this reason, despite a significant thickness of A horizons, the ***Pachic*** qualifier was not use.

The last Profile 6 represents the soil lying beyond the foot of the slope and out of the colluvium accumulation zone. It was located on the biogenic plain at the bottom of the Toruń-Eberswalde ice-marginal valley. The entire profile is built of *organic* material amassed as peat and can only be classified as **Histosol**. Highly decomposed plant remains occur to a depth of 40 cm – ***Episapric***. At greater depths, moderately decomposed *histic* horizons dominate (***Katohemic***). The natural level of groundwater was artificially lowered by a network of drainage channels. Drainage led to an increased rate of mineralization and decomposition of plant residues, which is clearly visible in the form of coarse granular moderate structure in the uppermost horizon (***Murshic***).

Soil sequence

The above-described transect shows a significant transformation of soil cover triggered by agricultural activity. Properties of all analyzed profiles were strongly modified by human-induced erosion (Profile 1–5) or artificial drainage (Profile 6). Profiles 1–3 are located in the degradation zone of the investigated slope. Initially (before the erosion phase) they were probably **Luvisols** or **Retisols** with *argic* Bt horizons and the eluvial zone with a thickness of tens of centimeters. Nowadays, the first and the third pedon represent a strongly eroded stage – with the excavated Bt horizon, while Profile 2 has properties of completely eroded soil – it was truncated to a depth of the *calcic* horizon (Świtoniak, 2014). Intense slope processes have occurred here in the past. Soils developed in the redistributed colluvial deposits dominate in the middle and lower parts of the slopes (Profiles 4 and 5). At present, the slope processes have been hindered by the introduction of grass vegetation, which also leads to the improvement of humus horizons' properties. In Profile 2, accumulation of the humus material was noticed on the top of the pedon, which combined with the influence of grass vegetation led to the development of thick *mollic* horizons. Moreover, surface horizons in Profiles 3, 4 and 5 were also enriched with organic compounds and transformed by grasses into *mollic*. The positive impact of grass vegetation is reflected in the systematic position of the described soils. Profile 2 with *mollic* and *calcic* horizons was classified as **Kastanozem**, strongly eroded soil with *mollic* and *argic* horizons (Profile 3) and two colluvial soils (Profiles 4 and 5) as **Phaeozems**. Profile 6 – **Histosol** – was the only pedon not affected by slope processes. However, the impact of human activities in this profile is visible – the upper part of peat was drained and transformed into material with coarse granular moderate structure.

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Strongly weathered soils of the karst plateau (Slovak Karst) and the Rimavská intra–mountain basin

Martin Saksa, Rastislav Skalský

Fig. 1. Location

The Slovak Karst (Slovenský Kras in Slovak) is the largest karst area in Slovakia. It is one of the mountains ranges of the Slovenské Rudohorie Mountains in the Western Carpathians, in the southeast part of Slovakia. It consists of a complex of huge karst plains and plateaux. Since 2002, it was declared the Slovak Karst National Park. It is also a UNESCO Biosphere reserve and part of it forms a UNESCO World Heritage site – Caves of Aggetelek Karst and Slovak Karst. The Rimavská kotlina basin is one of the intra-mountain basins in the Western Carpathians. It lies in the middle and lower river basin of the Slaná, Blh and Rimava rivers.

Lithology and topography

Slovak Karst is almost entirely built of the main tectonic unit called Silicikum, represented by Silický spill with middle and upper Triassic limestones and dolomites. Quaternary sediments are different on plateaux, in basins, hilly lands and river valleys. Sediments originated from weathering of limestone complexes dominate on plateaux. They are connected with karst phenomena and slope formation. When dissolving limestones and dolomites, insoluble residues accumulate and then move (colluviated) and transported to the lower parts (basins and valleys) forming clayey sediments known as terrae calcis. Basins and river valleys are characteristic, with polycyclic development of fluvial river terrace sediments and prolluvial sediments of alluvial cones. Karst topography is distinguished mostly by carbonate rocks of the Slovak Karst´s plateaux and their forelands. Karst topography was formed by degradation of the plain surface – the pannonian middle-mountain plateau and is typical for the presence of various karst landforms (as sinkholes, dry valleys, semi-blind and blind valleys, ravines, karst poljes, caves, gaps, exhumed surfaces). Skalické polje has smoothly modelled, erosion/denudation topography. Topography of the Rimavská kotlina basin was created by gradual degradation (segmentation) of the former flattened upper Pliocene river plain, mainly by fluvial activity of the Slaná and Rimava rivers, resulting in today`s alluvial plains and river terraces of different age (mindel, riss, würm).

Vegetation

Vegetation cover of Slovak Karst is mainly represented by beech (*Fagus sylvatica*), hornbeam (*Carpinus betulus*) and oak-tree (*Quercus robur, Quercus cerris*) forests and their mixtures and inclusions of managed and unmanaged grasslands and arable areas close to human settlements. Potential natural vegetation cover (oak forests) of the Rimavská kotlina basin at many locations was transformed into cultural landscape and is mainly used as arable land and grassland.

Profile 1 – Endocalcaric Endoskeletic Rhodic Endoleptic **Luvisol** (Clayic, Cutanic, Humic)
Localization: Silica (Slovak Karst), top of the karstic plateau, beech forest, 515 m a.s.l.;
N 48°33’9.42’’, **E** 20°30’19.62’’

Morphology:

A – 0–4 cm, loam, black (2.5YR 2.5/1), wet, medium crumbly structure, many roots, clear and broken boundary;

AB – 4–23 cm, transitional horizon, silty clay, red brown (5YR 4/3), wet, fine angular blocky structure, many roots, diffuse and wavy boundary;

Bt – 23–50 cm, argic horizon, clay, red brown (2.5YR 4/4), wet, fine angular blocky structure, few roots, gradual and wavy boundary;

B/R – 50– (90) cm, transition to bedrock, clay, dark red (2.5YR 3/6), wet, fine angular blocky structure, few roots;

Table 1. Texture

Horizon	Depth [cm]	Percentage of fraction [mm]			Bulk density [g·m^{-3}]	Pc [bulk %]	RVK [bulk %]	VZK [bulk %]	Ks [cm·day^{-1}]
		0.05	0.05 – 0.002	<0.002					
A	0–4	36.4	41.3	22.3	1.07	60.0	47.9	9.44	258.7
A/B	4–23	9.4	44.0	46.6	1.23	52.4	42.1	8.54	54.2
Bt	23–50	7.2	30.6	62.2	–	–	–	–	–
B/R	50–(90)	11.6	30.6	57.8	–	–	–	–	–

Table 2. Chemical and physicochemical properties

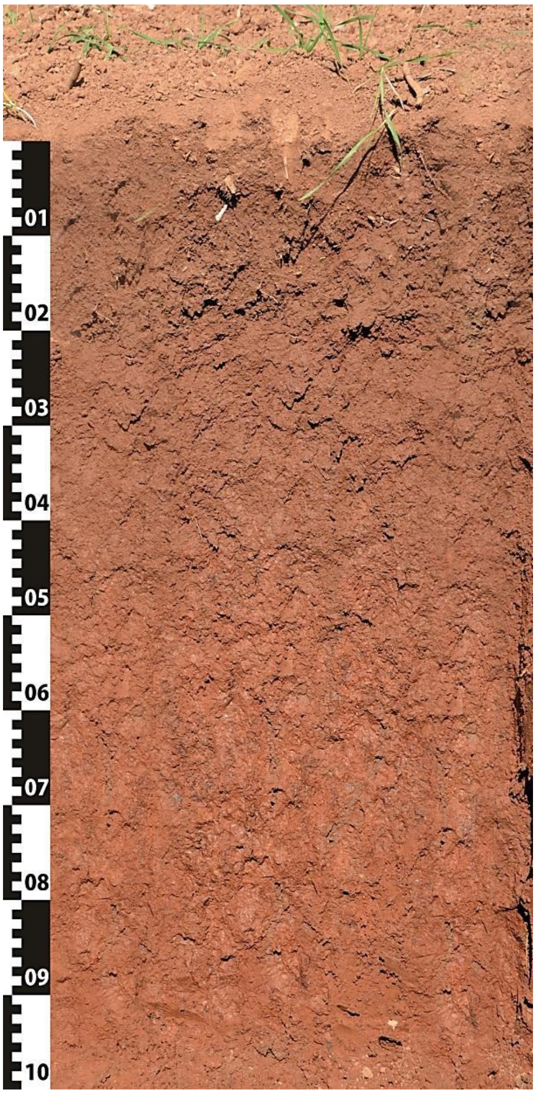
Horizon	Depth [cm]	pH			CEC [cmol(+)·kg^{-1}]	$CaCO_3$ [g·kg^{-1}]	H [nmol·kg^{-1}]	OC [g·kg^{-1}]	N_t [g·kg^{-1}]
		H_2O	KCl	$CaCl_2$					
A	0–4	6.0	5.5	5.7	37.6	0.5	61.7	120.2	9.5
A/B	4–23	6.1	4.9	5.6	39.2	0.8	38.8	28.3	2.6
Bt	23–50	6.8	5.4	6.0	38.0	1.9	21.6	11.4	1.3
B/R	50–(90)	7.9	7.1	7.4	34.1	57.6	2.21	6.4	1.0

Table 3. Content of selected forms of iron and aluminum

Horizon	Depth [cm]	Kaolinite	Illite	Smectite	Chlorite	Mix structure	Q clast.
A/B	4–23	+++	++	+	*	–	Q
Bt	23–50	+++	++	+	–	–	Qh

+++ Predominance, ++ substantial representation, + present, * admixture, Q silica, h hematite

Profile 2 – Chromic Endostagnic **Luvisol** (Aric, Clayic, Ochric)
Localization: Gemerská Hôrka (Skalické polje), summit of local hill in the polje, arable land, 271 m a.s.l.;
N 48°32’41.86’’, **E** 20°21’15.23’’



Morphology:

Ap – 0–20 cm, silty clay loam, dark brown (7.5YR 3/4), wet, fine angular blocky structure, few roots, clear and smooth boundary;

Bt – 20–50 cm, *argic* horizon, clay, red (2.5YR 4/6), wet, medium angular blocky structure, very few roots, clear and smooth boundary;

Btg – 50–(120) cm, *argic* horizon with stagnic conditions, clay, dark red (2.5YR 3/6, 7.5YR 4/3), wet, medium prismatic structure, few oximorphic mottles, none roots;

Table 4. Texture

Horizon	Depth [cm]	Percentage of fraction [mm]			Bulk density [g·m^{-3}]	Pc [bulk %]	RVK [bulk %]	VZK [bulk %]	Ks [cm·day^{-1}]
		>0.05	0.05 – 0.002	<0.002					
Ap	0–20	11.4	51.2	37.4	1.59	40.2	34.6	3.98	33.9
Bt	20–50	7.7	37.3	55.0	1.48	45.4	37.9	5.71	21.2
Btg	50–(120)	7.6	40.1	52.3	1.53	44.9	36.6	7.39	22.2

Table 5. Chemical and physicochemical properties

Horizon	Depth [cm]	pH			CEC [cmol(+)·kg^{-1}]	$CaCO_3$ [g·kg^{-1}]	H [nmol·kg^{-1}]	OC [g·kg^{-1}]	N_t [g·kg^{-1}]
		H_2O	KCl	$CaCl_2$					
Ap	0–20	6.2	5.1	5.65	25.8	<0.5	27.8	15.6	1.7
Bt	20–50	6.5	5.1	5.89	28.4	0.6	19	6.1	1.0
Btg	50–(120)	6.7	5.3	6.11	23.1	0.7	17.6	5.7	0.9

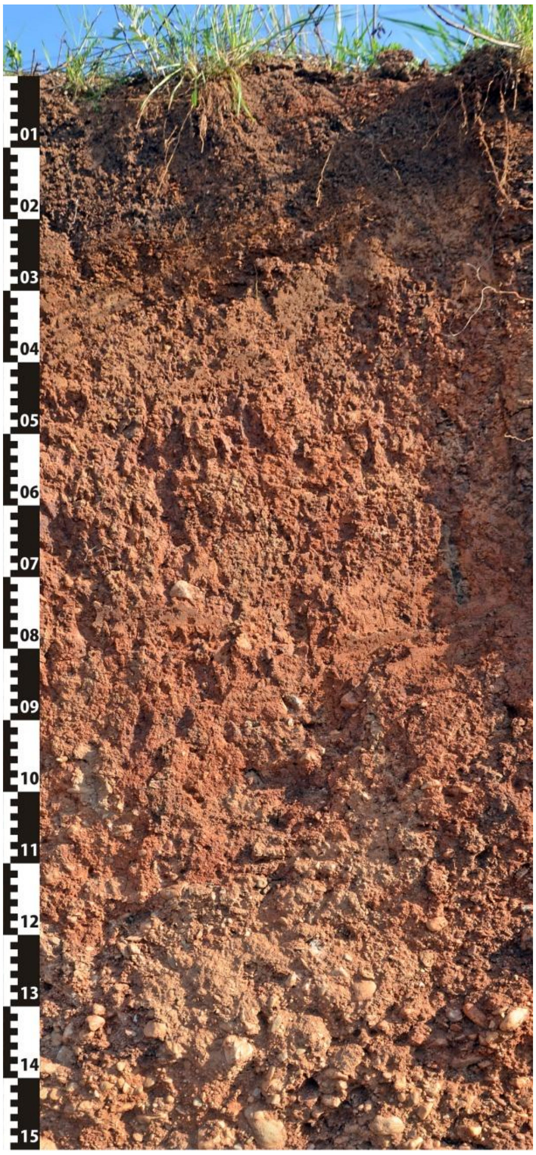
Table 6. Content of selected forms of iron and aluminum

Horizon	Depth [cm]	Kaolinite	Illite	Smectite	Chlorite	Mix structure	Q clast.
Ap	0–20	+++	+++	++	*	*	Q
Bt	20–50	+++	++	++	*	–	Q
Btg	50–(120)	+++	++	++	–	–	–

+++ Predominance, ++ substantial representation, + present, * admixture, Q silica

Profile 3 – Chromic Katostagnic **Luvisol** (Clayic, Episiltic, Cutanic, Bathydensic, Ochric)

Localization: Tornaľa – Stárňa (Rimavská basin), river terrace of Slaná river, arable land (close to area with surface mining of gravelsands with 5–7 m high profile in terrace sediments), 196 m a.s.l.; **N** 48°26'37.46'', **E** 20°20'54.10''



Morphology:

Ap – 0–25 cm, silt loam, brown (10YR 4/3), wet, fine angular blocky structure, common roots, gradual and smooth boundary;

Btg1 – 25–50 cm, argic horizon with stagnic con–ditions, silty clay, brown (10YR 4/3, 5YR 4/4), wet, medium angular blocky structure, few oximorphic mottles, few roots, gradual and wavy boundary;

Btg2 – 50–120 cm, argic horizon with stagnic conditions, silty clay, red brown (2.5YR 3/6, 7.5YR 4/3), wet, medium prismatic structure, few oximorphic mottles, few roots;

2BC – 120–(150) cm, fluvial deposits, gravel, medium subangular weak/single grain structure;

Table 7. Texture

Horizon	Depth [cm]	Percentage of fraction [mm]			Bulk density [$g \cdot m^{-3}$]	Pc [bulk %]	RVK [bulk %]	VZK [bulk %]	Ks [$cm \cdot day^{-1}$]
		>0.05	0.05 – 0.002	<0.002					
Ap	0–25	16.3	57.7	26.0	1.41	46.57	24.55	10.06	74.53
Btg1	25–50	13.0	45.9	41.0	1.54	42.55	34.73	6.08	88.78
Btg2	50–120	15.2	42.6	42.2	1.60	41.01	35.37	4.74	41.02

Table 8. Chemical and physicochemical properties

Horizon	Depth [cm]	pH			CEC [$cmol(+) \cdot kg^{-1}$]	$CaCO_3$ [$g \cdot kg^{-1}$]	H [$nmol \cdot kg^{-1}$]	OC [$g \cdot kg^{-1}$]	N_t [$g \cdot kg^{-1}$]
		H_2O	KCl	$CaCl_2$					
Ap	0–25	6.3	5.4	5.5	22.1	<0.5	24.1	14.8	1.7
Btg1	25–50	6.5	5.1	5.9	28.7	<0.5	19	6.5	1.0
Btg2	50–120	6.7	5.3	6.1	26.9	<0.5	14.8	5.3	0.9

Table 9. Content of selected forms of iron and aluminum

Horizon	Depth [cm]	Kaolinite	Illite	Smectite	Chlorite	Mix structure	Q clast.
Ap	0–25	++	+++	++	*	+	Q
Btg1	25–50	++	+++	+	*	–	Q
Btg2	50–120	++	+++	+	–	–	Q

+++ Predominance, ++ substantial representation, + present, * admixture, Q silica

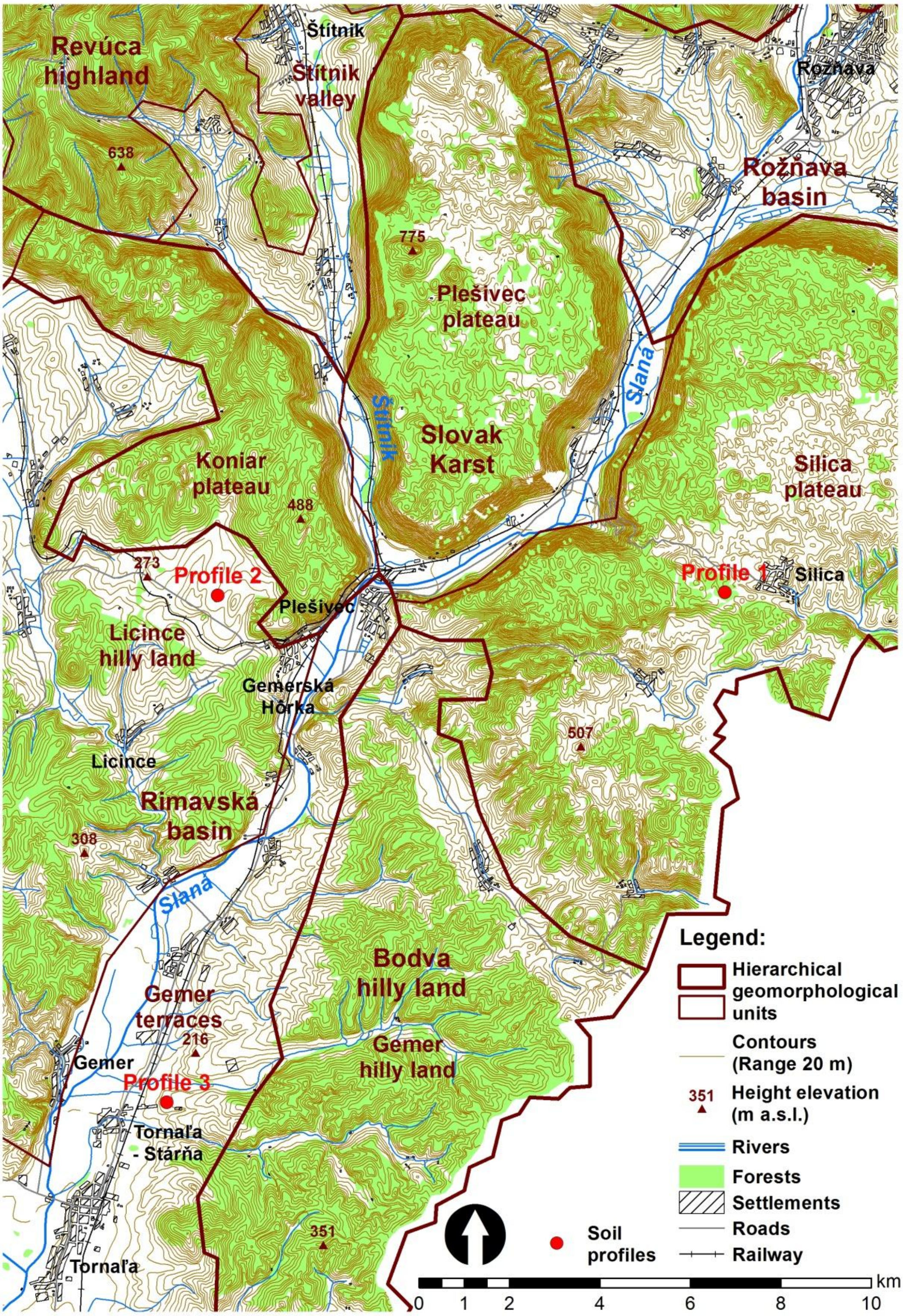


Fig. 2. Localization of Soil profiles

Climate

The region is located in the snow climate, fully humid with warm summer (Kottek et al., 2006). According to Climatogeographical types of Slovakia (Tarábek, 1980), this region is characterized by mountainous, slightly warm climate (karst plateaux) with average temperature of the warmest month (July) of 17–17.5°C, while the coldest month is January (from –3.5 to –6°C). The average annual precipitation ranges from 650 to 850 mm; and the slightly warm climate of the basin (Rimavská kotlina basin) with average temperature of the warmest month (July) 17–18.5 °C, while the coldest month is January (from –2.5 to –5 °C). The average annual precipitation ranges from 600 to 800 mm.

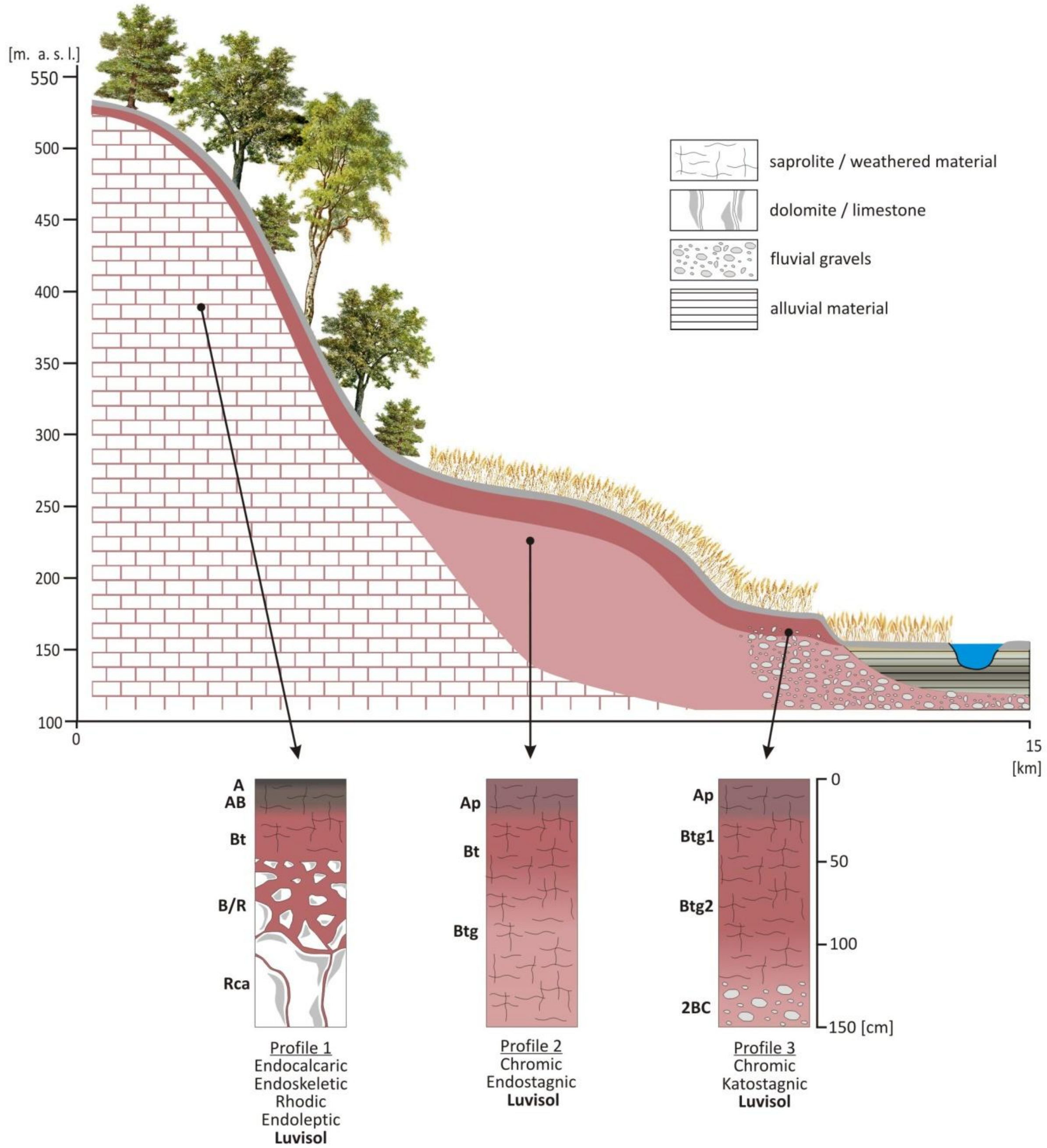


Fig. 3. Topo-lithosequence of Luvisols

Soil genesis and systematic position

The current soil cover is a result of a long and complicated formation. This particularly true for the soils in the area of Slovak Karst and its foreland of the *Rimavská kotlina* basin. Their present morphological, physical, and chemical properties are a result of old pedogenetic processes and weathering of carbonate rocks (*terrae-calcis* substrates), erosion cycles and subsequent accumulation of fresh mineral material during the glacial and interglacial periods, geomorphological development of the area as well as anthropogenic influence in the recent period.

All three selected soils can be classified in WRB 2014 as **Luvisols**, based on the presence of the *argic* horizon with higher clay content than the overlying *ochric* A-horizon, caused by an illuvial accumulation of clay. However, the morphological and analytical features of these soils indicate that each of these soils went through different evolution and is characterized by different features. There is a great importance of relict processes and features in these soils.

The first profile is located at the top of the karstic plateau (*Silická planina* plateau) in beech forest. The soil was classified according to WRB (2014) as ***Endocalcaric Endosleketic Rhodic Endoleptic* Luvisol**. The *argic* horizon has red brown color and meets the color criteria for the ***Rhodic*** principal qualifier. At a depth of more than 50 cm, it is extremely skeletic, having more than 75% of limestone subangular rocks (Ø 5 – 15 cm) and boulders (Ø 25 – 50 cm), therefore the ***Endocalcaric***, ***Endoskeletic*** and ***Endoleptic*** principal qualifiers were applied.

Two other profiles, ***Chromic Endostagnic* Luvisol** and ***Chromic Katostagnic* Luvisol,** both have the *argic* horizon with red color and meet only color criteria for the ***Chromic*** principal qualifier. Both have *stagnic* properties and *reducing conditions* present in the soil profile, therefore the ***Stagnic*** principal qualifier was applied. In Profile 2, starting from 50 cm – ***Endostagnic*** and in Profile 3, *stagnic* properties and *reducing conditions* starts > 0 and < 50 cm and has its lower limit ≥ 100 cm of the soil surface – ***Katostagnic***.

All profiles were characterized by the clay texture (supplementary qualifier – ***Clayic***).
Abundant occurrence of clay coatings was observed on the aggregate surface in the *argic* horizon, therefore the ***Cutanic*** supplementary qualifier was applied.

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Soils of the southern slopes of the Villány Hills, SW Hungary

Szabolcs Czigány, Szabolcs Ákos Fábián, Gábor Nagy, Tibor Jozsef Novák

The study area comprises the summit region, the southern slopes and the foothill region of the Villány Hills, SW Hungary. The range spans about 30 km in an east-west direction from the village of Hegyszentmárton to the town of Villány.

Fig. 1. Location of the Villány Hills

Lithology and topography

The Villány Hills form the southernmost hill range in Hungary. The hills are predominantly built of Triassic, Jurassic and Cretaceous limestone and dolomite, covered by Pleistocene loess at lower elevation (Lovász and Wein, 1974; Lovász, 1977), mostly below the summit region and at the foothills. In the summit regions, with the exception of the lowest elevation, the central part of the hills, limestone and dolomite are commonly found as outcrops (Wein, 1967). The range is built of uplifted and imbricated horsts. The sedimentary rocks that form the bulk of the range were thrust on each other in a thrust fault style forming blocks or "shingles" (Dezső et al. 2004; Sebe, 2017). The blocks are bordered by faultlines that dip to the west (Lovász, 1977). The blocks are tilted to the west, northwest, in the case of the Csarnóta block to the south and in the Szársomlyó block – to the north. Additional Mesozoic horsts and outcrops are found in the southern foreground of the range including the Siklós Castle Hill, the Beremend Hill and the Kistapolca Hill (Czigány, 1997). The summit regions are covered by shallow sediments and soils in a discontinuous fashion, while limestone caverns are filled in by Pliocene red clay (Lovász, 1973).

The highest point of the westernmost block is 268 m (Kopasz Hill). The limestone is common on the surface and a significant portion is exposed in the Csarnóta Limestone Quarry about 300 meters from the pass (Tenkes-csárda) where road 58 crosses the range. The average height of the block to the east (Csukma block) is around 340 meters with the Tenkes Hill (408 m), which is the second highest peak in the entire range. The summit elevation then decreases to about 240 m a.s.l. in the central, lowest part of the range (Város Hill block), north of the town of Siklós. In this block, the consolidated bedrock (limestone and dolomite) is only found in the surface of restricted areas, only in road cuts and in places where it is exposed by gullies and torrential creeks (field observation of the authors, 2017). To the east, the range again gains height to the Fekete Hill (358 m) and to the highest point of the entire range, Szársomlyó (442 m a.s.l.). The "devil's ploughfield" on the southern slopes of the Szársomlyó Hill is essentially the faces of the tilted limestone layers that dip to the north. Loess cover is only found in foothill regions, both on the northern and the southern sides of the hill (Lovász and Wein, 1974, Czigány, 1998).

Profile 1 – Endocalcaric **Cambisol** (Siltic, Ochric)

Localization: Southern slope – inclination 10°, under closed canopy forest, 205 m a.s.l., **N** 45°52'45.19" **E** 18°18'57.67"

Morphology:

Ah – 0–10 cm humus horizon, silt loam, very dark grayish brown (10YR 3/2 – moist) angular–subangular, blocky and granular fine–very fine structure, many roots, gradual and smooth boundary;

Bw – 10–40 cm, *cambic* horizon, silt loam, dark yellowish brown (10YR 3/4 – moist), angular–subangular blocky, fine structure, few roots, gradual and smooth boundary;

BC – 40–65 cm, transitional horizon, silt loam, dark yellowish brown (10YR 4/4 – moist), angular blocky, medium structure, few roots, gradual and smooth boundary;

C – 65–(80), parent material, loess, silt loam, light olive brown (2.5 Y 5/4 – moist), angular blocky, fine–medium structure;

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		2.0–0.5	0.5–0.2	0.2–0.1	0.1–0.05	0.05–0.02	0.02–0.01	0.01–0.005	0.005–0.002	0.002–0.001	<0.001	
Ah	0–10	0.0	0.0	5.4	11.3	41.6	17.8	9.4	5.7	2.8	6.0	SiL
Bw	10–40	0.0	0.0	2.1	8.6	34.6	12.6	8.2	9.2	5.6	18.9	SiL
BC	40–65	0.0	0.0	5.8	5.3	36.4	17.4	9.7	7.9	5.2	12.3	SiL
C	65–(80)	0.0	0.0	2.8	8.7	43.6	20.3	9.4	6.7	2.3	6.2	SiL

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	OC [g·kg^{-1}]	pH		$CaCO_3$ [g·kg^{-1}]
			H_2O	KCl	
Ah	0–10	85.1	7.0	6.8	1.53
Bw	10–40	9.3	7.4	6.9	1.44
BC	40–65	8.4	7.6	7.1	1.93
C	65–(80)	5.2	8.0	7.5	2.58

Profile 2 – Somerirendzic **Leptosol** (Humic, Siltic)

Location: karstic surface with limestone blocks on surface, edge of a quarry, summit, inclination 3°, 191 m a.s.l., **N** 45°53'06.2" **E** 18°13'53.7"

Morphology:

Ah – 0–15 cm, shallow humus rich horizon *mollic*, silt loam, dark brown (7.5YR 3/2), slightly moist, medium moderate granular structure, very fine abundant roots, gradual and smooth boundary;

ABw – 15–28 cm, *cambic* horizon with high content of calcium carbonates, silt loam, dark brown (7.5YR 3/3), slightly moist, medium moderate granular structure, fine abundant roots, abrupt and smooth boundary;

R – 28–42 cm, bedrock, (limestone);

CR – 42– 65 cm, *cambic* horizon, silt loam, brown (5.5YR 4/8, 7.5YR 4/4), slightly moist, coarse strong angular structure, many clay coatings, fine and very few roots, clear and wavy boundary;

R – 65 cm, bedrock (limestone, dolomite);

Heterogeneous spatial distribution due to limestone outcrops: Alternative horizonation: Ah, ABw, C, BwC, R

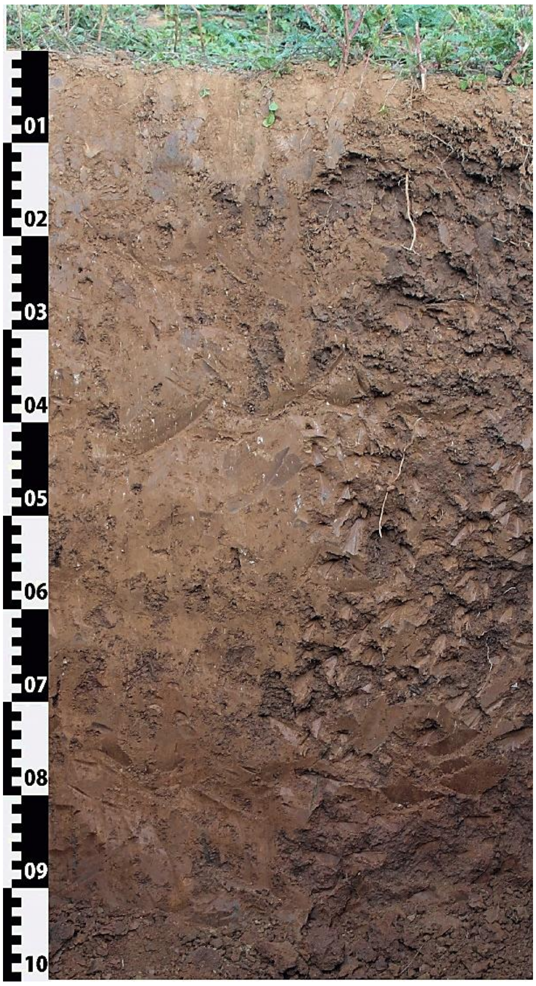
Table 3. Texture of profile 2

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		2.0–0.5	0.5–0.2	0.2–0.1	0.1–0.05	0.05–0.02	0.02–0.01	0.01–0.005	0.005–0.002	0.002–0.001	<0.001	
Ah	0–15	3.5	5.5	6.3	13.3	23.2	15.0	14.5	13.6	4.4	0.7	SiL
ABw	15–28	2.0	10.2	5.6	13.4	22.6	14.5	13.8	13.0	4.3	0.64	SiL
CR	42–65	10.8	3.2	0.5	5.2	14.3	23.7	26.1	11.3	3.2	1.8	SiL

Table 4. Chemical and physicochemical properties of profile 2

Horizon	Depth [cm]	OC [g·kg^{-1}]	pH		$CaCO_3$ [g·kg^{-1}]
			H_2O	KCl	
Ah	0–15	7.22	7.7	7.2	280.2
ABw	15–28	2.75	7.8	7.2	333.5
CR	42–65	0.13	8	7.4	804.6

Profile 3 – Haplic **Luvisol** (Aric, Colluvic, Cutanic, Humic, Pantosiltic, Protocalcic)
Localization: Mid slope – inclination 5°, fallow, formerly vineyard, 154 m a.s.l., **N** 45˚52’23.6’’ **E** 18˚19’11.2’’



Morphology:

Ap – 0–20 cm, humus horizon, colluvial material, silt loam, dark yellowish brown (10YR 3/4 – moist), angular–polyhedric blocky, platy, fine to medium, strong, compacted structure, distinct carbonates, clear and smooth boundary;

Ah – 20–40 cm, humus horizon, colluvial material, silt loam, dark yellowish brown (10YR 3/4 – moist), angular–subangular blocky fine–very fine structure, clear and smooth boundary;

Ah2 – 40–55 cm, humus horizon, colluvial material, silt loam, dark yellowish brown (10YR 3/4 – moist), angular blocky, fine structure, clear and smooth boundary;

Btg – 55–165 cm, *argic* horizon, colluvial material, silt loam, stagnic pattern – dark yellowish brown, dark brown, very dark grayish brown (10YR 4/4, 10YR 3/3, 10YR 3/2 – moist) angular blocky, fine to medium structure, clear and smooth boundary;

Bw – 165–200 cm, colluvial material, silt loam, dark yellowish brown (10YR 4/4 – moist), angular blocky, fine to medium structure, gradual and smooth boundary;

C – 200–(220) cm, silt loam, light olive brown (2.5 Y 5/4 – moist), distinct carbonates;

Table 5. Texture of profile 3

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0–0.63	0.63–0.2	0.2–0.1	0.1–0.05	0.05–0.02	0.02–0.01	0.01–0.005	0.005–0.002	< 0.002	
Ap	0–20	0.00	0.00	13.0	5.6	14.5	28.7	13.7	11.7	8.9	3.9	SiL
Ah	20–40	0.00	0.00	11.2	15.9	19.0	27.4	9.8	8.0	5.9	2.8	SiL
Ah2	40–55	0.00	0.00	5.3	9.2	17.5	31.8	13.6	10.9	7.9	3.8	SiL
Bt	55–165	0.00	0.00	5.2	7.3	4.3	32.1	13.9	11.5	8.7	4.0	SiL
Bw	165–200	0.00	0.00	0.4	3.7	19.7	36.2	14.8	11.8	8.8	4.6	SiL
C	200–(220)	0.00	0.00	0.3	3.9	20.2	35.8	15.0	12.0	8.4	4.4	SiL

Table 6. Chemical and physicochemical properties of profile 3

Horizon	Depth [cm]	OC [g·kg^{-1}]	P [mg·kg^{-1}]	Conductivity [µS/cm]	Salts [m/m%]	pH		$CaCO_3$ [g·kg^{-1}]
						H_2O	KCl	
Ap	0–20	16.1	1070	344	0.03	7.1	7.4	89.6
Ah	20–40	14.0	741	314	<0.02	7.2	6.9	110.0
Ah2	40–55	11.1	592	311	<0.02	7.2	7.5	123.7
Bt	55–165	10.5	–	323	<0.02	7.2	6.9	90.9
Bw	165–200	10.3	–	310	<0.02	7.1	7.4	79.4
C	200–(220)	–	–	306	<0.02	7.9	7.5	

Profile 4 – Calcaric **Luvisol** (Aric, Colluvic, Cutanic, Humic, Pantosiltic)
Location: foot slope – inclination 3°, vineyard, slope 124 m a.s.l.,
N 45°52'05.6" **E** 18°18'34.4"

Morphology:

Ap – 0–20 cm silt loam, brown (10YR 4/3 – moist), strong angular blocky/granular fine structure, very few roots, clear and smooth boundary;

Ah – 20–60 cm, horizon, colluvic material, sandy silt loam, brown (10YR 4/3 moist), strong angular blocky structure, few roots, clear and smooths boundary;

Bt – 60–140 cm, *argic* horizon with distinct and common cutans, silt loam, brown (7.5 YR 4/4 – moist) strong angular blocky structure, very few roots;

Ck – 140–(160) cm, parent material with primary and secondary carbonates, silt loam, brown (7.5 YR 4/4 – moist) medium angular blocky structure, very few roots;

Table 7. Texture of profile 4

Horizon	Depth [cm]	Percentage share of fraction [mm]										Textural class
		> 2.0	2.0–0.63	0.63–0.2	0.2–0.1	0.1–0.05	0.05–0.02	0.02–0.01	0.01–0.005	0.005–0.002	< 0.002	
Ap	0–20	0.00	0.00	0.00	1.0	10.4	29.8	21.3	19.3	13.3	4.9	SiL
Ah	20–60	0.00	0.00	0.00	2.4	18.5	37.8	16.0	12.3	8.9	4.1	SiL
Bt	60–140	0.00	0.00	0.8	2.6	14.3	34.2	17.3	14.5	11.1	5.2	SiL
Ck	140–(160)	0.00	0.00	0.3	4.0	20.2	35.8	14.9	12.0	8.4	4.4	SiL

Table 8. Chemical and physicochemical properties of profile 4

Horizon	Depth [cm]	OC [g·kg^{-1}]	Conductivity [µS/cm]	pH		$CaCO_3$ [g·kg^{-1}]
				H_2O	KCl	
Ap	0–20	18.3	326	6.8	6.7	52.4
Ah	20–60	12.9	322	6.8	7.0	62.2
Bt	60–140	11.5	324	6.8	6.5	62.6
Ck	80–100	4.3	214	6.5	6.1	72.2

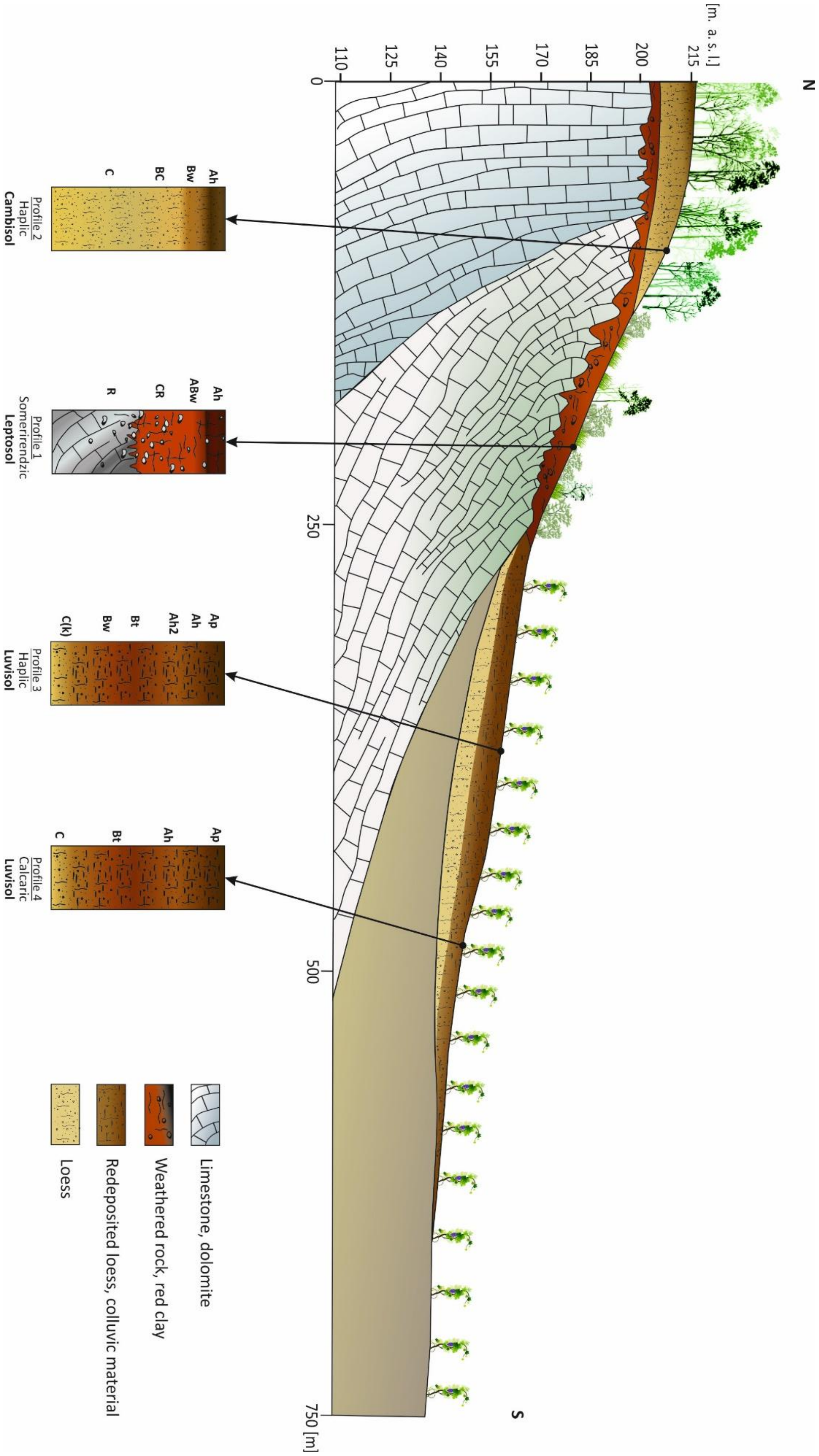


Fig. 2. Topo-lithosequence of soils in the southern slopes of the Villány Hills near Siklós, Hungary

Land use

There is a pronounced mesoclimatic and vegetational difference between the southern and northern slopes in terms of vegetation. The loess-covered northern slopes and summit regions are dominated by silver lime (*Tilia tomentosa*) hornbeam (*Carpinus betulus*), pedunculated oak (*Quercus robur*), Turkey oak (*Quercus cerris*) and, in some places, by beech (*Fagus sylvatica*).

The natural vegetation on the southern slopes is characterized by karstic wooded steppe (xerothermic wooded grassland) spotted, in places, with sparse rocky grasslands (Borhidi and Dénes, 1997). Trees in the wooded grasslands are dominated by South European flowering ash (*Fraxinus ornus*) and downy oak (*Quercus pubescens*), west of the village of Máriagyűd on the Tenkes Csukma blocks and the summit region of the Csukma block. A typical Mediterranean karstic steppe is found on the limestone surface of the southern slopes of the Szársomlyó Hill, with downy oak, South European flowering ash and invasive tree of heaven (*Ailanthus altissima*). The Szársomlyó is the only Hungarian habitat for some Mediterranean herbaceous plants, like *Trigonella gladiata* and *Colhicum hungaricum* (Lehmann, 1975; Borhidi and Dénes, 1997).

The loess-covered slopes on the southern side of the hills are extensively cultivated and used as vineyards (Tengler, 1997). To access the vineyards, unpaved dirt roads are used that are deepened into the loess and redeposited alluvial fans in the foothill loess sediments (Czigány, 1997; Czigány and Nagyváradi, 2000).

Climate

The study area belongs to the south-eastern Transdanubian Hills macro-region (Dövényi, 2010). The region is located in the temperate, fully humid climate zone with hot summers (Lovász, 1977; Kottek et al. 2006), with Mediterranean and sub-Mediterranean influence and arid continental influences. The average annual temperature is 10.8°C. The average temperature of the coldest month (January) is –0.5°C, while the warmest month is July with mean temperature of 22.5°C. The average total annual precipitation is around 680 mm in the region. The 30-year average value is 661 mm for the town of Siklós, 684 mm for Nagytótfalu, 694 mm for Villány and 701 mm for the town of Harkány (1971 to 2000 data, Hungarian Meteorological Services). Based on the meteorological data sets covering the period from the 1980s to 2010, February is the driest (32 mm) month, while the highest precipitation is recorded in June (83 mm) (Bötkös, 2006).

Soil genesis and systematic position

The investigated soil profiles exhibit high diversity of soil cover within the slopes of Villány Hills in SW Hungary. The soil sequence represents a typical series of soils starting from the summit covered by loess, which overlays the weathering products of limestone. In the steepest slope section, the loess cover is eroded, or was not even accumulated, hence the outcrops of the weathering limestone residuum and locally the rock. These are mostly protected areas, preserving the native vegetation cover, or therefore farming activities are precluded in the area.

The upper section and the most convex part of the slope is covered by ***Endocalcaric* Cambisol (*Siltic, Ochric*)** (IUSS Working Group WRB, 2015). This soil was formed under deciduous forest vegetation of silver lime (*Tilia tomentosa*) and black locust tree (*Robinia pseudoacacia*) (Fig. 2.). The texture in the entire soil profile is typical of soils formed on loess deposits, i.e. mainly silty loam (***Siltic***). The amount of organic carbon (>0.6%), structure and color of the A horizon is typical of the *mollic* horizon. Nevertheless, it does not meet the criteria for *mollic* according to the thickness (10 cm), therefore it was designated as the ***Ochric*** qualifier only. The carbonate content of the parent material is leached and depleted in the uppermost 60 cm, being less than 2%, the calcareous character is present only below 60 cm, therefore the ***Endocalcaric*** qualifier have to be added.

Profile 2 is located on a summit position on the rocky plateau of the Kopasz Hill, south of the village of Csarnóta. (Fig. 2). It represents a shallow soil with the *mollic* horizon developed on limestone outcrops (***Somerirendzic*** qualifier) and its loamy weathering products, containing sand and silt fraction, having the silty loam texture throughout (***Siltic*** qualifier) (Table 3). The diagnostic horizons in the discussed profile are: (i) Ah shallow humus-rich topsoil, (ii) a weakly-developed transitional ABw horizon rich in calcium carbonates, and (iii) heterogeneous parent material, which is composed of limestone blocks and boulders and its weathering product from Pliocene in the form of red 'clay' infillings. The most important feature of the profiles is the presence of coarse fragments in the subsoils and the shallow, carbonate-rich, humic surface epipedon. Due to the shallow profile and the proximity of the limestone and its weathered deposits, the carbonate content and the base saturation of the soil are extremely high, with 280.2 and 333.5 g kg^{-1} carbonate for the Ah and ABw horizons, respectively. The occurrence of soils with rendzic properties (Rendzinas in the Hungarian soil classification system) has already been pointed out by Lovász (1977). Due to the shallowness of the soil, it is uncultivated and only covered with a karstic wooded steppe dominated by South European flowering ash (*Fraxinus ornus*) and downy oak (*Quercus pubescens*).

Profile 3 – ***Haplic*** **Luvisol** ***(Aric, Colluvic, Cutanic, Humic, Pantosiltic, Bathycalcic)*** has been developed dominantly on colluvial material and translocated loess-paleosol deposits. The profile was excavated in an abandoned vineyard where cultivation was ceased in 2002. Soils in the vineyard were regularly fertilized and manured (***Humic***). The profile indicates a certain degree of leaching and clay translocation (***Cutanic***), as well as marked textural differences. Texture is dominated by the silt fraction (***Pantosiltic***). This part of the Villány Hills has been cultivated for the longest period of time, therefore colluvial and redeposited sediments have not only been formed by gravitational (derasional) processes but also by farming practices due to viticulture in the area since the Roman Ages (***Aric***). Moreover, the high amount of $CaCO_3$ with distinct secondary forms in the profile at a depth below 80 cm allows the identification of *calcaric* material. The carbonate content at this depth is high since the colluvial material is carbonate-rich too; due vertical leaching of carbonates, secondary carbonate concretions are also present. However, the carbonate content of the horizon does not meet the criteria of the *calcic* horizons, therefore it is ***Protocalcic.***

Profile 4 - ***Calcaric*** **Luvisol (*Aric, Colluvic, Cutanic, Humic, Pantosiltic*)** eventually had the same WRB classification and qualifiers as in the case of the soil in profile 3. This soil represents a relatively young soil developed as a consequence of *colluvic material* accumulation (***Colluvic*** supplementary qualifier). This material has been transported as a result of erosion from upslope since the area has been used as arable land in the past (***Aric***) (Lovász 1977; Tengler 1997; Czigány 1998). The texture of slope deposits is mainly silt (***Pantosiltic***). *Colluvic material* have a ***Humic*** character in the entire profile which is likely caused by the erosion of the topsoils further upslope. During the accumulation of the *colluvium,* certain periods of stabilization and low-degree erosional periods are identified in the profile. Nonetheless, the sporadic but rather torrent runoff and infiltration events caused heavy rainfalls triggered pronounced leaching and clay translocation processes in the soil (***Cutanic***). These soil forming processes are clearly represented in the profile and also reflected in the deeper dark horizons containing a high concentration of organic carbon. The contemporary surface horizons of these soils are enriched with humus by manuring and fertilization. However, their properties (color, structure) do not meet the criteria of *mollic* horizons. The soil in the profile is enriched with carbonates due to the colluvial processes and the proximity of loess deposits **(*Calcaric*).**

Soil sequence

The above-described transect (catena) shows a typical morpho-lithosequence for the Villány-Hills, formed according to its parent materials (limestone, loess and colluvium), surface topography and relief, and subsequently modified by agricultural activities and natural erosional processes. Properties of all analyzed profiles, with the exception of Profile 1, were strongly influenced by human-induced erosion. Profile 1 is a rather natural profile on a very gently sloping summit plateau. Although erosional processes are also observable here, they did not contribute significantly to the removal of the loess cover completely, only inhibited deeper soil development and organic carbon accumulation. Profile 2 is located in the erosional section of the investigated slope. The shallow soils here are discontinuous and scattered, altering with rock outcrops and hence bare surfaces, and do not form an uninterrupted soil cover. Formerly, profile 2 was also likely covered by loess, but we may also deduce that dust deposition itself was not possible here due to steep slopes, and soils have always developed on weathering products of limestone, and soils were also Leptosols in earlier times. Nevertheless, the presence of former and existing *cambic* Bw or even *argic* Bt horizons is also possible in the case of thicker weathered material, which could be eroded later as a consequence of human influence (deforestation, grazing etc.). Today profile 2 represents a strongly eroded stage: the shallow topsoil was likely truncated. Intense erosional and derasional processes must have occurred here in the past, probably due to land use (quarrying, vineyards), but also from natural reasons (steep slope, lack of dense forest cover). Lately, however, over the past decade or two (as of 2017), no-till farming practices have been prevailing in the region.

Soils developed on redeposited colluvial deposits dominate the middle and lower sections of the slopes (Profiles 3 and 4). Currently, the slope processes (primarily erosion) have been restrained by the introduction of grass vegetation and no-till viticulture, which also leads to improved organic matter characteristics of the studied profiles. In Profile 4, humus material accumulation was detected in the pedon, likely due to the resupply of organic matter in the form of manure and fertilizers.

The impact of erosion, horizontal translocation and redeposition according to the slope position is reflected in the systematic sequence of the described soils. Profile 1 has been markedly eroded and truncated, therefore profile development is poor, thus it was classified as **Cambisol**. Profile 2 with a shallow *mollic* horizon, but developed from material with a significant amount of coarse limestone fragments was classified as **Leptosols**. Profiles 3 and 4 are both of colluvial origin with distinct clay translocation after deposition of slope deposits and were classified as **Luvisols**. However, the marked impact of human activities in this catena is clearly visible in Profiles 1, 2 and 3, as the upper part of these profiles were eroded, redeposited and transformed into material with coarse granular moderate structure.

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Soils of the Ljubljana basin western edge (foot slopes of the Polhograjsko hills)

Blaž Repe

The study area comprises the eastern foot slopes of the Polhograjsko hills, on the western edge of the Ljubljana basin. Both entities are part of the Pre-Alpine region, which extends south of the Alps, across the entire country. The Pre-Alpine area is characterized by middle range hills (up to 1000 m a.s.l.) and swift changes of parent material, especially older siliceous and younger carbonate rocks (Ogrin and Plut, 2009).

Fig. 1. Location

The studied soil sequence is located in the transition between two mesoregions: the Ljubljana Basin and the Polhograjsko hills, west of the Ljubljana capital city. The sequence is typical of this region and it represents a soil genesis on different slope positions on the carbonate parent material (Gabrovec, 1989).

Lithology and topography

The foot slopes of the Polhograjsko hills is a set of 2 to 3 km wide ranges of slopes, rising from the sediments of the Ljubljana basin to the first summits (600–700 m a.s.l.). The hills were formed during the Alpine orogenesis and were lifted above the basin, which started to descend in Pliocene. During the Pleistocene ice ages, the basin was filled with glacial and alluvial gravel and sand, mostly of the carbonate origin. The hard rock bottom of the basin consists of the Carboniferous and Permian, hard, siliceous clay- and sandstones. The same parent material is also typical of the lower parts of the Polhograjsko hills slopes. Thick layers of hard and compact Triassic limestone and dolomites represent the upper part of slopes and summits. Karstic features and hydrology developed on these rocks (Grad and Ferjančič, 1976). In some parts, carbonate material reaches the basin, while in others, siliceous rocks extend nearly to the summits, which makes the area very diverse and complicated in terms of the soil cover (Repe, 2006).

The area represents the lowest part of Slovenia's Pre-Alpine hills, which hardly reaches 1000 m a.s.l. in the highest part (Tošč, Pasja Ravan), thus most of the area is at 500 to 700 m above the local erosion base (the Ljubljana Basin). The average height is only 540 m a.s.l., but the average slope inclination is more than 20° (Repe, 2006). The area is dissected by ravines and small-scale valleys of occasionally appearing streams, which are all of the extremely torrential nature. They are the main reason for floods in the settlements on the edge of the Ljubljana basin and the capital itself (Radinja, 1996). The transition between the ground of the basin and the slopes of the hills is covered with thick layer of colluvial and delluvial material, consisting mainly of the carbonate gravel and siliceous silt and sand.

Profile 1 – Eutric Anocolluvic Skeletic **Regosol** (Nechic, Ochric, Siltic)

Localization: Transition between ravine bottom and slope, mixed colluvial material, next to the dry riverbed, inclination 4°, mixed beech, alder and ash forest, 335 m a.s.l., **N** 46°04'47.0" **E** 14°26'07.9"

Morphology:

Ah – 0–25 cm, *ochric* horizon, loam, dusky red (2.5YR 3/2, moist), slightly moist, moderate subangular structure, soft consistency, common roots, gradual boundary, many rounded coarse fragments, <u>colour comes mainly from purplish Permian sandstone;</u>

AC – 25–35 cm, loam, yellowish red (5YR 4/6, moist), slightly moist, moderate subangular structure, soft consistency, common roots, gradual boundary, many rounded coarse fragments;

C1 – 35–50 cm, silty loam, yellowish brown (10YR 5/6), slightly moist, weak subangular structure, many rounded coarse fragments;

C2 – 50–(60) cm, dominant rounded coarse fragments of mainly siliceous Permian sandstone (75%) and Triassic limestone (25%);

Table 1. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]					Textural class
		2-0,2	0,2-0,05	0,05-0,02	0,02-0,002	<0,002	
Ah	0–25	16	34	6	29	15	L
AC	25–35	17	35	15	22	11	L
C1	35–50	37	30	23	8	2	SL
C2	50–(60)	46	34	17	2	1	LS

Table 2. Chemical and physicochemical properties

Horizon	Depth [cm]	$CaCO_3$ [$g \cdot kg^{-1}$]	pH [KCl]	OC [$g \cdot kg^{-1}$]
A	0–25	5.1	6.3	16
AC	25–35	6.6	6.5	7
C1	35–50	7.0	6.5	–
C2	50–(60)	14	6.6	–

Table 3. Sorption properties

Horizon	Depth [cm]	TEB	CEC	BS [%]
		[cmol(+)$\cdot kg^{-1}$]		
A	0–25	20.8	24.6	84.6
AC	25–35	18.8	22.5	83.6
C1	35–50	–	–	–
C2	50–(60)	–	–	–

Profile 2 – Eutric Dolomitic Skeletic Lithic **Leptosol** (Nechic, Protic)
Localization: Very steep lower slope (local change), inclination 45°, hard Triassic dolomite, heavy erosion, beech and spruce forest, 350 m a.s.l., **N** 46°04'37.9" **E** 14°26'07.1"

Morphology:

OC – 0–7 cm, extremely shallow, 10YR 2.5/1 (very dark brown, moist), sandy loam, granular, weakly developed structure, common fine roots, extreme content of coarse fragments (fresh angular gravel, > 75%), coarse fragments are common as a surface cover (heavy sheet erosion), abrupt and irregular boundary, very strongly calcareous (dolomite), OM is raw and poorly decomposed;

R – 7–(50) cm, compact Triassic dolomite, slightly cracked at the contact;

Table 4. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]					Textural class
		2-0,2	0,2-0,05	0,05-0,02	0,02-0,002	<0,002	
OC	0–7	45	23	25	6	1	SL
R	7–(50)	–	–	–	–	–	–

Table 5. Chemical and physicochemical properties

Horizon	Depth [cm]	$CaCO_3$ [$g \cdot kg^{-1}$]	pH [KCl]	OC [$g \cdot kg^{-1}$]
OC	0–7	230	6.8	140
R	7–(50)	–	–	–

Table 6. Sorption properties

Horizon	Depth [cm]	TEB	CEC	BS [%]
		[cmol(+)·kg^{-1}]		
OC	0–7	35.2	42.5	82.7
R	7–(50)	–	–	–

Profile 3 – Dolomitic Leptic Rendzic **Phaeozem** (Hyperhumic, Loamic)

Localization: Steep middle slope, inclination 18°, hard Triassic dolomitic limestone, beech forest with some meadows, 390 m a.s.l., **N** 46°04'39.6" **E** 14°25'59.3"

Morphology:

A1 – 0–18 cm, *mollic* horizon, silty clay loam, dark reddish brown (7.5YR 3/3, moist), slightly moist, strong subangular blocky structure, slightly hard consistency, gradual and smoot boundary, common angular coarse fragments, few fine roots;

AB – 18–27, *mollic* horizon, clay loam, dark reddish brown (2.5YR 3/3, moist), slightly moist, strong subangular blocky structure, slightly hard consistency, gradual and smoot boundary, many angular coarse fragments, few fine roots;

AC – 27–33, *mollic* horizon, clay loam, brown (7.5YR 4/2, moist), slightly moist, strong subangular blocky structure, slightly hard consistency, clear and wavy and smoot boundary, abundant angular coarse fragments, few fine roots;

R – 33–(60) cm, compact Triassic dolomitic limestone, slightly cracked at the contact;

Table 7. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]					Textural class
		2-0,2	0,2-0,05	0,05-0,02	0,02-0,002	<0,002	
A1	0–18	4	17	13	31	35	SCL
A2B	18–27	6	19	14	31	30	CL
A3C	27–33	16	24	17	15	28	CL
R	33–(60)	–	–	–	–	–	–

Table 8. Chemical and physicochemical properties

Horizon	Depth [cm]	$CaCO_3$ [g·kg^{-1}]	pH [KCl]	OC [g·kg^{-1}]
A1	0–18	42	7	98
A2B	18–27	45	7.5	95
A3C	27–33	53	7.5	92
R	33–(60)	–	–	–

Table 9. Sorption properties

Horizon	Depth [cm]	TEB	CEC	BS [%]
		[cmol(+)·kg^{-1}]		
A1	0–18	57.8	61.6	94.0
A2B	18–27	61.6	64.3	95.8
A3C	27–33	54.8	58.0	94.6
R	33–(60)	–	–	–

Profile 4 – Endodolomitic Epileptic **Luvisol** (Neocambic, Cutanic,Epidystric, Anoloamic, Ochric)
Localization: karstic, levelled part of the middle slope, undulating, partly colluvic, inclination 0°, hard Triassic dolomite, beech forest, 370 m a.s.l., **N** 46°04'57.1" **E** 14°26'02.0"

Morphology:

O – 2–0 cm, decomposed and dried beech leaves (*Fagus sylvatica*);

A – 0–10 cm, ochric, silty loam, brown (7.5YR 4/3, moist), slightly moist, very few medium gravel angular–subrounded slightly weathered coarse fragments; moderate nutty subangular blocky structure, soft consistency, common fine roots, clear and smooth boundary;

Bw – 10–31 cm, silty loam, yellowish brown (10YR 5/6, moist), slightly moist, very few fine gravel, angular–subrounded slightly weathered coarse fragments; moderate subangular blocky structure, friable consistency, common fine and medium roots, gradual and smooth boundary;

Bt – 31–41 cm, *argic* horizon, silty clay loam, strong brown (7.5YR 5/6, moist), slightly moist, very few fine gravel, angular–subrounded slightly weathered coarse fragments; strong subangular blocky structure, firm consistency, common fine and medium roots, gradual and smooth boundary;

BtC – 41–44 cm, silty clay loam, strong brown (7.5YR 5/6, moist), slightly moist, many fine gravel, angular–subrounded slightly weathered coarse fragments; strong subangular blocky structure, firm consistency, few medium roots, clear and wavy boundary;

R – 44–(60) cm, compact Triassic dolomite, moderately weathered (dolomitic sand and silt) and slightly cracked at the contact;

Table 10. Texture

Horizon	Depth [cm]	Percentage share of fraction [mm]					Textural class
		2-0,2	0,2-0,05	0,05-0,02	0,02-0,002	<0,002	
O	2–0	–	–	–	–	–	–
A	0–10	4	7	20	58	11	SL
Bw	10–31	6	8	18	54	14	SL
Bt	31–41	5	10	13	45	27	SCL
BtC	41–44	12	8	9	43	28	SCL
R	44–(60)	–	–	–	–	–	–

Table 11. Chemical and physicochemical properties

Horizon	Depth [cm]	$CaCO_3$ [g·kg^{-1}]	pH [KCl]	OC [%]
O	2–0	–	–	–
A	0–10	9	6.2	27
Bw	10–31	2	6.3	6
Bt	31–41	8	6.9	2
BtC	41–44	15	7.4	–
R	44–(60)	–	–	–

Table 12. Sorption properties

Horizon	Depth [cm]	TEB	CEC	BS [%]
		[cmol(+)·kg^{-1}]		
O	2–0	–	–	–
A	0–10	8.8	19.1	46.1
Bw	10–31	7.3	17.9	40.7
Bt	31–41	14.3	21.0	68.3
BtC	41–44	16.4	22.4	73.3
R	44–(60)	–	–	–

Land use

The vegetation and land use is typical of the Pre-Alpine hills, which is a dense forest cover. The dominant species is beech (*Fagus sylvatica*), present in more than ¾ of the wood reserves. Beech forest are of two main types (Marinček, 1987):

- Acidophilus, on siliceous parent material and acid soils:
    - *Blechno-Fagetum* on shallower and very acid soils and;
    - *Casteno sativae-Fagetum* on thicker and acid soils.
- The *Hacquetio-Fagetum* association dominates on carbonate parent material and on shallow, slightly acid or neutral soils.

These forests have frequently a protective function, due to the steep slopes and heavy erosion processes (Ogrin et al., 2017).

Due to steep slope inclinations, shallow and sometimes acid soils, lack of surface waters (karst) and remoteness from the centers, former fields, orchards, meadows and pastures have long been abandoned. They exist only in the very close vicinity of the very few settlements and isolated farms (Repe, 2006).

Climate

The research area belongs to the temperate climate of central Slovenia. It could be described as moderately continental or moderately warm and humid climate with warm summers (Ogrin, 1996). Slopes are well drained with udic regime, but the valleys and basins are often aquic (Vrščaj, Repe, Simončič, 2017). The average temperature of the coldest month (January) is −2°C, while the warmest month is July (18°C). The average annual precipitation is above average for central Slovenia and reaches 1700 mm. The distribution of precipitation does not differ much between seasons, but the wettest months are autumn (November, 200 mm) and the driest – winter months (February, 90 mm) (ARSO, 2005).

Fig. 2. Topography and one of the side valley entering the hills (Blaž Repe)

Fig. 3. View of the foot slopes landscape (Blaž Repe)

Soil genesis on hard and compact carbonate parent material

Soil genesis in the foot of the Polhograjsko hills shows a modified sequences, already described by Stritar (1991) in his book Landscapes and landscape systems. Among which, he also described soil sequences or using his terminology pedosequences on hard carbonate rocks (limestones and dolomites). He states this is the most important soil sequence in Slovenia, because it appears in all natural regions (high and low mountains and hills and especially in karstic areas).

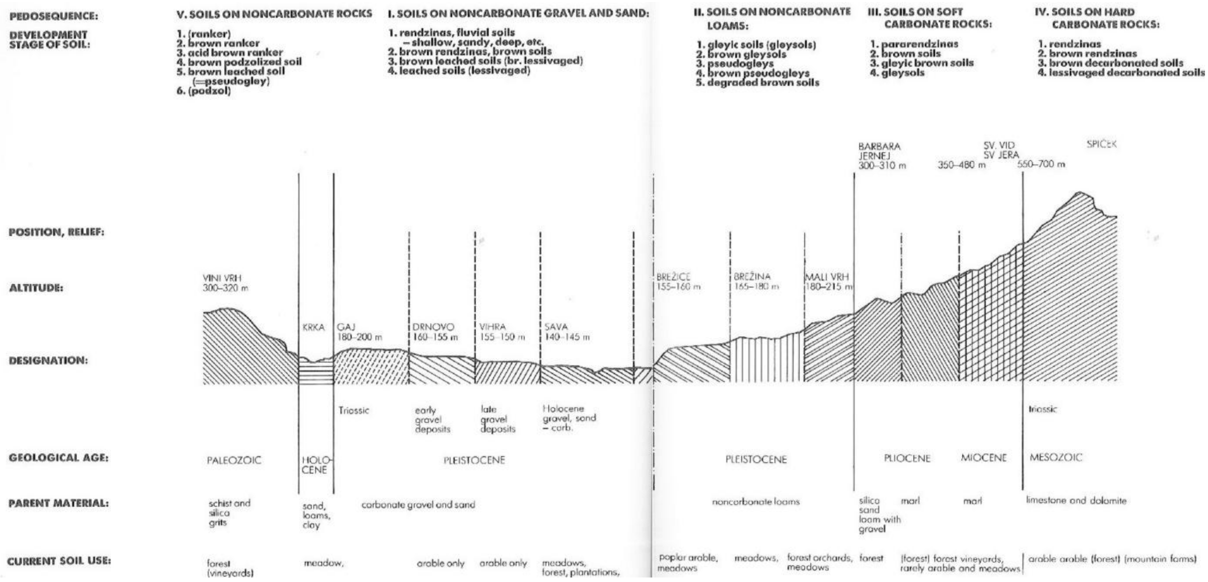


Fig. 4. Connection between chronological base and pedosequence (an example of Krško Polje and its surroundings) (Stritar, 1991)

The developing stages of soil on hard carbonate rocks show considerable regularity in appearance (limestones and dolomites of different periods) throughout the regions of Slovenia. The variety of soil groups on limestones and dolomites is closely connected or conditioned by specific geomorphology of these surfaces, which are modulated by irregularly distributed sinkholes, smaller valleys and precipitous, larger plateaux, terraces and undulating valleys. This varied relief would not have been the cause of such sudden changes and variations in soil forms if it had not been for the associated microrelief of the rock. It dissects the surface: numerous pockets, cracks, crevices and hollows, as well as larger rocks and boulders, which have broken through the soil cover to the surface and hinder or even prevent the use of this land for agricultural purposes. Only the dolomite base does not show this diversity; rocks and boulders are very rare on the surface and the surface is equally covered with soil. Humic Leptosols are quite deep (around 20 cm) and equally thick. More developed decalcified soils (Cambisols and Luvisols) have a larger proportion of clays (Sušin, 1964).

In the selected area, hard, Triassic, carbonate rocks prevail and in this special case – dolomites. There are certain differences compared to pure limestone areas:

- The area is typically karstic and undulating but it has little rock outcrops.
- Dolomite is more prone to mechanical weathering, which results in larger contribution of coarse rock fragments and somewhat higher soil clay content. Nevertheless, soils are still very shallow.
- The contact between soil and hard parent rock is irregular and broken. It depends on micro-scale, local fractures and corrosiveness of the rock. Soil shows extreme mosaic micropattern that cannot be effectively predicted by general parameters of lithology, topography or

hydrology. Mosaic distribution reflects swift changes in the distribution and appearance of rock outcrops, Leptosols, Phaeozems, Cambisols, Luvisols and sometimes even Regosols (Fig. 4).

– Due to the very good water permeability of soils, karstic areas show very typical automorphic soil genesis. However, dolomite is less permeable than limestone, therefore Stagnic properties can developed at some locations in Bt horizons.
– In Slovenia, soils on dolomite can have extreme carbonate content. However, this parameter is difficult to estimate in the field (not clearly recognizable) as warm HCl solution is required.

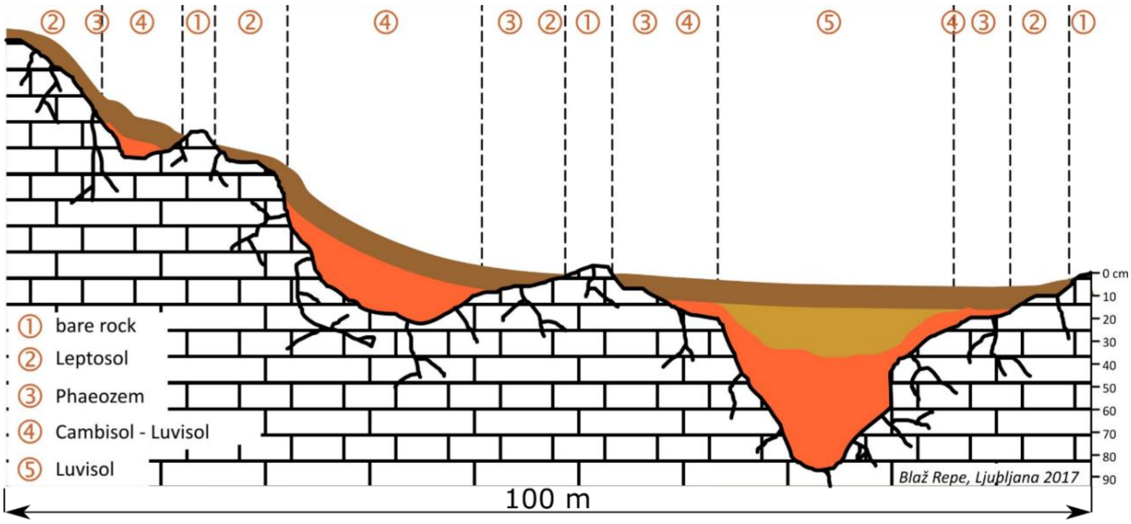
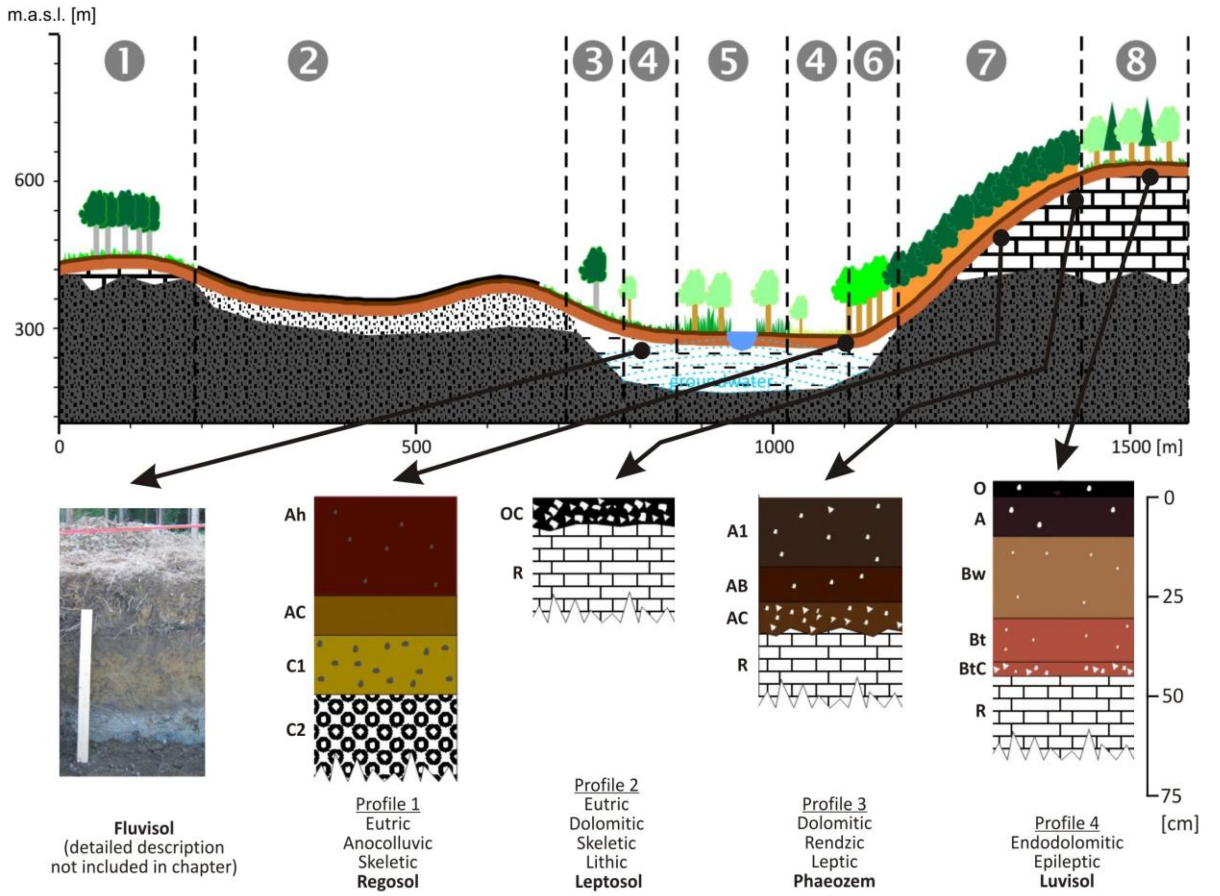


Fig. 5. Mosaic pattern of soil groups on carbonate rocks

Soil sequences hard and compact carbonate parent material

The basic interaction between slope processes, landforms in fluvial geomorphic systems and soil formation or other soil parameters is more or less known (Gerrard, 1992). The question remains what is the impact of the relief and its elements on soils in the karst geomorphic system where slope processes are different. In karst, vertical drainage dominates and the surface runoff is almost absent. Chemical weathering usually dominates over physical weathering and denudation occurs mostly in the form of solution. Accumulation of once weathered material (bedrock) on the other hand is negligible (Bergant, 2011).

Due to the mosaic soil patterns (Fig. 4), the soil sequence on hard and compact carbonate parent material is very difficult to estimate, model or predict. The sequence follows some general rules, which mainly depend on slope inclination i.e. Regosol – Leptosol – Phaeozem – **Cambisol / Luvisol** with increasing inclination. Bergant (2011) performed different graphical and statistical analyses based on measurable topography parameters in the karstic area near the town of Postojna. As he expected, the ***Rendzic*** **Leptosols** and ***Chromic*** **Cambisols** were two predominant soil types found during the sampling. Soil samples were distinguished by their depth and thickness of horizons, organic matter content, water content, form of structural aggregates, texture etc. An extreme mosaic structure of soil types and depth distribution was found, however, a detailed analysis of sampled transects proved the relationship between topography and soil horizon incidence, thickness and other soil morphological properties. The relationship between measurable relief elements and soil depth was calculated using the Pearson correlation coefficient and multiple regression analysis (soil depth / slope inclination r = -0.54; soil depth / curvature r = -0.27; *log (soil.depth) = 1.577 – 0.015 x inclination – 0.041 x curvature ±0.14*).



	parent material	topography	soil group (part of the soil sequence)	land use
1	conglomerate	undulating	deep, acid Luvisols	acidophilous *Fagus sylvatica* or *Pinus sylvestris* forest
2	carbonate gravel	flat, river terraces	Skeletic Eutric Leptosol	fileds
3	fine, clay and silt sediments	flat	deep, acid Stagnic Luvisols	meadows or *Pinus sylvestris* forest
4	fine, clay and silt sediments, with deeper ground water	alluvial plain	Stagnosols and Gleysols	meadows and poor fields
5	fine, clay and silt sediments, with shallow ground water	flood plain	Gleysols, Fluvisols	wet forest (*Salix Alba*, *Fraxinus excelsior* and *Alnus sp.*) and meadows
6	colluvium	foot slope	Regosols and Stagnosols	moist forest (*Acer sp.*, *Fraxinus excelsior*, *Ulmus sp.*)
7	dolomite / limestone	irregular slope	mosaic pattern of Rendzic Leptosols, Chromic Cambisols and occasionally Haplic Luvisols	beech forest (*Fagus sylvatica* with *Hacquetia epipactis* or *Lamium orvala*)
8	dolomite / limestone	karstic, undulating	mosaic pattern of Haplic Luvisols, Chromic Cambisols, Phaeozems and occasionally Rendzic Leptosols	beech forest (*Fagus sylvatica* with *Acer pseudoplatanus* and *Abies alba*)

Fig. 6. Soil sequences in the foot of the Polhograjsko hills

Using the recorded slope data and total curvature derived from DEM 12.5 as input variables, a weak (R = 56.2, only 31.6% of the variability can be explained), but statistically significant correlation between the dependent and independent variable (soil depth) was proved. Similar results were obtained by Repe (2006) in the study of digital soil mapping in the Polhograjsko hills were 39.4% of the variability had been explained by carbonate parent material. Higher slope inclinations have proportionally shallower soils, higher content of coarse fragments and smaller content of clay, higher pH value, more carbonates and less advanced soil development. Conditions are opposite on gentler slopes with heavy leaching of carbonates.

In addition to the slope inclination, most of the soil variability can be accounted for by the micro distribution of cracks, impurities and destructions of parent material that can only be exactly determined in the field.

Theoretical suppositions have been partially confirmed in this field research on the soil sequence (Fig. 6):

- The transition between flat and inclined surface, on slope ravines and former river terraces is indicated by the accumulation of soil particles (**Regosols**). They are of colluvial and delluvial origin, where water loses its erosive power and starts to accumulate (unsorted material, moister soils, hygrophilous plant species, poor meadows, fields are rare) (Repe, 2007).
- Slopes are covered with shallow and extremely shallow soils (**Leptosols**). Soil genesis is extremely slow and is additionally hindered by heavy sheet erosion processes and denudation. Cutting of trees in the past accelerated this process of soil cover thinning. The only significant processes (besides erosion) are accumulation of humus and very slow mechanical weathering of bedrock (accumulation of rock fragments).
- The transition between inclined and undulating surface is indicated by the increase in the fine particles, soils are thicker and move toward **Phaeozem / Cambisol** group. Coarse fragments move down to the lithic contact. The water movement is still downslope, therefore there is no noticeable leaching or argic properties development. There is a considerable amount of meadows, pastures or orchards on these soils.
- Undulating karstic topography is generally marked by **Cambisols** and especially **Luvisols**, since the water movement is mostly vertical, through the profile and cracks into the parent material. The clay content increases considerably (especially in the concave cracks, fissures and karst dolines) and can be attributed mainly to the residium of former, less resistant bedrock cover (e.g. flysch), colluviation processes from higher positions and the remnants of corrosion of carbonate rocks (iron oxides and other impurities). The percentage of fields and meadows increased considerably (Repe, 2007).
- Soil genesis on hard carbonate parent material is very slow, 2000–3000 years for 15–20 cm of soil (Vidic, 1998). On slopes, it is greatly exceeded by erosion.
- Despite favorable physical and chemical properties of all soils in this sequence, they represent a serious restriction for agriculture (Gams, 1974). This can mainly be contributed to shallow soils with many rock outcrops and lack of surface waters (running or stagnant). The percentage of forest cover in land use is the highest in Slovenia and can be up to 70 or even 90%. On slopes with northern expositions, it is an exclusive land use type. These soil sequences are typical areas of beech forest associations (*Hacquetio-Fagetum*, *Lamio orvalae-Fagetum* and *Omphalodo-Fagetum*) (Vrščaj, Repe, Simončič 2017).

The very frequent occurrence of soil types with quite different properties provides a sound basis only for forest. On steep locations and in the mountain and high mountain karst in general, younger and shallower soil forms predominate along with a number of Leptosol groups, which are sometimes covered with grasslands and more often by forest. Rural development in these regions is relatively slow because of the problematic supply of water and problems of wastewaters. Sunny aspects of slopes suitable for construction are located in closed valley systems that can communicate with more developed areas. This is also a relatively stable land in terms of earthquakes. In this soil sequence, a clear separation of urban and rural space would be necessary. Unregulated settlement usually uses good arable land, which is not overabundant in this soil sequence. There are usually more suitable sunny less steep locations with shallow soil (Leptosol, Phaeozem, eroded Cambisols soil etc.), which provides a good ecological base for settlement (Stritar, 1991).

Fig. 7. Rapidly growing suburban residential areas at foot of the Polhograjsko hills (A. Jesenšek)

This is especially the case of the researched slopes of Polhograjsko foothills. It nowadays became one of the most desirable, most eminent, most expensive and the fastest growing suburban residential areas around the capital (Fig. 7).

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A sequence of Technosols developed from ashes from "Pątnów" and "Konin" thermal power stations (central Poland) combusting lignite

Łukasz Uzarowicz

The study area is located on abandoned ash settling ponds of the "Pątnów" and "Konin" thermal power stations (TPSs), the town of Konin (central Poland) (Fig. 1), combusting Miocene lignite. The studied soil profiles (K2, K3, and K5) can be arranged into a sequence from the least to the best developed in the following order: K2 ≈ K3 < K5. The approximate age of all soils is 40 years. Profile K5 was the best developed, as it was a result of reclamation which accelerated soil-forming processes and profile development. Detailed characterization of soil properties, mineral transformations, and evolution of the studied soils is presented elsewhere (Uzarowicz and Zagórski, 2015; Uzarowicz et al., 2017, 2018). According to Kondracki (2002), the studied soil sequence is located in the Gniezno Lakeland mesoregion, which is part of the Great Poland Lakeland macroregion.

Fig. 1. Location

Properties of parent material

The investigated soils were technogenic soils (Technosols) developed from industrial wastes, which are fly ashes and bottom ashes being an effect of combustion of lignite in thermal power stations. Lignite always contains some mineral admixtures (clay minerals, quartz, carbonates, sulfides etc.) accompanying organic matter (e.g. Vassilev and Vassileva, 1996). Therefore, some quantities of mineral residues (e.g. fly ash and bottom ash) are left after lignite combustion. These residues are products of high temperature transformations of minerals occurring initially in lignite. Fly ash is a light fine-grain residue which goes up with flue gases and is caught on precipitators. Bottom ash is a coarse-grain residue which is heavy and therefore goes down the combustion chamber.

Land use

All studied soil were located on industrial wastelands. Profile K2 was covered with a meadow consisting mainly of grasses (predominantly reed grass), young seedlings of birch, willow, and white poplar. Profile K3 was covered with a sparse meadow with patchy plant cover containing grasses, lichens, single seedlings of willow, white poplar, and birch. Profile K5 was covered with a young sparse forest consisting of birch, Scots pine, and willow. The groundcover contained grasses, mosses, clover and other perennials.

Climate

The average annual temperature in the study area is about 8°C (Woś, 2010). The average temperature of the coldest month (January) is –4°C, whereas July is the warmest month (18°C). The average annual precipitation is about 550 mm.

Profile K2 – Spolic **Technosol** (Alcalic, Epiarenic, Endoloamic, Protocalcic, Fluvic, Hyperartefactic, Laxic, Vitric)

Location: an abandoned, unreclaimed quarter of the settling pond near the "Pątnów" TPS, after closure used as a place for evaporation of alkaline waters from TPS, a flat surface, 88 m a.s.l., **N** 52°17'59,2", **E** 18°12'05,4"

Morphology:

C – 0–16 cm, a yellowish chalky calcareous material weakly laminated, pale brown (2.5Y 7/4), slightly moist, very friable to friable consistence, crumbly structure, few roots, abrupt boundary;

2C – 16–32 cm, dark gray (2.5Y 4/1), slightly moist, very friable to friable consistence, weak crumbly structure, few roots, clear boundary;

3C – 32–50 cm, gray (2.5Y 6/1), slightly moist, friable consistence, single grain structure, very few roots, clear boundary, an ash material, clearly laminated;

4C – 50–110 cm, very dark gray (GLEY1 3/N), slightly moist, firm consistence, platy / angular blocky structure, very few roots, clear boundary, a laminated material with alternating silty and sandy layers, little (a few mm) fragments of unburned lignite occurred in the horizon;

5C – 110–(115) cm, gray (2.5Y 5/1), slightly moist, very firm consistence, angular blocky / platy / single grain structure, none roots, a sandy ash material containing thin (a few mm) layers of fine material;

Table 1. Texture of profile K2

Horizon	Depth [cm]	Percentage share of fraction [mm]									Textural class
		> 2.0	2.0–1.0	1.0–0.5	0.50–0.25	0.25–0.10	0.10–0.05	0.05–0.02	0.02–0.002	<0.002	
C	0–16	0	–	–	–	–	–	–	–	–	–
2C	16–32	1.2	1	9	30	43	10	4	3	0	S
3C	32–50	0.7	0	15	42	39	3	1	0	0	S
4C	50–110	8.1	0	1	4	21	25	25	22	2	SL
5C	110–(115)	29.7	–	–	–	–	–	–	–	–	–

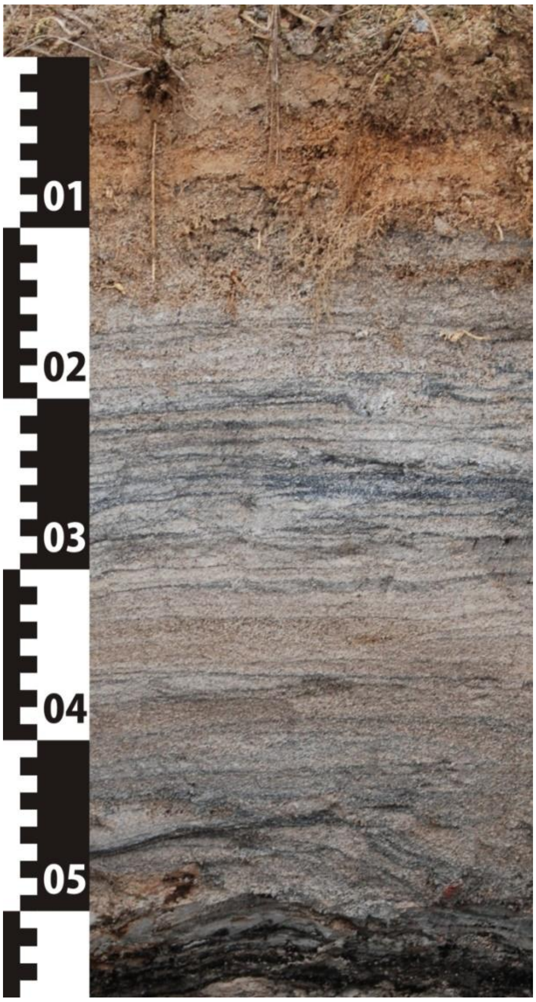
Table 2. Chemical and physicochemical properties of profile K2

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	St [g·kg^{-1}]	pH_{KCl}	$CaCO_3$ [g·kg^{-1}]	Phosphate retention (%)
C	0–16	–	0.6	–	6.4	10.3	827	–
2C	16–32	0	0.2	–	1.1	9.8	33	67.9
3C	32–50	0	0	–	1.3	10.7	6	31.1
4C	50–110	0	0	–	9.0	10.5	62	61.3
5C	110–(115)	0	0	–	2.7	11.7	17	92.8

Table 3. Sorption properties of profile K2

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	TEB	HA	CEC	BS [%]
		[cmol(+)·kg^{-1}]							
C	0–16	247.1	0.7	1.2	1.4	250.4	0.2	250.6	99.9
2C	16–32	26.4	2.3	2.2	1.0	31.8	0.0	31.8	100
3C	32–50	7.7	2.6	0.9	0.3	11.5	0.0	11.5	100
4C	50–110	139.0	13.2	3.3	4.0	159.4	0.0	159.4	100
5C	110–(115)	31.9	6.5	1.0	0.5	39.8	0.0	39.8	100

Profile K3 – Endoleptic Spolic **Technosol** (Alcalic, Protocalcic, Fluvic, Hyperartefactic)
Location: an abandoned, unreclaimed quarter of the Gosławice settling pond near the “Pątnów” TPS, a flat surface, 82 m a.s.l., **N** 52°16'53,6", **E** 18°14'55,9"



Morphology:

Oi/C – 0–1 cm, weakly decomposed grass and moss litter;

AC – 1–3 cm, yellowish brown (10YR 5/4), slightly moist, very friable to friable consistence, crumbly structure, common roots, clear boundary, a yellowish chalky calcareous material;

C – 3–7 cm, yellowish brown (10YR 5/4), slightly moist, very friable to friable consistence, crumbly structure, many roots, clear boundary;

2C – 7–12 cm, gray (10YR 5/1), slightly moist, firm consistence, single grain structure, many roots, clear boundary, a sandy ash material loosened by roots;

3C – 12–25 cm, grayish brown (10YR 5/2), slightly moist, very to extremely firm consistence, coherent material with weak single grain structure, few roots, gradual boundary, a clearly laminated and cemented sandy layer (grey layers with quartz and thin black laminae with magnetite can be distinguished), sand can be scraped using a knife;

4C – 25–50 cm, grayish brown (10YR 5/2), slightly moist, very firm consistence, coherent material with weak single grain structure, none roots, clear boundary, a clearly laminated and cemented sandy layer (grey layers with quartz and thin black laminae with magnetite can be distinguished), sand can be scraped using a knife;

5C – 50–(55) cm, brown (10YR 5/3), slightly moist, very to extremely firm consistence, coherent material with weak single grain and platy structure, none roots, a cemented layer consisting of fine ash material, large amounts of unburned fragments of lignite occurred in the horizon;

Table 4. Texture of profile K3

Horizon	Depth [cm]	Percentage share of fraction [mm]									Textural class
		> 2.0	2.0–1.0	1.0–0.5	0.50–0.25	0.25–0.10	0.10–0.05	0.05–0.02	0.02–0.002	<0.002	
Oi/C	0–1	–	–	–	–	–	–	–	–	–	–
AC	1–3	4.1	–	–	–	–	–	–	–	–	–
C	3–7	4.3	–	–	–	–	–	–	–	–	–
2C	7–12	12.8	0	25	48	20	2	3	2	0	S
3C	12–25	44.3	0	17	46	28	4	3	2	0	S
4C	25–50	14.2	1	33	49	11	2	2	2	0	S
5C	50–(55)	60.1	–	–	–	–	–	–	–	–	–

Table 5. Chemical and physicochemical properties of profile K3

Horizon	Depth [cm]	OC [$g \cdot kg^{-1}$]	Nt [$g \cdot kg^{-1}$]	C/N	St [$g \cdot kg^{-1}$]	pH_{KCl}	$CaCO_3$ [$g \cdot kg^{-1}$]	Phosphate retention (%)
Oi/C	0–1	24	1.3	19	10.1	9.0	8	–
AC	1–3	17	0.8	22	9.1	9.2	392	–
C	3–7	7	0.1	122	7.0	9.6	433	–
2C	7–12	3	0	–	11.6	10.9	17	62.5
3C	12–25	0	0	–	14.0	11.7	14	63.0
4C	25–50	0	0	–	13.5	11.6	12	10.7
5C	50–(55)	43	0.1	296	15.0	11.6	67	–

Table 6. Sorption properties of profile K3

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	TEB	HA	CEC	BS [%]
		[$cmol(+) \cdot kg^{-1}$]							
Oi/C	0–1	247.2	21.9	3.8	4.7	277.6	0.3	277.8	99.9
AC	1–3	254.0	27.0	3.8	4.8	289.6	0.1	289.8	100
C	3–7	230.8	28.0	2.8	5.2	266.8	0.0	266.8	100
2C	7–12	59.4	7.9	0.3	0.3	67.9	0.0	67.9	100
3C	12–25	56.0	7.2	0.2	0.3	63.7	0.0	63.7	100
4C	25–50	28.0	3.5	0.2	0.3	32.0	0.0	32.0	100
5C	50–(55)	212.4	35.6	1.1	1.3	250.4	0.0	250.4	100

Profile K5 – Endoleptic Spolic **Technosol** (Alcalic, Epiloamic, Calcic, Hyperartefactic, Laxic, Epirelocatic, Vitric)
Location: an abandoned, reclaimed settling pond near the “Konin” TPS, a flat surface, 85 m a.s.l.
N 52°16'39,7", **E** 18°16'35,6"

Morphology:

Oe – 0–2 cm, weakly to moderately decomposed grass, leaf, and needle litter;

A – 2–7 cm, dark grayish brown (10YR 4/2), slightly moist, very friable to friable consistence, granular/crumbly structure, common roots, clear boundary, relatively well developed humus horizon;

AC1 – 7–25 cm, grayish brown (10YR 5/2), slightly moist, firm consistence, crumbly / single grain structure, common roots, gradual boundary, a brown soil material with fragments of cemented ash (a layer of underlying ash was crushed during reclamation works);

AC2 – 25–60 cm, dark gray (10YR 4/1), slightly moist, firm to very firm consistence, crumbly / angular blocky structure, few roots, abrupt boundary, a brown soil material with fragments of cemented ash (a layer of underlying ash was crushed during reclamation works);

2C – 60–70 cm, light gray (10YR 7/1), slightly moist, very to extremely firm consistence, a coherent material, none roots, clear boundary, a stratified light grey cemented layer of fly ash;

3C – 70–76 cm, white (10YR 8/1), slightly moist, very to extremely firm consistence, a coherent material with weak single grain structure, none roots, clear boundary, a stratified light grey or whitish layer of fly ash, the layer crumbles in some places;

4C – 76–(80) cm, gray (GLEY1 6/N), slightly moist, very to extremely firm consistence, a coherent material with platy structure, none roots, a stratified light grey cemented layer of fly ash;

Table 7. Texture of profile K5

Horizon	Depth [cm]	Percentage share of fraction [mm]									Textural class
		> 2.0	2.0–1.0	1.0–0.5	0.50–0.25	0.25–0.10	0.10–0.05	0.05–0.02	0.02–0.002	<0.002	
Oe	0–2	–	–	–	–	–	–	–	–	–	–
A	2–7	13.1	8	11	6	14	23	21	15	2	SL
AC1	7–25	32.0	6	9	4	9	23	27	20	2	SL
AC2	25–60	42.0	6	10	5	8	20	26	22	3	SL
2C	60–70	cemented	–	–	–	–	–	–	–	–	–
3C	70–76	58.9	–	–	–	–	–	–	–	–	–
4C	76–(80)	cemented	–	–	–	–	–	–	–	–	–

Table 8. Chemical and physicochemical properties of profile K5

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	St [g·kg^{-1}]	pH_{KCl}	$CaCO_3$ [g·kg^{-1}]	Phosphate retention (%)
Oe	0–2	137	5.6	25	2.0	8.9	120	–
A	2–7	44	1.9	23	2.7	8.9	230	88.2
AC1	7–25	29	0.5	61	4.4	9.1	317	87.6
AC2	25–60	53	0.5	108	13.9	9.3	257	95.6
2C	60–70	5	0	–	50.8	12.1	125	91.1
3C	70–76	16	0	336	18.2	12.0	341	94.4
4C	76–(80)	4	0	–	26.9	12.0	119	95.1

Table 9. Sorption properties of profile K5

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	TEB	HA	CEC	BS [%]
		[cmol(+)·kg^{-1}]							
Oe	0–2	160.6	13.2	4.1	0.3	178.1	–	–	–
A	2–7	239.5	13.7	3.7	0.4	257.3	0.5	257.8	99.8
AC1	7–25	227.5	12.9	0.9	0.5	241.8	0.3	242.1	99.9
AC2	25–60	242.8	14.7	1.5	0.4	259.4	0.2	259.7	99.9
2C	60–70	435.2	52.5	0.1	0.2	488.0	0.0	488.0	100
3C	70–76	376.9	4.6	0.9	0.4	382.8	0.0	382.8	100
4C	76–(80)	308.4	30.6	0.4	0.2	339.6	0.0	339.6	100

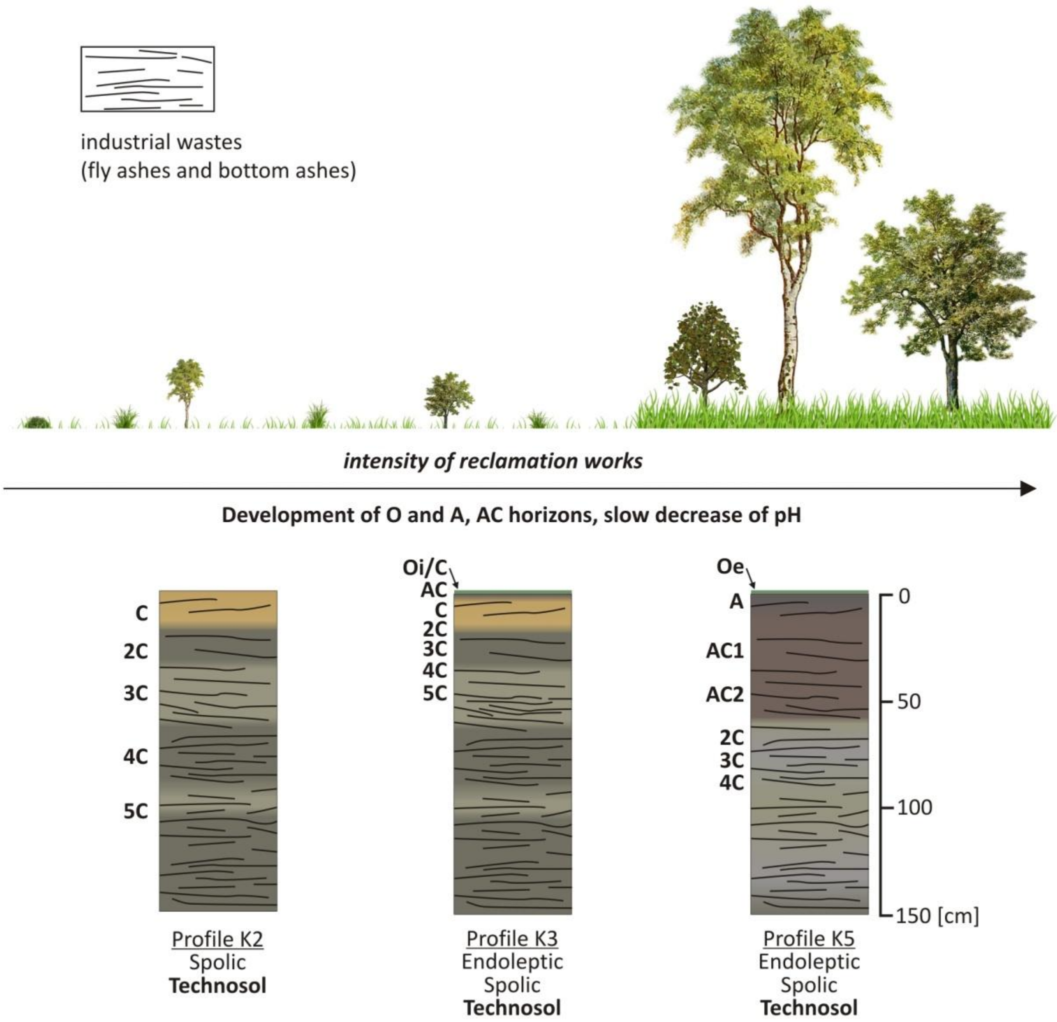


Fig. 2. Sequence of soils developed from ashes

Soil sequence and parent material

The investigated soils comprise a sequence of soils developed from ashes from the Pątnów and Konin thermal power stations (TPSs) combusting lignite. All studied soils formed on the surface of settling ponds where ashes were deposited in the form of slurry. As a result of natural succession or reclamation works, settling ponds became overgrown with vegetation. The deposition of ashes on the land surface initiated weathering processes and subsequent development of plant cover initiated soil-forming processes. Therefore, soil cover began to form in the superficial parts of disposal sites. The sequence of soils shows the first effects of soil-forming processes, which have lasted for about 40 years that have elapsed since the deposition of ashes on the land surface.

The parent material of the investigated **Technosols** were fly ashes and bottom ashes (and their mixtures), which are very specific industrial materials. It is necessary to know the initial properties of fresh (unweathered) fly and bottom ashes in order to discuss the genesis and evolution of the studied Technosols. The comparison of properties of fresh ashes and similar ashes constituting a substrate of the investigated soils gives an idea about the direction of transformations taking place during pedogenesis of the analyzed **Technosols**.

Fresh fly ash obtained after lignite combustion was produced in November 2012. It was homogenous brown-grey and had a texture of sandy loam. It contained 3% of clay (< 0.002 mm) and no rock fragments (> 2 mm). The pH_{KCl} of the fly ash was 14. The content of $CaCO_3$ was 16 $g \cdot kg^{-1}$. There was no TOC in the studied fly ash. Quartz and aluminosilicate glass predominated in mineral composition of the fly ash, followed by lower content of anhydrite, lime, periclase, calcite, magnetite, hematite, corundum, bredigite, and sanidine.

Fresh bottom ash derived from lignite combustion was produced in November 2012. It had a texture of sand and contained 1.4% of rock fragments (> 2 mm). The ash fraction < 2 mm of the ash was primarily composed of quartz grains. The fraction >2 mm of the ash contained variable amounts of unburned (coked) lignite. The pH_{KCl} of the bottom ash was 11.3. The studied bottom ash contained < 1% of clay (< 0.002 mm), 6 $g \cdot kg^{-1}$ of $CaCO_3$, and 3 $g \cdot kg^{-1}$ of TOC. Quartz predominated in mineral composition of the bottom ash, followed by lower content of aluminosilicate glass, maghemite, hematite, calcite, corundum, and cristobalite.

Profile K2 (soil age: ~40 years) was a very weakly developed bipartite soil profile. A layer of yellowish laminated calcareous material was present in the topsoil (down to 16 cm). That layer developed as a result of precipitation of fine calcite crystals from alkaline waste waters supplied from TPSs and poured onto the surface of a settling pond after the cessation of ash deposition. Well-stratified ash material with alternating coarse grain (gravel, sand) and fine grain (silt) layers occurred below 16 cm.

Profile K3 (soil age: ~40 years) was a very weakly developed bipartite soil profile. A layer of yellowish laminated calcareous material occurred in the topsoil (down to 7 cm). The origin of that layer is similar as in profile K2. Well-laminated ash material with sandy texture showing very firm consistency was present below 7 cm. Dark laminas containing high concentration of magnetite grains are visible in that part of the profile. A cemented layer built of fine material, containing vast amounts of unburned lignite occurred below 50 cm.

Profile K5 was developed from lignite fly ashes deposited in a settling pond in the vicinity of the Konin TPS (central Poland) (Uzarowicz et al., 2017). The deposition of fly ash ended in the 1970s (soil age: ~40 years). Fly ash underwent strong cementation due to crystallization of carbonates after deposition in a settling pond (Maciak et al., 1976). The pond was reclaimed in the 1970s by crushing a layer of cemented ash of about 50–60 cm, addition of soil organic matter (e.g. peat), and mixing that material in the course of a few-year intense cultivation of grasses and legumes (Maciak et al., 1976). The effect of this process is K5 profile which has (1) cemented, well-stratified, whitish and light-grey calcareous ash in the subsoil (below 60 cm), (2) a layer of crushed fly ash in the middle part of the profile (7–60 cm) consisting of brownish sandy loamy material containing hard fragments of cemented fly ash dispersed in soil material, and (3) the O and A horizons in the topsoil (0–7 cm), which developed due to soil organic matter accumulation after reclamation was completed. Profile K5 is much better developed than other profiles due to reclamation works which accelerated soil-forming processes.

Soil classification and systematic position

Due to large amounts of artefacts (i.e. ashes from TPSs), the investigated soils were classified as ***Spolic* Technosols** (IUSS Working Group WRB, 2015), or rarely ***Leptic Spolic* Technosols**, using various supplementary qualifiers. The use of these qualifiers is discussed below.

The ***Alcalic*** qualifier was used due to high pH of soil material and/or the dominance of basic cations in the sorption complex. The sorption complex of the investigated Technosols was dominated by Ca and Mg, and the base saturation in most samples studied was close to 100%. It has to be emphasized that TEB and CEC in the studied soils are strongly overestimated, because cations extracted by ammonium acetate used in the method are not only exchangeable cations but also cations being an effect of dissolution of the most soluble mineral compounds (sulphates, carbonates).

Based on the texture, the soils under study meet the definitions of ***Arenic*** or ***Loamic*** qualifiers (depending on the texture of specific layers). It was not possible to assign any of these qualifiers in the case of K3 profile (cemented layer started < 60 cm from the mineral soil surface).

There is microscopic evidence of the formation of pedogenic carbonates in the studied Technosols (Uzarowicz et al., 2017). In profiles K2 and K3, pedogenic carbonates were dispersed in soil material and constituted rather minor constituents of soil. Therefore, the ***Protocalcic*** qualifier can be used in the case of the studied soils. On the other hand, the best developed soil profile (K5) contained plenty of pedogenic carbonates in the topsoil (A, AC1, and AC2 horizons). Therefore, the ***Calcic*** qualifier was used in that case.

The ***Fluvic*** qualifier was used in the case of K2 and K3 profiles, as soil material was deposited in a pond as slurry. Criteria of the Fluvic qualifier were not met in K5 profile, as fluvic materials occurred in these profiles below 75 cm from the mineral soil surface.

All the studied **Technosols** satisfied the definition of the ***Hyperartefactic*** qualifier, as they had ≥ 50% artefacts (ash from TPSs) within 100 cm of the soil surface or up to the continuous rock.

All soils studied, except K3 profile, satisfied the definition of the ***Laxic*** qualifier, as they had a ≥ 20 cm thick mineral soil layer between 25 and 75 cm from the mineral soil surface, which had a bulk density of ≤ 0.9 $g \cdot cm^{-3}$.

The humus horizon (A, AC1, and AC2 horizons) of the best developed profile K5 almost totally met criteria for the ***Mollic*** qualifier except one: lighter color than the required one (value of 4 for a moist sample).

The ***Relocatic*** qualifier was used in profile K5, which was in situ remodeled by human activity to a depth of ≥ 100 cm due to mixing soil material during reclamation works.

Profiles K2 and K5 satisfied the definition of the ***Vitric*** qualifier (had ≥ 5% glass by grain count, the Alo + ½Feo value of ≥ 0.4%, and phosphate retention of ≥ 25%).

According to the Polish Soil Classification (2011), all the studied soils were classified as Raw industrizems (in Polish: *gleby industrioziemne inicjalne*) (Świtoniak et al., 2016). This soil unit includes e.g. **Technosols** developed on the surface of industrial waste disposal sites (Kabała et al., 2016).

Soil genesis

The studied sequence is composed of weakly developed soils which are of similar age (~40 years). Nevertheless, profile K5 is best developed despite the similar age of all soils. This is due to the fact that the profile was reclaimed, which accelerated weathering and soil-forming processes. Therefore, profile K5 is the best example showing the influence of these processes on the development of soils from ashes after lignite combustion. That profile contains a layer of cemented ash (below 60 cm) which is not changed by pedogenesis and represent the properties of ashes formed immediately after ash deposition in a settling pond. On the other hand, a layer above 60 cm is altered by pedogenic processes. The comparison of properties of both parts of K5 profiles gives an idea about the directions of pedogenic transformations taking place in technogenic soils developed from lignite ashes.

As a consequence of weathering and soil-forming processes, original properties of ashes altered. The most striking transformation is a drop of pH from strongly alkaline (pH 14) in fresh ashes to less alkaline (pH about 11–12) after deposition, which is expressed by properties of the subsoil of profile K5. Finally, the pH stabilizes at about 8–9 after reclamation (above 60 cm in profile K5). **Technosols** developed from lignite ashes are more alkaline and richer in Ca carbonates than soils developed from bituminous coal ashes.

High content of carbonates in soils developed form lignite ashes caused strong cementation of ash material. Ashes cemented immediately after deposition in a pond. The studies showed that cementation is stable until crushing by natural factors (e.g. root development) or an anthropogenic factor (e.g. reclamation works). Pedogenesis changes the morphology of the studied soil profiles by crushing cemented layers. Moreover, it has to be emphasized that profile K5 has features of **Calcisols** due to the high content of pedogenic carbonates in a layer above 60 cm (Uzarowicz et al., 2018). Such a feature is uncommon in soils of Poland.

Another effect of pedogenesis is the accumulation of soil organic matter in the topsoil. After about 40 years, a relatively well-developed A horizon can develop, which is visible in the upper part (about 7 cm) of profile K5.

Important aspects of pedogenesis of **Technosols** developed from industrial wastes are mineral transformations. A comparison of mineral composition of the subsoil and the topsoil of profile K5 expresses very well mineral alterations taking place in soils developed from lignite ashes.

The subsoil of profile K5 comprised a layer of uncrushed cemented fly ash (which can be regarded as the parent material of soil) (Uzarowicz et al., 2017). It contained a variety of secondary minerals (vaterite, calcite, bassanite, gypsum, ettringite, hydrotalcite, and brucite), most of which are uncommon in soil environment (Uzarowicz et al., 2018). They originated during the transport of ash as slurry and subsequent drying of that material in a settling pond. These minerals were formed as an effect of rapid transformations of highly reactive phases occurring originally in lignite ashes (e.g. lime, periclase, anhydrite, and aluminosilicate glass). The mineral paragenesis consisting of the above mentioned secondary minerals, as well as containing phases inherited from ash (i.e. glass, quartz, hematite) can be regarded as an initial mineral assemblage. Reclamation works included the crushing of cemented fly ash, the addition of organic matter, followed by a drop of pH, accelerated transformations of that assemblage. Reclamation and 40 years of pedogenesis led to the origin of new mineral paragenesis in the topsoil consisting of high content of pedogenic calcite as well as lower concentrations of glass, quartz, hematite, gypsum, hydrotalcite, and traces of ettringite or bassanite inherited from weathered fly ash.

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A sequence of Technosols developed from ashes from the "Łaziska" thermal power station (southern Poland) combusting bituminous coal

Łukasz Uzarowicz

The study area is located at abandoned ash disposal sites (settling ponds and dry landfills) of the "Łaziska" thermal power station (TPS), the town of Łaziska Górne (southern Poland) (Fig.1), combusting Upper Carboniferous bituminous coal. The studied soil profiles (from L1 to L4) can be arranged into a chronosequence in the following order (from the youngest to the oldest): L1 < L2 < L3 < L4. Their approximate age was ~5, ~20, ~35, and ~60 years, respectively. Detailed characterization of soil properties, mineral transformations, and evolution of the studied soils is presented elsewhere (Uzarowicz and Zagórski, 2015; Uzarowicz et al., 2017, 2018). According to Kondracki (2002), the studied soil sequence is located in the Katowice Upland mesoregion, which is part of the Silesian Upland macroregion.

Fig. 1. Location

Properties of parent material

The investigated soils were technogenic soils (Technosols) developed from industrial wastes which are fly ashes and bottom ashes being an effect of combustion of bituminous coal in a thermal power station. Coals always contain some mineral admixtures (clay minerals, quartz, carbonates, sulfides etc.) accompanying the organic matter (e.g. Vassilev and Vassileva, 1996). Therefore, some quantities of mineral residues (e.g. fly ash and bottom ash) are left after coal combustion. These residues are products of high temperature transformations of minerals occurring initially in coals. Fly ash is a light fine-grain residue which goes up with flue gases and is collected on precipitators. Bottom ash is a coarse-grain residue which is heavy and therefore goes down the combustion chamber.

Land use

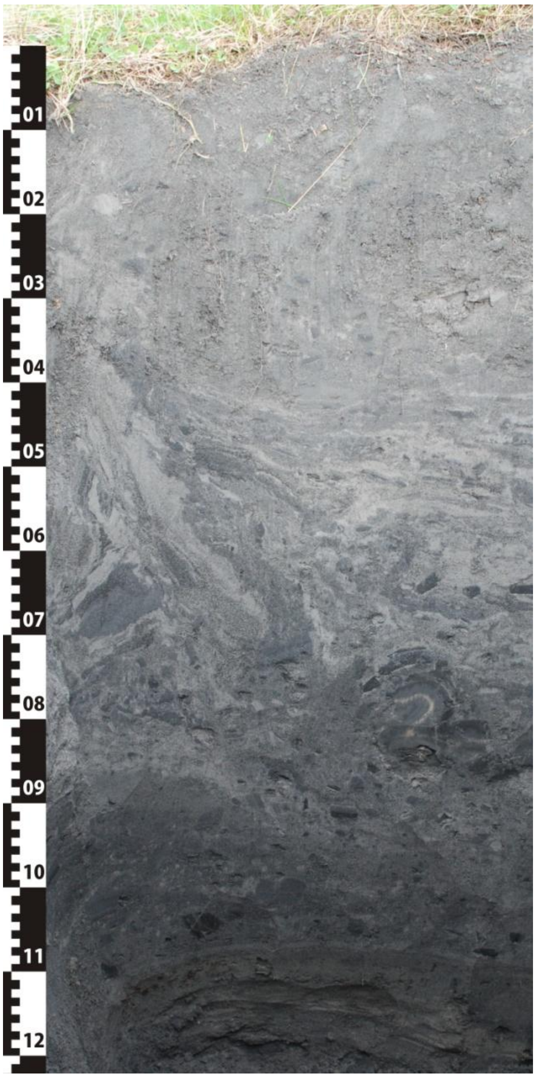
All studied soils were located on industrial wastelands. Profile L1 was covered with a meadow consisting mainly of grasses, clover, and mosses. Profile L2 was covered with a meadow composed of grasses (mainly reed grass), mosses and lichens, single pine seedlings and perennials. Profile L3 was covered with a meadow consisting mainly of grasses (mainly reed grass), mosses, single thistles, seedlings of snowberries, walnuts, and birches. Profile L4 was covered with the richest plant community compared to other sites (sparse birch and aspen forest with grasses and thistles in groundcover).

Climate

The average annual temperature in the study area is about 8°C (Woś, 2010). The average temperature of the coldest month (January) is –3.6°C, whereas July is the warmest month (19°C). The average annual precipitation is about 680 mm.

Profile L1 – Spolic **Technosol** (Alcalic, Epiarenic, Endoloamic, Endoprotocalcic, Hyperartefactic, Laxic, Pantorelocatic, Tephric)

Location: a reclaimed embankment located in one of the quarters of the Gardawice settling pond; a slope slightly inclined (1°) towards the north, 279 m a.s.l.; **N** 50°06'42,9", **E** 18°48'34,4"



Morphology:

Oi/C – 0–1 cm, Weakly to moderately decomposed grass and moss litter mixed with ash material;

AC – 1–5 cm, black (GLEY1 2.5/N), slightly moist, very friable to friable, single grain / weak crumbly structure, many roots, gradual boundary;

C – 5–30 cm, black (GLEY1 2.5/N), slightly moist, firm consistence, single grain / weak crumbly structure, common roots, gradual boundary;

2C – 30–70 cm, black (GLEY1 2.5/N), slightly moist, firm consistence, weak angular blocky structure, very few roots, gradual boundary, a few aggregates of crushed ash layers (ash material disturbed during reclamation works) occurred in the horizon;

3C – 70–110 cm, black (GLEY1 2.5/N), slightly moist, firm consistence, weak angular blocky structure, none roots, clear boundary, a few aggregates of crushed ash layers (ash material disturbed during reclamation works) occurred in the horizon;

4C – 110–(125) cm, black (GLEY1 2.5/N), slightly moist, firm consistence, weak angular blocky / platy structure, none roots, slightly laminated ash material, brown spots (most likely remnants of plants) occurred in the horizon;

Table 1. Texture of profile L1

Horizon	Depth [cm]	Percentage share of fraction [mm]									Textural class
		> 2.0	2.0–1.0	1.0–0.5	0.50–0.25	0.25–0.10	0.10–0.05	0.05–0.02	0.02–0.002	<0.002	
Oi/C	0–1	–	–	–	–	–	–	–	–	–	–
AC	1–5	1.1	1	3	8	30	25	16	15	2	SL
C	5–30	3.6	1	3	9	34	26	15	11	1	LS
2C	30–70	0.3	0	0	9	49	29	8	5	0	S
3C	70–110	0.7	0	2	10	41	27	12	8	0	LS
4C	110–(125)	0.3	0	0	1	27	38	22	11	1	SL

Table 2. Chemical and physicochemical properties of profile L1

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	St [g·kg^{-1}]	pH_{KCl}	$CaCO_3$ [g·kg^{-1}]	Phosphate retention (%)
Oi/C	0–1	111	2.7	41	1.4	8.3	3	–
AC	1–5	110	1.4	79	1.2	8.8	9	51.4
C	5–30	109	1.7	64	1.3	9.1	8	42.7
2C	30–70	89	1.7	51	1.2	9.2	10	16.5
3C	70–110	114	2.0	58	1.5	9.0	19	17.1
4C	110–(125)	105	1.2	90	1.3	8.6	13	23.0

Table 3. Sorption properties of profile L1

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	TEB	HA	CEC	BS [%]
		[cmol(+)·kg^{-1}]							
Oi/C	0–1	10.2	4.5	1.0	0.2	15.9	0.8	16.6	95.4
AC	1–5	13.1	2.3	0.5	0.2	16.1	0.4	16.4	97.6
C	5–30	13.8	2.8	0.3	0.2	17.1	0.3	17.4	98.4
2C	30–70	12.3	2.7	0.3	0.2	15.6	0.2	15.7	99.1
3C	70–110	18.8	4.0	0.5	0.4	23.7	0.3	24.0	98.6
4C	110–(125)	17.5	3.4	0.6	0.7	22.2	0.4	22.6	98.1

Profile L2 – Spolic **Technosol** (Alcalic, Arenic, Endoprotocalcic, Fluvic, Hyperartefactic, Laxic, Amphivitric)
Location: an abandoned, unreclaimed quarter of the Gardawice settling pond, a flat surface, 281 m a.s.l.,; **N** 50°06'27,0", **E** 18°48'37,9"

Morphology:

Oi/C – 0–1 cm, weakly decomposed grass, moss, and lichen litter mixed with ash material;

AC1 – 1–4 cm, 5Y 2.5/1, slightly moist, loose consistence, single grain / weak crumbly structure, many roots, clear boundary;

AC2 – 4–6 cm, 5Y 2.5/1, slightly moist, loose consistence, single grain / weak crumbly structure, many roots, gradual boundary, an insertion of rusty material rich in Fe oxides occurred in the horizon;

C – 6–25 cm, 5Y 3/1, slightly moist, friable to firm consistence, single grain / weak crumbly structure, common roots, gradual boundary;

2C – 25–45 cm, 2.5Y 3/1, slightly moist, firm consistence, single grain / weak crumbly structure, very few roots, gradual boundary;

3C – 45–65 cm, 5Y 3/1, slightly moist, firm consistence, single grain / weak crumbly structure, none roots, clear boundary;

4C – 65–68 cm, a layer of reddish bottom ash, 10YR 4/2, slightly moist, firm consistence, single grain / weak crumbly structure, none roots, clear boundary;

5C – 68–73 cm, GLEY1 2.5/N, slightly moist, friable to firm consistence, single grain / weak crumbly structure, none roots, clear boundary;

6C – 73–80 cm, dark grey layer with dark grains, GLEY1 2.5/N, slightly moist, friable to firm consistence, single grain / weak crumbly structure, none roots, abrupt boundary;

7C – 80–108 cm, 5Y 3/1, slightly moist, friable to firm consistence, single grain / weak crumbly structure, none roots, clear boundary;

8C – 108–110 cm, a brown layer of bottom ash, 10YR 5/2, slightly moist, friable to firm consistence, single grain / weak crumbly structure, none roots, clear boundary;

9C – 110–120 cm, 2.5Y 4/1, slightly moist, firm consistence, platy structure, none roots, clear boundary, laminated material, more silty than in the layer below;

10C – 120–128 cm, 2.5Y 4/1, slightly moist, firm consistence, platy structure, none roots, clear boundary, laminated material, more sandy than in the layer above;

11C – 128–(153) cm, 10YR 4/1, slightly moist, firm consistence, platy / angular blocky structure, none roots, clear boundary, laminated material with alternating silty and sandy layers;

Table 4. Texture of profile L2

Horizon	Depth [cm]	Percentage share of fraction [mm]									Textural class
		> 2.0	2.0–1.0	1.0–0.5	0.50–0.25	0.25–0.10	0.10–0.05	0.05–0.02	0.02–0.002	<0.002	
Oi/C	0–1	–	–	–	–	–	–	–	–	–	–
AC1	1–4	29.1	10	19	18	32	14	4	3	0	S
AC2	4–6	22.9	–	–	–	–	–	–	–	–	–
C	6–25	40.7	13	22	21	31	9	2	2	0	S
2C	25–45	41.0	14	26	25	26	7	1	1	0	S
3C	45–65	37.1	16	27	22	26	7	1	1	0	S
4C	65–68	33.8	–	–	–	–	–	–	–	–	–
5C	68–73	11.6	3	9	21	42	18	5	2	0	S
6C	73–80	3.7	–	–	–	–	–	–	–	–	–
7C	80–108	12.0	11	24	26	30	7	1	1	0	S
8C	108–110	4.8	–	–	–	–	–	–	–	–	–
9C	110–120	0.9	0	1	6	20	19	23	27	4	SiL
10C	120–128	6.6	6	13	23	37	12	4	5	0	S
11C	128–153	0.2	0	0	0	6	24	31	35	4	SiL

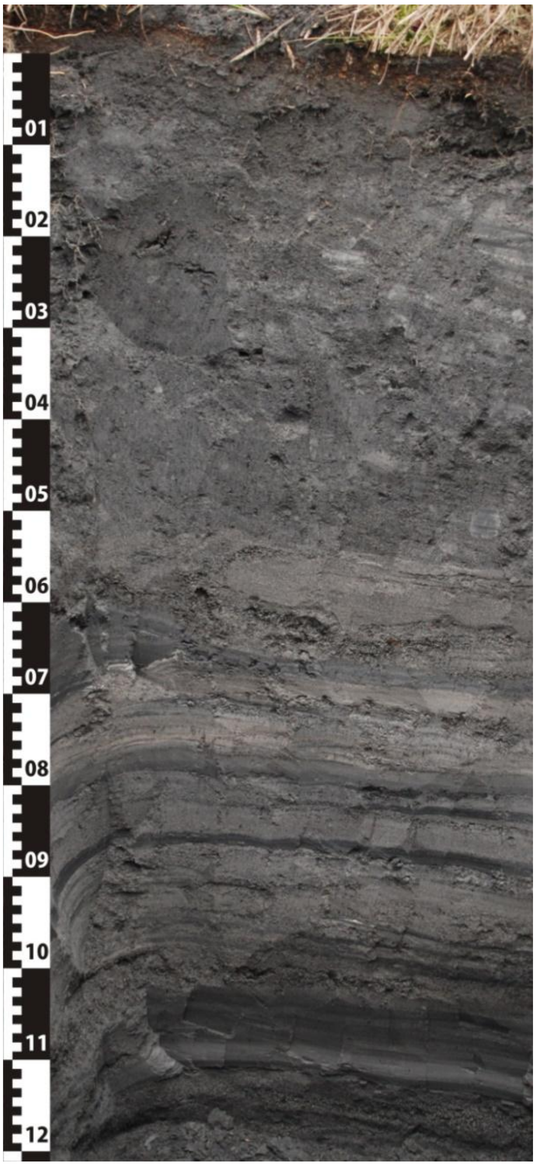
Table 5. Chemical and physicochemical properties of profile L2

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	St [g·kg^{-1}]	pH_{KCl}	$CaCO_3$ [g·kg^{-1}]	Phosphate retention (%)
Oi/C	0–1	–	3.0	–	3.7	6.3	0	–
AC1	1–4	36	0.8	44	5.5	9.0	8	15.5
AC2	4–6	8	0.1	61	7.1	5.2	0	–
C	6–25	12	0.2	61	4.8	10.0	14	19.5
2C	25–45	10	0.1	102	4.1	10.0	7	26.9
3C	45–65	23	0.2	116	2.3	9.8	1	15.2
4C	65–68	12	0.1	167	1.2	9.8	2	20.6
5C	68–73	95	0.7	130	1.2	8.9	0	10.1
6C	73–80	195	1.3	148	2.0	8.5	4	13.8
7C	80–108	11	0.2	64	1.7	10.2	20	25.9
8C	108–110	0	0.1	0	0.3	10.4	10	25.8
9C	110–120	0	0.5	0	1.0	9.6	40	15.1
10C	120–128	29	0.3	87	0.7	9.8	18	21.9
11C	128–153	4	0.4	10	0.8	9.7	27	23.4

Table 6. Sorption properties of profile L2

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	TEB	HA	CEC	BS [%]
		[cmol(+)·kg^{-1}]							
Oi/C	0–1	6.0	1.9	1.2	0.1	9.2	–	–	–
AC1	1–4	12.4	2.6	0.3	0.1	15.4	0.4	15.8	97.4
AC2	4–6	1.2	0.5	0.1	0.1	1.9	4.6	6.5	29.1
C	6–25	15.8	4.3	0.2	0.1	20.3	0.1	20.4	99.6
2C	25–45	9.8	3.6	0.2	0.1	13.6	0.1	13.7	99.5
3C	45–65	6.0	2.2	0.3	0.1	8.5	0.2	8.7	98.2
4C	65–68	4.8	2.1	0.3	0	7.2	0.2	7.4	97.7
5C	68–73	6.0	2.2	0.4	0.1	8.7	0.5	9.2	94.3
6C	73–80	11.8	3.4	0.5	0.2	15.9	0.7	16.6	95.6
7C	80–108	15.6	7.0	0.3	0.1	23.0	0.0	23.0	100
8C	108–110	10.1	4.6	0.3	0.1	15.0	0.0	15.0	100
9C	110–120	31.1	5.6	0.5	0.2	37.4	0.2	37.6	99.6
10C	120–128	14.5	3.4	0.4	0.2	18.5	0.1	18.7	99.2
11C	128–153	24.7	5.1	0.6	0.2	30.6	0.2	30.8	99.5

Profile L3 – Spolic **Technosol** (Eutric, Endoprotocalcic, Hyperartefactic, Laxic, Epirelocatic, Amphivitric)
Location: a reclaimed surface of the Gostyń settling pond, a flat surface, 268 m a.s.l.,;
N 50°07'32,4", **E** 18°50'35,1"



Morphology:

Oe/C – 0–2 cm, weakly to moderately decomposed grass and moss litter mixed with ash material;

Oa/C – 2–6 cm, moderately to well decomposed grass and moss litter mixed with ash material;

AC – 6–15 cm, GLEY1 2.5/N, slightly moist, firm consistence, crumbly structure, many roots, clear boundary, uniform grey horizon containing many roots, black and yellowish spots occurred in the horizon;

C – 15–37 cm, GLEY1 2.5/N, slightly moist, firm to very firm consistence, weak crumbly / angular blocky structure, common roots, gradual boundary, silty aggregates mixed within sandy material occurred in the horizon, strongly mixed material (no stratification is visible in the horizon);

2C – 37–57 cm, GLEY1 3/N, slightly moist, firm to very firm consistence, single grain / angular blocky structure, very few roots, abrupt boundary, silty aggregates mixed within sandy material occurred in the horizon, strongly mixed material (no stratification is visible in the horizon);

3C – 57–67 cm, 2.5Y 3/1, slightly moist, firm consistence, single grain / angular blocky / platy structure, very few roots, abrupt boundary, gravely to sandy layer of bottom ash material;

4C – 67–78 cm, 2.5Y 4/1, slightly moist, firm consistence, single grain / angular blocky / platy structure, none roots, abrupt boundary, laminated material with alternating silty and sandy layers;

5C – 78–90 cm, 2.5Y 3/1, slightly moist, firm consistence, single grain / angular blocky / platy structure, none roots, abrupt boundary, laminated material with alternating silty and sandy layers;

6C – 90–100 cm, 2.5Y 4/1, slightly moist, firm consistence, single grain / angular blocky / platy structure, none roots, abrupt boundary, laminated material with alternating silty and sandy layers;

7C – 100–107 cm, 2.5Y 3/1, slightly moist, firm consistence, single grain / angular blocky / platy structure, none roots, abrupt boundary, laminated material with alternating silty and sandy layers;

8C – 107–122 cm, 2.5Y 4/1, slightly moist, firm consistence, angular blocky / platy structure, none roots, abrupt boundary, laminated silty layer;

9C – 122–(130) cm, 2.5Y 3/1, slightly moist, firm consistence, single grain structure, none roots, gravely to sandy layer of bottom ash material;

Table 7. Texture of profile L3

Horizon	Depth [cm]	Percentage share of fraction [mm]									Textural class
		> 2.0	2.0–1.0	1.0–0.5	0.50–0.25	0.25–0.10	0.10–0.05	0.05–0.02	0.02–0.002	<0.002	
Oe/C	0–2	–	–	–	–	–	–	–	–	–	–
Oa/C	2–6	–	–	–	–	–	–	–	–	–	–
AC	6–15	3.4	5	16	17	20	15	14	12	1	LS
C	15–37	2.3	4	13	15	19	15	15	17	2	SL
2C	37–57	2.2	5	12	16	24	16	12	13	2	LS
3C	57–67	10.1	6	14	23	36	13	5	3	0	S
4C	67–78	5.2	4	8	9	20	21	18	18	2	SL
5C	78–90	1.3	–	–	–	–	–	–	–	–	–
6C	90–100	15.2	5	14	17	27	17	10	9	1	LS
7C	100–107	0.7	–	–	–	–	–	–	–	–	–
8C	107–122	1.5	1	1	1	5	13	28	45	6	SiL
9C	122–(130)	12.6	7	24	33	27	5	2	2	0	S

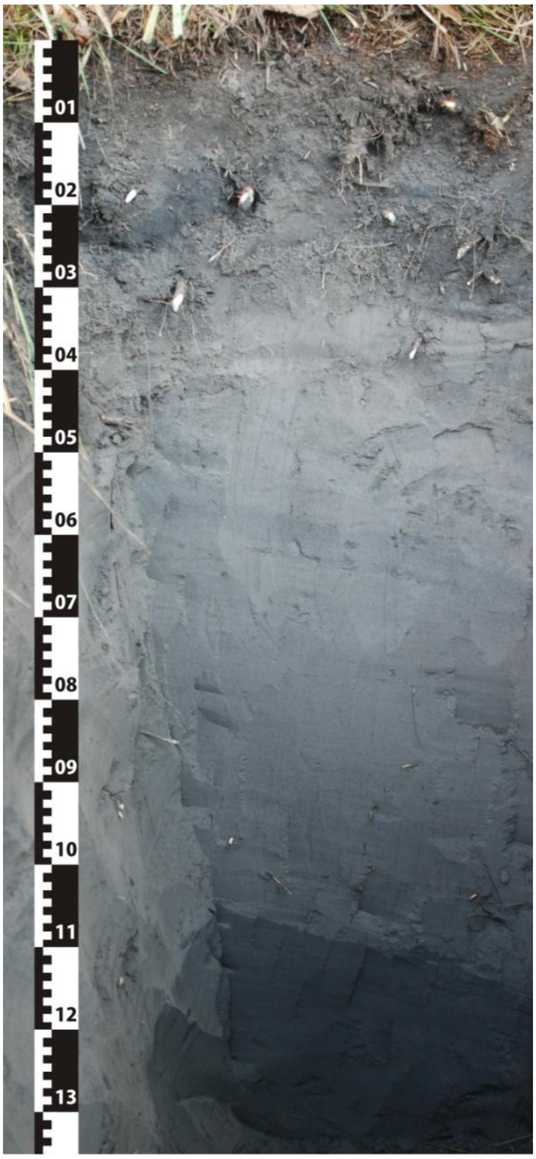
Table 8. Chemical and physicochemical properties of profile L3

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	St [g·kg^{-1}]	pH_{KCl}	$CaCO_3$ [g·kg^{-1}]	Phosphate retention (%)
Oe/C	0–2	42	5.2	8	1.4	6.2	0	–
Oa/C	2–6	122	4.6	27	1.3	6.2	0	–
AC	6–15	54	1.0	53	0.8	6.7	0	41.6
C	15–37	52	0.4	128	0.6	8.1	4	58.2
2C	37–57	68	0.5	141	0.8	8.4	12	51.5
3C	57–67	51	0.5	94	0.8	8.5	10	41.7
4C	67–78	49	0.3	156	0.5	8.6	5	46.4
5C	78–90	47	0.3	161	0.4	8.6	2	–
6C	90–100	55	0.3	172	0.7	8.5	3	26.5
7C	100–107	57	0.4	157	0.7	8.5	3	–
8C	107–122	28	0.1	250	0.4	8.9	15	57.8
9C	122–(130)	49	0.3	170	1.5	9.4	16	54.6

Table 9. Sorption properties of profile L3

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^+	Na^+	TEB	HA	CEC	BS [%]
		[cmol(+)·kg^{-1}]							
Oe/C	0–2	8.6	4.7	1.7	0.1	15.0	–	–	–
Oa/C	2–6	7.8	4.0	1.4	0.1	13.2	–	–	–
AC	6–15	5.1	2.7	0.6	0.1	8.5	2.3	10.8	78.5
C	15–37	8.6	2.4	0.4	0.1	11.4	0.8	12.2	93.4
2C	37–57	12.7	2.2	0.7	0.1	15.7	0.4	16.1	97.4
3C	57–67	11.6	3.0	0.8	0.1	15.5	0.4	15.8	97.8
4C	67–78	8.1	1.9	0.5	0.1	10.5	0.5	11.0	95.9
5C	78–90	7.3	2.0	0.5	0.1	9.9	0.5	10.4	95.3
6C	90–100	6.7	1.3	0.6	0.1	8.6	0.5	9.1	94.2
7C	100–107	7.5	1.4	0.5	0.1	9.6	0.5	10.1	94.8
8C	107–122	12.8	3.1	0.6	0.1	16.5	0.4	16.9	97.8
9C	122–130	14.1	6.1	0.8	0.1	21.1	0.0	21.1	100

Profile L4 – Spolic **Technosol** (Eutric, Endoprotocalcic, Hyperartefactic, Laxic, Katovitric)
Location: an old landfill, a slope slightly inclined (5°) towards the south, 317 m a.s.l.
N 50°08'08,5", **E** 18°50'28,7"



Morphology:

Oe – 0–3 cm, weakly to moderately decomposed grass and leaf litter;

A1 – 3–10 cm, very dark gray (2.5Y 3/1), slightly moist, very friable consistence, granular / crumbly structure, many roots, gradual boundary, relatively well developed humus horizon;

A2 – 10–18 cm, very dark gray (2.5Y 3/1), slightly moist, friable consistence, granular / crumbly structure, many roots, gradual boundary, relatively well developed humus horizon;

AC – 18–30 cm, very dark gray (2.5Y 3/1), slightly moist, friable to firm consistence, granular / crumbly structure, many roots, clear boundary, hard aggregates (most likely related to original structure of ash rather than pedogenesis) occurred in the horizon;

C – 30–70 cm, very dark gray (2.5Y 3/1), slightly moist, firm consistence, angular blocky structure, few roots, gradual boundary, an uniform ash material with no stratification, hard aggregates (similar to those from AC horizon) occurred in the horizon;

2C – 70–115 cm, dark gray (2.5Y 4/1), slightly moist, firm consistence, angular blocky structure, very few roots, abrupt boundary;

3C – 115–(135) cm, very dark gray (2.5Y 3/1), slightly moist, very firm consistence, angular blocky / platy structure, none roots, a dark–grey layer which is clearly darker than the overlying material;

Table 10. Texture of profile L4

Horizon	Depth [cm]	Percentage share of fraction [mm]									Textural class
		> 2.0	2.0–1.0	1.0–0.5	0.50–0.25	0.25–0.10	0.10–0.05	0.05–0.02	0.02–0.002	<0.002	
Oe	0–3	–	–	–	–	–	–	–	–	–	–
A1	3–10	0	1	4	7	24	27	22	14	1	SL
A2	10–18	1.0	1	2	6	22	25	26	17	1	SL
AC	18–30	2.6	1	3	4	16	25	30	19	2	SL
C	30–70	0.4	0	2	8	24	23	23	19	1	SL
2C	70–115	0	0	2	3	12	21	30	30	2	SiL
3C	115–(135)	0	0	1	6	25	27	27	14	0	SL

Table 11. Chemical and physicochemical properties of profile L4

Horizon	Depth [cm]	OC [g·kg^{-1}]	Nt [g·kg^{-1}]	C/N	St [g·kg^{-1}]	pH_{KCl}	$CaCO_3$ [g·kg^{-1}]	Phosphate retention (%)
Oe	0–3	199	7.4	27	2.4	6.9	0	–
A1	3–10	99	2.9	35	1.8	7.1	0	20.6
A2	10–18	44	3.5	13	1.0	8.3	6	64.1
AC	18–30	35	1.7	20	0.9	8.6	15	66.5
C	30–70	32	0.6	53	0.9	8.7	18	62.0
2C	70–115	46	1.5	31	1.1	8.7	18	63.3
3C	115–(135)	24	0.4	59	1.2	9.3	21	49.6

Table 12. Sorption properties of profile L4

Horizon	Depth [cm]	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	TEB	HA	CEC	BS [%]
		[cmol(+)·kg^{-1}]							
Oe	0–3	17.0	9.1	3.1	0.3	29.5	–	–	–
A1	3–10	6.7	3.2	1.1	0.3	11.3	3.1	14.4	78.3
A2	10–18	9.0	3.1	0.6	0.2	13.0	0.8	13.8	94.1
AC	18–30	17.2	4.0	0.8	0.3	22.3	0.5	22.8	97.7
C	30–70	16.6	3.5	0.8	0.3	21.3	0.5	21.7	97.9
2C	70–115	15.6	5.4	1.0	1.1	23.2	0.5	23.6	98
3C	115–(135)	17.0	7.8	0.8	0.8	26.5	0.2	26.7	99.2

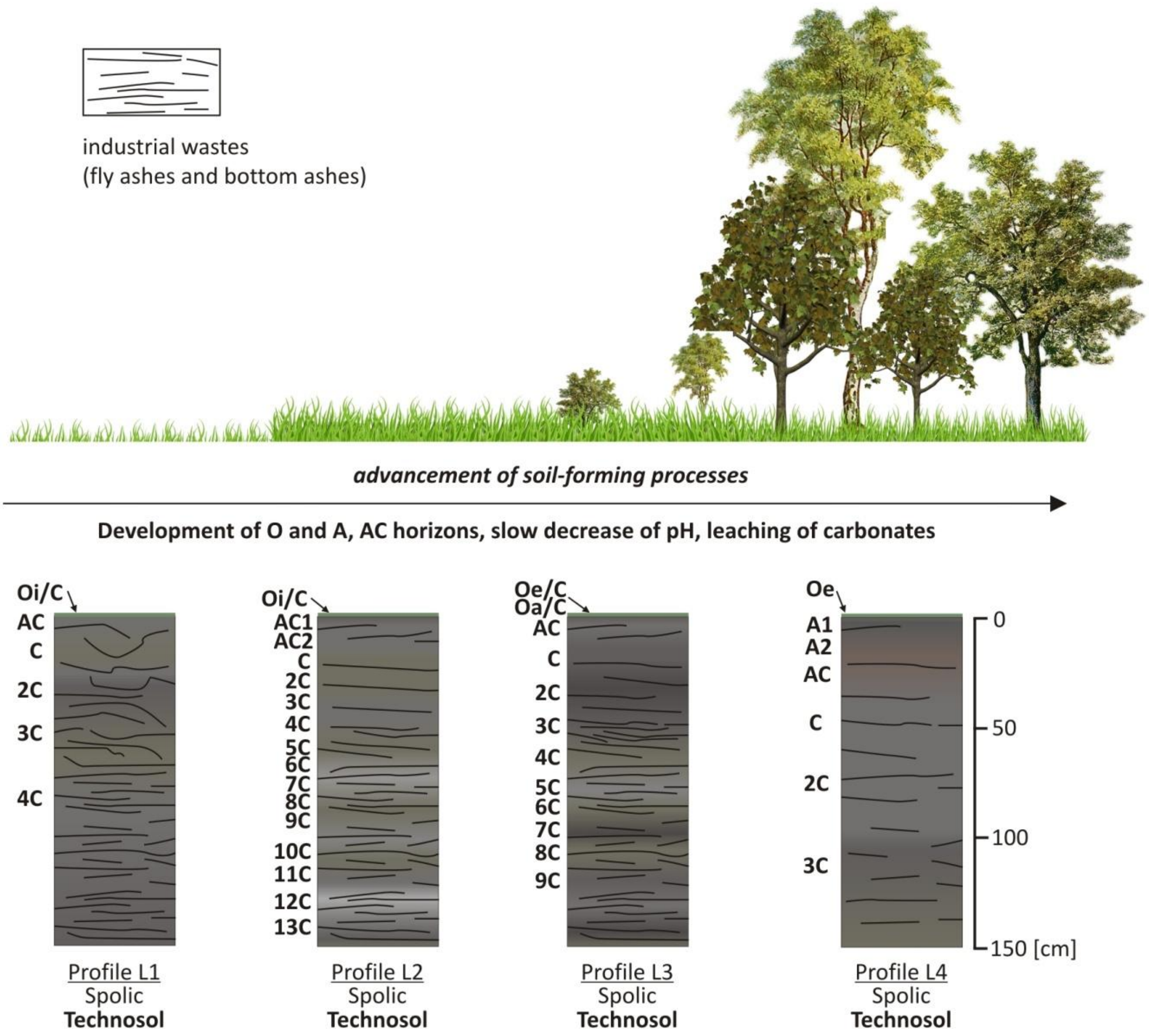


Fig. 2. Chronosequence of soils developed from ashes from the "Łaziska" thermal power station

Soil sequence and parent material

The investigated soils comprise a chronosequence of soils developed from ashes from the Łaziska thermal power station (TPS) combusting bituminous coal. They formed on the surface of settling ponds (profiles L1, L2, and L3) and a landfill (profile L4) where ashes were deposited. Settling ponds were surface impoundments that received ashes in the form of slurry (i.e. ashes were mixed with water, transported through a pipe and sluiced to a pond). Dry landfills are areas where dry ashes were transported from TPS and deposited. Subsequently, ponds and landfills became overgrown with vegetation as a result of natural succession or reclamation works. The development of plant cover initiated soil-forming processes and therefore soil cover began to form in the superficial parts of disposal sites. The current sequence of soils indicates the first stage of development in about 60 years that have passed since the deposition of ashes on land surface.

Parent material of the investigated **Technosols** were fly ashes and bottom ashes (and their mixtures), which are very specific industrial materials. It is necessary to know the initial properties of fresh (unweathered) fly and bottom ashes in order to discuss the genesis and evolution of the studied Technosols. The comparison of properties of fresh ashes and similar ashes constituting a substrate of the investigated soils gives an idea about the direction of transformations taking place during pedogenesis of the analyzed **Technosols.** It has to be stressed that properties of contemporary "fresh" ashes could be different from those generated several decades ago due to differences in properties of coal combusted in a TPS and technology of fuel combustion.

Fresh fly ash derived from bituminous coal combustion was produced in October 2012. It was a homogenous grey material having a texture of silt loam. It contained 8% of clay (< 0.002 mm) and no rock fragments (> 2 mm). The pH_{KCl} of the fly ash was 13.9. Fly ash was a material lacking $CaCO_3$ and TOC. Aluminosilicate glass, mullite, and quartz predominated in mineral composition of the fly ash, followed by lower content of magnetite, hematite, maghemite, native iron, anhydrite, and corundum. Moreover, lime (CaO) also occurred in fly ash, however, it was not detected based on the methods used in mineralogical analysis (XRD, SEM-EDS, FTIR spectroscopy) (Uzarowicz et al., 2018).

Fresh bottom ash derived from bituminous coal combustion was produced in October 2012. It had a texture of sand and contained 39% of rock fragments (> 2 mm). The fraction >2 mm of the ash was primarily composed of vitreous and porous (ceramic-like) sinters of various colors (grey, olive, reddish). The fraction > 2 mm of the ash contained variable amounts of unburned (coked) coal. Bottom ash contained < 1% of clay (< 0.002 mm), 5 $g \cdot kg^{-1}$ of $CaCO_3$, and 17 $g \cdot kg^{-1}$ of TOC. The pH_{KCl} of the bottom ash was 11.9. Aluminosilicate glass, quartz, and mullite predominated in mineral composition of the bottom ash, followed by lower concentrations of magnetite, hematite, maghemite, native iron, albite and corundum (Uzarowicz et al., 2018).

Profile L1 (age: <5 years) was a very weakly developed soil occurring on the surface of a former settling pond. In the upper part of the profile (down to 110 cm), the ash material was mixed due to reclamation works. No stratification was visible in that part of the profile. Moreover, fragments of several centimeters large aggregates of crushed ash layers occurred. Below 110 cm, ashes were slightly stratified. Stratification is a typical feature of materials deposited in ponds.

Profile L2 (age: ~20 years) was a very weakly developed soil occurring on the surface of a former settling pond. Rusty material enriched with slightly weathered magnetite occurred in the topsoil at a depth of approximately 5 cm. Coarse grain (gravels, sand) stratified material predominated in the upper part of the profile (> 110 cm). Fine grain (silt) well-stratified material occurred below 110 cm.

Profile L3 (age: ~35 years) was a very weakly developed soil occurring on the surface of a former settling pond. The ash material is mixed in the upper part of the profile (down to 57 cm) due to reclamation works. No stratification was visible in that part of the profile. Fragments of several centimeters large aggregates of crushed ash layers (previously compacted) occurred there. Well stratified material with alternating coarse grain (gravel, sand) and fine grain (silt) layers occurred below 57 cm.

Profile L4 (age: ~60 years) was a weakly developed soil occurring on the surface of a former dry landfill. Therefore, the morphology of soil material is uniform as the profile was built of ashes which were not stratified. A humus horizon with a thickness of approximately 30 cm developed in the topsoil. Compared with the other soils, L4 profile was the best developed soil in the present chronosequence.

Soil classification and systematic position

Due to large amounts of artefacts (i.e. ashes from TPSs), the soils investigated were classified as ***Spolic*** **Technosols** (IUSS Working Group WRB, 2015) with various supplementary qualifiers. The use of these qualifiers is discussed below.

Alcalic or ***Eutric*** qualifiers were used due to high pH of soil material and/or the dominance of basic cations in the sorption complex. The sorption complex of the investigated **Technosols** was dominated by Ca and Mg, and the base saturation in most samples studied was higher than 95%. It has to be emphasized that TEB and CEC in the studied soils are most likely overestimated, because cations extracted by ammonium acetate used in the method are not only exchangeable cations but also cations being an effect of dissolution of the most soluble mineral compounds (sulphates, carbonates). Nevertheless, the current definition of the ***Alcalic*** or ***Eutric*** qualifier was not met in the studied soils. It should be assessed that they could be unofficially used due to high pH and predominance of basic cations in the sorption complex of the soils studied.

Based on the texture, the studied soils satisfied the definitions of ***Arenic*** or ***Loamic*** qualifiers (depending on the texture of specific layers). It was not possible to assign any of these qualifiers in the case of the L3 profile, because sandy or loamy layers were too thin (< 30 cm) to satisfy both definitions.

There is microscopic evidence of the formation of pedogenic carbonates in the **Technosols** studied (Uzarowicz et al., 2017). In the majority of soil profiles under study, pedogenic carbonates were dispersed in soil material and constituted rather minor constituents of soil. Therefore, the ***Protocalcic*** qualifier can be used in the case of the studied soils.

The ***Fluvic*** qualifier was used in the case of Profile L2 developed on settling ponds only, as soil material was deposited there as slurry forming a layered pattern. Definition of the ***Fluvic*** qualifier was not satisfied in L1 and L3, as fluvic materials occurred in these profiles below 75 cm from the mineral soil surface.

All studied Technosols satisfied the definition of the ***Hyperartefactic*** qualifier, as they had ≥ 50% artefacts (ash from TPSs) within 100 cm of the soil surface or to the continuous rock.

All soils satisfied the definition of the ***Laxic*** qualifier, as they had a mineral soil layer ≥ 20 cm thick between 25 and 75 cm from the mineral soil surface, which had a bulk density of ≤ 0.9 $g \cdot cm^{-3}$.

Definition of the ***Mollic*** qualifier was almost totally satisfied for the humus horizon of the best developed Profile L4. In that profile, the following criterion was not met: the content of soil organic carbon was not ≥ 0.6% (absolute) higher than in the parent material, which has a Munsell color value of ≤ 4, moist.

The ***Relocatic*** qualifier was used in profiles L1 and L3, which were in situ remodeled by human activity to a depth of ≥ 100 cm due to mixing soil material during reclamation works.

The soils studied had features of soils developed from volcanic ash (e.g. Uehara, 2005; Arnalds, 2008), as they satisfied the definition of ***Tephric*** (≥ 30% glass and lack of vitric properties) and the ***Vitric*** qualifier (had ≥ 5% glass (by grain count), the Alo + ½Feo value of ≥ 0.4%, and phosphate retention of ≥ 25%) (Uzarowicz et al., 2017). The similarities with soils developed from volcanic ash were suggested earlier by Warren and Dudas (1985), Zevenbergen et al. (1999), and Zikeli et al. (2002, 2005). Tephric materials were typical of the very young (several years) L1 profile. On the other hand, vitric properties predominated in the 60 year old LA4 profile.

According to the Polish Soil Classification (2011), all the studied soils were classified as Raw industrizems (in Polish: *gleby industrioziemne inicjalne*) (Świtoniak et al., 2016). This soil unit includes e.g. Technosols developed on the surface of industrial waste disposal sites (Kabała et al., 2016).

Soil genesis

The properties of the studied **Technosols** are primarily influenced by the following soil-forming factors: parent material, vegetation, human activity, and climatic/weather conditions (Uzarowicz et al., 2017). Parent material (i.e. ash from TPSs) is the most important factor. Its properties are strongly dependent on (1) the type of ash (fly ash vs. bottom ash) and (2) the mode of deposition and the type of disposal site (settling pond vs. dry landfill). The type of ash (fly ash vs. bottom ash) strongly affects the texture of soils. Sandy or coarser texture is related to the predominance of bottom ash in the soil substrate, whereas soil materials with the predominance of the silt fraction are primarily composed of fly ash. The mode of deposition on a disposal site influences the morphology of soils developed on such a site. Technosols developed on settling ponds are characterized by the stratification of soil material caused by the sedimentation of ash grains. Technosols developed on dry landfills show uniform morphology with no lamination. Vegetation is a factor causing the accumulation of soil organic matter leading to the formation of O and A horizons. Human activity is expressed by the reclamation of disposal sites where ashes were deposited. Climatic conditions typical of Poland, and particularly the predominance of precipitation over evaporation, contribute to the leaching of soluble compounds (e.g. carbonates) from the soil profile.

The pedogenesis of the studied **Technosols** over a period of several decades led to the accumulation of soil organic matter in the topsoil resulting in the development of the A horizon having crumbly and/or granular structure (Uzarowicz et al., 2017). These structures were found, in particular, in A horizons of the best developed soil profile L4. This suggests that soil organic matter is an important constituent responsible for aggregation in the studied soils.

One of the most prominent indicators of pedogenesis of the studied Technosols is a decrease in pH from > 11 in fresh (unweathered) ashes to pH of approximately 8–9, and occasionally to 6 or lower (e.g. topsoil of L2 profile). A decrease in pH in the topsoil was previously described by e.g. Maciak et al. (1976) and Zikeli et al. (2002, 2005). Very high initial pH of fresh ashes is related to the occurrence of Ca and Mg oxides (e.g. Mattigod et al., 1990; Koukouzas et al., 2006; Uzarowicz and Zagórski, 2015). After disposal, the pH drops due to the formation of carbonates in the soil environment.

Another indicator of pedogenesis of the studied **Technosols** is the formation of pedogenic carbonates and their subsequent leaching from the topsoil. Carbonates are minor constituent of fresh ashes. They develop due to weathering (e.g. carbonatization of CaO) after the deposition of ash on a disposal site. At the first stage of soil development, carbonates are present throughout the profile (see profile L1). After several decades, carbonates are totally leached from the topsoil (e.g. L3 and L4 profile). The carbonate-depleted zone appears in the first 10–15 centimeters in soils within a period of 35–60 years.

Pedogenic processes in the studied soil are followed by mineral transformations (Uzarowicz et al., 2018). Aluminosilicate glass, mullite, quartz, iron oxides (magnetite, hematite, maghemite), and traces of sulfates (e.g. barite) inherited from bituminous coal ashes predominated in the composition of Technosols developed from these ashes. About 60 years of pedogenesis led to (a) the formation of small content (up to several %) of pedogenic calcite and its further leaching from the soil profile, (b) the formation of pedogenic iron oxyhydroxides (goethite, lepidocrocite, and ferrihydrite) at the expense of inherited iron oxides (magnetite, hematite, maghemite), and (c) the transformation of aluminosilicate glass and likely formation of short-range order Si- and Al-containing phases.(Uzarowicz et al., 2018).

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