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Physical, water and redox properties of vertisols of the Sępopol Plain in north-eastern Poland

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Abstract

Vertisols occurring in the Sępopol Plain in north-eastern Poland are characterized by high natural fertility. They belong to the group of soils with high clay content, which show the ability of periodic shrinking and swelling of clay minerals. As a result of variable moisture conditions, deep cracks and sliding surfaces are formed on the surface of the soil aggregates. The purpose of this research was to determine the chemical, physical, air-water and redox properties of vertisols developed from glaciolimnic sediments of the Weichselian glaciation, and having textures of clay (C), loam (L) and heavy clay (HC). The studied soils had high field water capacity (pF 2.0) and high content of water unavailable to plants (pF 4.2), as well as low volume of air pores. A significant positive correlation was found between the amount of clay and the volume of water unavailable to plants (pF 4.2), and a negative correlation between the amount of clay and content of water available to plants (AWC), including water readily available to plants (RAWC). The distribution of soil pores was unfavourable, and the ratio of macropores to mesopores to micropores in humic horizons was 1:2.7–5.1:1.5–5.4. The studied vertisols had low values of redox potential (Eh) and oxygen diffusion rate (ODR). The values of the Eh were above 300 mV, a threshold value for oxidised and reduced soil, only in surface horizons.

1. Introduction

Vertisols were separated as a new taxonomic unit in the fifth (Polish Soil Classification 2011) and the sixth (Kabała et al., 2019) edition of Polish Soil Systematics (SGP6). In the SGP6 they were classified into the type of vertisols in the order of swelling soils. These soils contain ≥ 30% of clay fraction and have a *wertik* horizon of thickness of ≥ 25 cm. Vertisols have fusiform or lenticular structural aggregates and/or sliding surfaces (slickensides) in ≥ 10% of the soil volume. Vertisols are soils which origin is closely related to the lithology and mineralogical composition of the parent material. As a result of swelling and shrinking of soil rich in clay minerals, deep cracks are formed (Kovda and Wilding, 2004; Łabaz and Kabała, 2014; IUSS Working Group WRB, 2015; Kabała et al., 2019, Miller et al., 2010). Due to their high natural fertility, vertisols are an important soil group widespread in countries such as Australia, China, India, (Wilding, 2004) USA (Miller et al., 2010), Senegal, Romania, Turkey, Bulgaria, Hungary, Serbia and southern Spain (Ahmad, 1996; Favre et al., 1997; DeCarlo and Caylor, 2019). On the Earth's surface, the majority of vertisols occur in the equatorial and subtropical zone. In Poland, vertisols occur in the southwestern part, near Wrocław (Łabaz and Kabała, 2014; Kabala et al., 2015; Dudek et al., 2019), near Ciechanów (Olszewski, 1956) and in the northern part of the country above 54° N – in the Sępopol Plain (Uggla and Witek, 1956; Długosz et al., 2009; Orzechowski et al., 2018) and around Gniew in the Starogard Lakeland (Prusinkiewicz, 2001; Mocek et al., 2009).

The origin of vertisols in Sępopol Plain is associated with the deglaciation of ice-dammed lakes of Pomeranian phase of Weichselian glaciation and accumulation of glaciolimnic deposits (Körnke, 1930; Roszko, 1968). These deposits were parent materials for black earths and vertisols of specific chemical, physical and hydraulic properties (Uggla and Witek, 1958; Orzechowski et al., 2018). The mentioned soils are compacted with low infiltration coefficient, frequently under gleyic conditions, which suggest reducing conditions in soils. In the past, due to the „heavy" granulometric composition, these soils were used as permanent grasslands. The use of these soils for grazing with average annual precipitation in the range of 580–600 mm and average annual air temperature of 7.2°C was beneficial for the development of grass vegetation and accumulation of soil humus (Uggla and Witek, 1958; Suchecki, 2010). Currently, vertisols are cultivated and winter wheat, winter oilseed rape, sugar beet and maize are grown on these soils.

The purpose of this research was to determine the chemical, physical, air-water and redox properties of vertisols developed from fine-grained glaciolimnic sediments in young glacial landscape of north-eastern Poland.

2. Materials and methods

The research was carried out in the Sępopol Plain and northern parts of the Masurian Lakeland – the areas of ice-dammed lakes origin of the Weichselian glaciation (Vistula) of the Pomeranian phase (Fig. 1). At five sites of ice-dammed lakes origin, with different size, relief, hypsometry and soil cover, five soil profiles were studied: near Reszel – Black vertisols (SGP6) – Pellic Vertisol (Aric, Mollic, Hypereutric, Grumic, Endostagnic) – WRB 2015, (054°02′53.90 N 021°05′31.93 E, located at 94.5 m a.s.l.) and Typical vertisols – Haplic Vertisol (Aric, Grumic, Hypereutric), (054°02′20.71 N 021°20′03.16 E, 88.0 m a.s.l.), near Kętrzyn – Gleyic vertisols – Haplic Vertisol (Mollic, Hypereutric, Gleyic) (054°02′28.80 N 021°20′34.32 E, 94.5 m a.s.l.), near Sępopol – Typical vertisols – Haplic Vertisol (Aric, Hypereutric, Mazic), (054°18′03.89 N 021°05′43.58 E, 41.5 m a.s.l.), and near Lidzbark Warmiński – Typical vertisols – Haplic Vertisol (Aric, Hypereutric, Grumic), (054°09′54.19 N 020°32′31.73 E, 90.0 m a.s.l.). Black and typical vertisols were under crop cultivation while gleyic vertisols were under permanent grasslands. The studied vertisols do not occur in large soil complexes, but in various geomorphological structures forming a mosaic with other soil types (black earths, lessive soils and brown soils).

In collected soil samples, using standard methods for mineral soil studies, the following soil properties were determined: soil texture by Bouyoucos-Cassagrande method modified by Prószynski, pH in H_2O and in 1 mol dm^{-3} KCl by the potentiometric method. The content of organic carbon (TOC) and total nitrogen (TN) was analysed using a CN Vario Max Cube Elementar analyser, the content of exchangeable base cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) was determined in the extract of ammonium acetate (1 mol dm^{-3}) at the pH of 7.0. Ca^{2+}, Mg^{2+}, K^+ and Na^+ were determined using iCAP 7400 ICP-OES Termo Scientific spectrometer. Hydrolytic acidity (HA) was determined by the method of Kappen after extraction in 1 mol dm^{-3} CH_3COONH_4 (Van Reeuwijk, 2002). The cation exchange capacity (CEC) was calculated as the sum of total exchange bases (TEB) and HA.

Particle density (Sd) was determined by pycnometric method and soil bulk density (Bd) in undisturbed 100 cm^3 soil samples taken at four replications, steel cylinders. Total porosity (Tp) was calculated according to the equation: $Tp = (Sd - Bd) \times Sd^{-1} \times 100$ (%).

Soil water retention properties were determined using low-pressure (in pF range 0–2.7) and high-pressure (in pF range 3.0–4.2) chambers. Water capacities (Wv/v) were examined at water potential of 98.1 hPa (pF 2.0), 981.0 hPa (pF 3.0) and 15 547.9 hPa (pF 4.2). The volume of the following soil pores and water capacities were calculated: macropores (total porosity-Wv/v at pF 2.0), micropores (Wv/v at pF 4.2), mesopores (Wv/v at pF 2.0 – Wv/v at pF 4.2). Mesopores are related to potential useful water retention because they contain water available to plants (AWC – available water capacity). Among AWC, readily available water capacity – RAWC (Wv/v at pF 2.0 – Wv/v at pF 3.0), and small pores available water capacity – SAWC (Wv/v at pF 3.0 – Wv/v at pF 4.2) were calculated (Zawadzki, 1973, Walczak et al., 2002). Redox potential (Eh) and oxygen diffusion rate (ODR) were determined with a REDOX apparatus for measuring potential and diffusion rate in soil Institute of Agrophysics, Polish Academy of Sciences in Lublin (Stępniewska 1988) and reduction rate assessment index (rH) was calculated according to the formula:
$rH = (Eh \times 29^{-1}) + 2 \times pH$

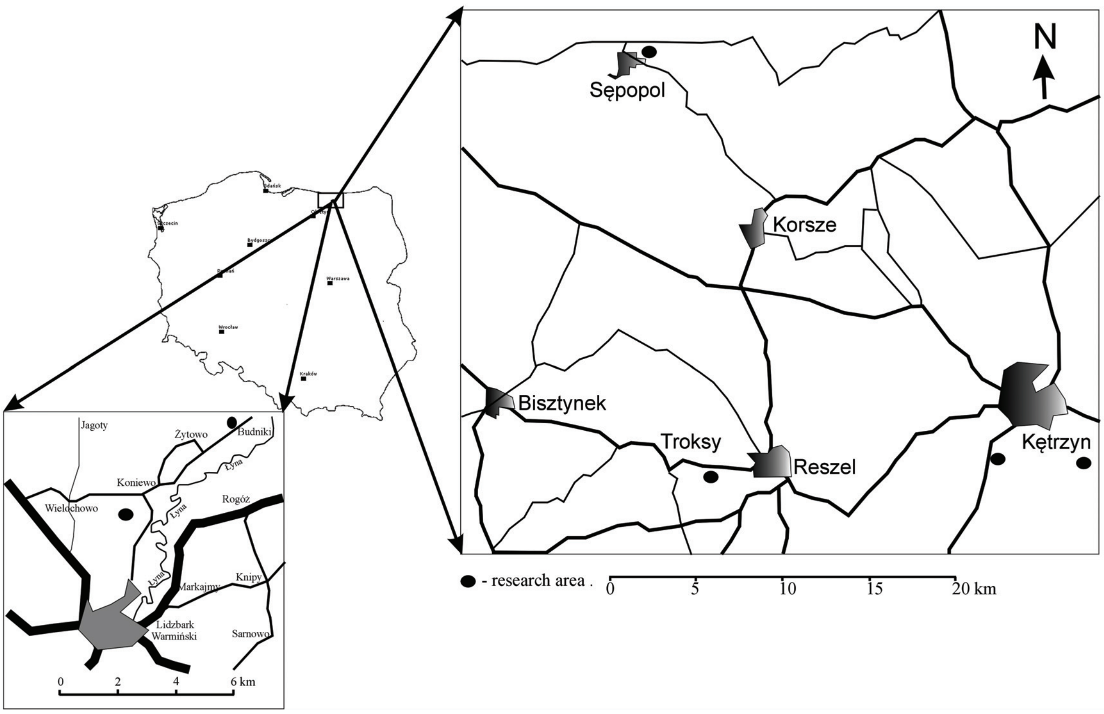


Fig. 1. Location of studied soil sites

Coefficient of linear extensibility (COLE) was calculated at the soil sample moisture content corresponding to a pressure of 33 kPa.

3. Results and discussion

3.1. Soil texture and some chemical properties

The soil reaction in humic horizons (A) ranged from slightly acid (pH_{KCl} 5.6) to neutral (pH_{KCl} 7.0). In the soil profiles the pH values were increasing with depth, and in subsurface horizons numerous carbonates precipitations occurred (Table 1). The carbonates contents in the parent material ranged from 0.6% to 16.4%. The studied soils had high amounts of TOC, which in humic horizons ranged from 16.0 g kg^{-1} to 58.0 g kg^{-1}. The TN content was between 1.81 g kg^{-1} and 3.87 g kg^{-1}. Gleyic vertisols, which were under permanent grasslands, had the highest contents of TOC and TN. The C/N ratio ranged from 7.3 to 15.0. Vertisols also had high CEC, above 23.81 cmol (+) kg^{-1}, including the content of base cations (TEB), which was over 21.90 cmol (+) kg^{-1}. A higher content of exchangeable cations in vertisols was found by Kishné et al. (2009) in the Texas Gulf Coast Prairie. The BS was very high and exceeded 89.3%. It is worth emphasizing that the content of base cations and base saturation was increasing with increasing depth in the soil profiles, which indicates the leaching processes from surface horizons. A particularly high base saturation, over 97%, was found in soils where precipitation of calcium carbonate occurred (Table 1).

Table 1
Chemical properties of the studied Vertisols

Soil horizon	Depth cm	pH		$CaCO_3$ %	TOC	TN	C/N	HA	TEB	CEC	BS %
		H_2O	KCl		g kg^{-1}			cmol(+) kg^{-1}			
R1 – *Black vertisols, Pellic Vertisol (Aric, Mollic, Hypereutric, Grumic, Endostagnic)*											
Ap	0–30	7.6	7.0	1.8	18.7	1.81	10.3	0.67	23.65	24.32	97.2
A2	30–46	7.7	7.0	1.3	19.5	1.93	10.1	0.57	23.97	24.54	97.7
Bikg	46–100	8.0	7.1	10.0	1.8	0.20	9.0	0.40	37.60	38.00	98.9
Cikg	100–160	8.1	7.2	16.4	–	–	–	0.84	47.17	48.01	98.3
Ckg2	160–180	8.1	7.2	13.8	–	–	–	1.19	44.98	46.17	97.4
K1 – *Gleyic vertisols, Haplic Vertisol (Mollic, Hypereutric, Gleyic)*											
A	0–42	6.8	6.2	–	58.0	3.87	15.0	2.32	25.23	27.55	91,6
Big	42–85	7.6	6.8	–	–	–	–	0.67	29.17	29.84	97.8
Ckgg	85–130	7.8	6.9	0.6	–	–	–	0.48	41.57	42.05	98.8
Ckgg2	130–150	8.1	7.2	9.7	–	–	–	0.52	47.76	48.28	98.9
S1 – *Typical vertisols, Haplic Vertisol (Aric, Hypereutric, Mazic)*											
Ap	0–32	7.3	6.8	–	19.2	1.95	9.8	1.91	21.90	23.81	92.0
Big	32–65	7.9	7.0	1.2	–	–	–	1.37	40.01	41.38	96.7
Cig	65–100	7.9	7.0	1.4	–	–	–	1.45	44.76	46.21	96.9
Ckg2	100–150	8.1	7.6	15.2	–	–	–	1.02	49.31	50.35	97.9
R2 – *Typical vertisols, Haplic Verisol (Aric, Grumic, Hypereutric)*											
Ap	0–30	7.5	6.9	4.6	16.4	1.94	8.4	0.65	25.57	26.22	97.5
Bik	30–80	8.0	7.1	5.6	1.1	0.15	7.3	0.19	31.10	31.29	99.4
Cik	80–150	8.1	7.2	12.5	–	–	–	0.22	28.60	28.82	99.2
Ck2	150–180	8.1	7.2	14.5	–	–	–	1.02	36.95	37.97	97.3
L1 – *Typical vertisols, Haplic Vertisol (Aric, Hypereutric, Grumic)*											
A	0–28	6.3	5.6	–	16.0	1.85	8.6	2.71	22.68	25.39	89.3
Bi	28–85	6.9	6.0	–	–	–	–	1.61	26.83	28.44	94.3
Cikg	85–150	7.9	7.1	14.7	–	–	–	1.21	68.92	70.13	98.3
Ckg2	< 150	7.9	7.2	13.1	–	–	–	1.18	69.46	70.64	98.3

Explanation: HA – potential (hydrolytic) acidity; TEB – total exchangeable bases; CEC – cation exchange capacity

The vertisols in the Sępopol Plain had the texture of clay (C), loam (L) and heavy clay (HC). In deeper horizons of the soil profiles, loam (L) and silty clay (SiC) frequently occurred. The studied soils were developed from fine-grained sediments of ice-dammed lakes origin with a high content of clay and did not contain skeletal fractions with a diameter > 2.0 mm. The content of sand (2.0–0.05 mm) was low and ranged from 5% to 43% (Table 2). In the silt fraction (0.05–0.002 mm), the fine silt sub-fraction (0.02–0.002 mm) prevailed, reaching 52%. The clay fraction (< 0.002 mm) amounted to up to 81% (55% on average). Clay fraction was predominated by swelling minerals, mainly smectite and mixed-packet type of illite / smectite (I / S), with a large share of smectite packets in their structure (Długosz et al., 2009). The high content of clay fraction rich in swelling clay minerals promotes the shrinking and swelling of vertisols. The confirmation of the occurrence of the *vertic* horizon in the soils of the Sępopol Plain were the values of the coefficient of linear extensibility, which exceeded 0.06. In B horizons of studied vertisols, the COLE ranged from 0.116–0.205 (Table 3). The calculated correlation coefficients showed that the content of clay had a significantly positive (r = 0.651) and sand had a significantly negative (r = –0.510) impact on the COLE values (Table 5). Kishné et al. (2009) and Reeve et al. (1980) stressed that the content of organic matter, carbonates and silica influence reduction of swelling and shrinking by increasing the cohesion forces.

Table 2
Texture of analysed Vertisols

Soil horizon	Depth cm	Percentage of particle-size fractions (mm)									Texture 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	0.02–0.002	< 0.002	PTG	USDA
R1 – Reszel: *Black vertisols* – SGP6 2019, *Pellic Vertisol (Aric, Mollic, Hypereutric, Grumic, Endostagnic)* – WRB 2015												
Ap	0–30	0	1	2	5	7	10	11	21	43	iz	C
A2	30–46	0	0	2	3	5	9	9	24	48	iz	C
Bikg	46–100	0	0	1	2	4	4	2	9	78	ic	HC
Cikg	100–160	0	0	1	2	4	3	2	19	69	ic	HC
Ckg2	160–180	0	0	1	1	2	5	2	39	50	ipy	SiC
K1 – Kętrzyn: *Gleyic vertisols, Haplic Vertisol (Mollic, Hypereutric, Gleyic*												
A	0–42	0	3	7	8	6	5	13	34	24	gz	L
Big	42–85	0	0	1	1	2	7	3	16	70	ic	HC
Ckgg	85–130	0	1	2	3	4	8	12	5	65	ic	HC
Ckgg2	130–150	0	0	1	1	1	9	7	7	74	ic	HC
S1 – Sępopol: *Typical vertisols, Haplic Vertisol (Aric, Hypereutric, Mazic)*												
Ap	0–32	0	3	5	6	10	13	16	24	23	gz	L
Big	32–65	0	0	1	2	2	5	5	7	78	ic	HC
Cig	65–100	0	0	2	2	3	2	1	14	76	ic	HC
Ckg2	100–150	0	4	6	10	12	11	7	33	17	gz	L
R2 – Reszel: *Typical vertisols, Haplic Verisol (Aric, Hypereutric, Grumic)*												
Ap	0–30	0	2	2	5	7	5	6	21	52	iz	C
Bik	30–80	0	0	2	4	6	5	8	7	68	ic	HC
Cik	80–150	0	0	1	2	3	4	2	20	68	ic	HC
Ck2	150–180	0	0	0	1	1	3	2	52	41	ipy	SiC
L1 – Lidzbark Warmiński: *Typical vertisols, Haplic Vertisol (Aric, Hypereutric, Grumic)*												
A	0–28	0	2	2	4	5	7	8	31	41	iz	C
Bi	28–85	0	0	0	2	2	3	3	9	81	ic	HC
Cikg	85–150	0	0	1	1	3	3	2	49	41	ipy	SiC
Ckg2	< 150	0	0	1	2	1	2	2	50	42	ipy	SiC

Explanation: gz – loam, ipy – silty clay, iz – clay, ic – heavy clay; L – loam, SiC – silty clay, C – clay, HC – heavy clay

3.2. Physical, water and retention properties

Soil water retention and water-air relationships in mineral soils depend largely on the humus content, degree of soil compaction, soil texture including clay content and cultivation technology (Rawls et al., 1991, Tietje and Tapkenhinrichs, 1993, Castellini et al., 2019). In the studied vertisols, the bulk density, which is an indicator of soil compaction, did not exceed 1.331 Mg m^{-3} in surface horizons (Table 3). The lowest particle density amounting to 1.150 Mg m^{-3}, and the highest total porosity 51.1% v/v was found in humic horizons of Gleyic Vertisols (Table 3). The bulk density above 1.33 Mg m^{-3} in the soils with high content of swelling clays may affect air conditions and limit oxygen macrodiffusion. The air pore volume in surface horizons (A) did not exceed 9.4% v/v, and in subsurface horizons and parent material it amounted to 2.1% v/v (Table 4). For the proper growth and development of the root system of most cultivated crops, the volume of macropores should range from 10% to 15% (Jarvis and Macney, 1979). The studied vertisols had improper distribution of soil pores because the ratio of macropores to mesopores to micropores in humic horizons was 1:2.7–5.1:1.5–5.4. This ratio was particularly unfavorable in some sub-humic horizons, where the volume of micropores exceeded the volume of mesopores twice and the volume of macropores more than 10 times.

Vertisols of the Sępopol Plain had high field water capacity (pF 2.0) and high content of water unavailable to plants (pF 4.2).

Table 3
Physical and redox properties

Soil horizon	Depth cm	Specific density Mg m^{-3}	Bulk density	Total porosity % v/v	Index COLE	ODR µg m^{-1} s^{-1}	Eh mV	rH
R1 – *Black vertisols, Pellic Vertisol (Aric, Mollic, Hypereutric, Grumic, Endostagnic)*								
Ap		2.377	1.204	49.3	0.120	56.1	310	24.7
A2	30–46	2.551	1.312	48.6	0.117	47.2	265	23.1
Bikg	46–100	2.457	1.244	49.4	0.183	38.3	220	21.8
Cikg	100–160	2.482	1.310	47.2	0.158	29.3	170	20.3
Ckg2	160–180	2.512	1.426	43.2	0.095	32.4	205	21.5
K1 – *Gleyic vertisols, Haplic Vertisol (Mollic, Hypereutric, Gleyic)*								
A	0–42	2.351	1.150	51.1	0.042	57.4	305	22.9
Big	42–85	2.558	1.228	52.0	0.116	38.4	265	22.7
Ckgg	85–130	2.494	1.258	49.6	0.110	33.0	205	20.9
Ckgg2	130–150	2.457	1.244	49.4	0.125	20.5	155	19.7
S1 – *Typical vertisols, Haplic Vertisol (Aric, Hypereutric, Mazic)*								
Ap	0–32	2.469	1.264	48.8	0.056	53.7	320	24.8
Big	32–65	2.470	1.402	43.2	0.116	37.1	295	24.2
Cig	65–100	2.480	1.383	44.2	0.104	29.4	215	21.4
Ckg2	100–150	2.520	1.460	42.1	0.032	19.1	180	21.4
R2 – *Typical vertisols, Haplic Verisol (Aric, Hypereutric, Grumic)*								
Ap	0–30	2.467	1.312	46.9	0.107	58.8	335	25.4
Bik	30–80	2.434	1.296	46.8	0.134	48.6	300	24.5
Cik	80–150	2.438	1.285	47.3	0.149	35.7	255	23.2
Ck2	150–180	2.490	1.414	40.8	0.107	38.4	280	24.1
L1 – *Typical vertisols, Haplic Vertisol (Aric, Hypereutric, Grumic)*								
A	0–28	2.506	1.331	46.9	0.198	53.6	325	22.0
Bi	28–85	2.591	1.343	48.2	0.205	43.4	300	22.3
Cikg	85–150	2.554	1.468	42.5	0.097	48.5	250	22.8
Ckg2	< 150	2.548	1.482	41.8	0.090	31.9	210	21.6

Explanation: ODR – oxygen diffusion rate; Eh – redox potential; rH – reduction rate assessment index

Table 4
Air-water properties of studied Vertisols

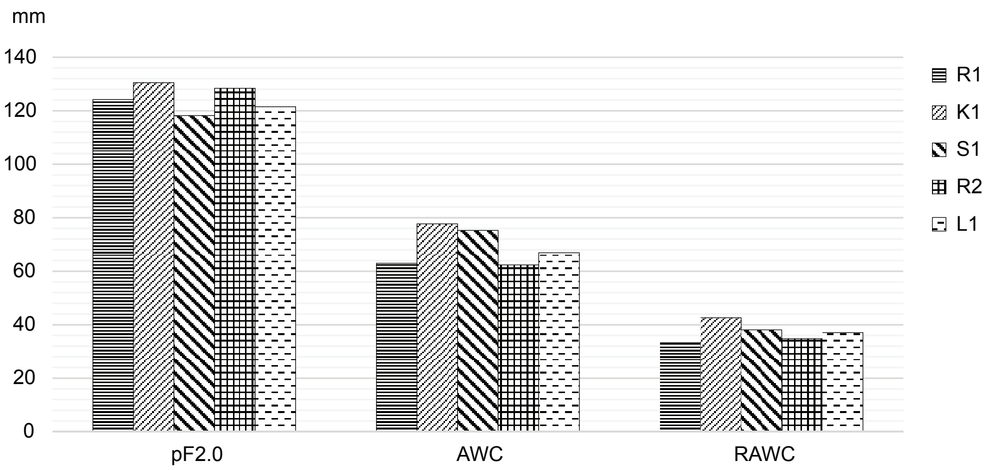
Soil horizon	Depth cm	pF 2.0	3.0	4.2	Macro-pores	AWC	RAWC	SAWC	Micro-pores	Ma/Tp	AWC/Tp	Mi/Tp	RAWC/AWC
		% v/v								%			
R1 – *Black vertisols, Pellic Vertisol (Aric, Mollic, Hypereutric, Grumic, Endostagnic)*													
Ap	0–30	41.4	30.3	20.4	7.9	21.0	11.1	9.9	20.4	16.0	42.6	41.4	52.9
A2	30–46	42.7	31.9	21.9	5.9	20.8	10.8	10.0	21.9	12.1	42.8	45.1	51.9
Bikg	46–100	46.2	38.5	28.4	3.2	17.8	7.7	10.1	28.4	6.5	36.0	57.5	43.7
Cikg	100–160	44.5	37.6	26.5	2.7	18.0	6.9	11.1	26.5	5.7	38.1	56.2	38.3
Ckg2	160–180	39.4	28.7	18.5	3.8	20.9	10.7	10.2	18.5	8.8	48.4	42.8	51.2
K1 – *Gleyic vertisols, Haplic Vertisol (Mollic, Hypereutric, Gleyic)*													
A	0–42	43.5	29.3	17.6	7.6	25.9	14.2	11.7	17.6	14.9	50.7	34.5	54.8
Big	42–85	49.1	41.8	30.0	2.9	19.1	7.3	11.8	30.0	5.6	36.7	57.7	38.2
Ckgg	85–130	47.0	41.2	30.2	2.6	16.8	5.8	11.0	30.2	5.2	33.9	60.9	34.5
Ckgg2	130–150	46.9	40.3	31.1	2.5	15.8	6.6	9.2	31.1	5.1	32.0	63.0	41.8
S1 – *Typical vertisols, Haplic Vertisol (Aric, Hypereutric, Mazic)*													
Ap	0–32	39.4	26.7	14.3	9.4	25.1	12.7	12.4	14.3	19.3	51.4	29.3	51.9
Big	32–65	41.0	34.9	27.7	2.2	13.3	6.1	7.2	27.7	5.1	30.8	64.1	45.9
Cig	65–100	42.1	35.7	27.2	2.1	14.9	6.4	8.5	27.2	4.8	33.7	61.5	43.0
Ckg2	100–150	37.5	24.3	16.8	4.6	20.7	13.2	7.5	16.8	10.9	49.2	39.9	63.8
R2 – *Typical vertisols, Haplic Verisol (Aric, Hypereutric, Grumic)*													
Ap	0–30	42.8	29.2	22.0	4.1	20.8	11.6	9.2	22.0	8.8	44.3	46.9	55.8
Bik	30–80	43.3	36.0	26.4	3.5	16.9	7.3	9.6	26.4	7.5	36.1	56.4	43.2
Cik	80–150	43.9	36.2	25.5	3.4	18.4	7.7	10.7	25.5	7.2	38.9	53.9	41.8
Ck2	150–180	37.2	29.8	19.2	3.6	18.0	7.4	10.6	19.2	8.8	44.1	47.1	41.1
L1 – *Typical vertisols, Haplic Vertisol (Aric, Hypereutric, Grumic)*													
A	0–28	40.1	27.5	17.8	6.8	22.3	12.6	9.7	17.8	15.0	47.5	38.0	56.5
Bi	28–85	46.0	37.0	23.4	2.2	22.6	9.0	13.6	23.4	4.6	46.9	48.6	39.8
Cikg	85–150	38.2	25.4	17.1	4.3	21.1	12.8	8.3	17.1	10.1	49.6	40.2	60.7
Ckg2	< 150	38.2	26.4	17.6	3.6	20.6	11.8	8.8	17.6	8.6	49.3	42.1	57.3

Explanation: AWC – available water capacity; RAWC – readily available water capacity; SAWC – small pores available water capacity; Ma – macropores; Mi – micropores; Tp – total porosity

The volume of field water capacity (pF 2.0) in humic horizons was from 39.4% v/v to 43.5% v/v, including the volume of water available to plants (AWC), which ranged from 20.8 to 25.9% v/v (Table 4). Walczak et al. (2002) as well as Orzechowski and Smólczyński (2010) found similar values of water retention properties in alluvial soils developed from clay deposits. Water resources corresponding to the field water capacity (pF 2.0) in the studied soils were high and in the 0–0.3 m soil layer they ranged from 118.2 mm to 130.5 mm, while in the 0–0.5 m layer they were between 199.9 and 228.7 mm (Fig. 2, 3). In the studied vertisols, approximately 50% of water resources of field water retention were available to plants (AWC), and in the 0–0.3 m layer these resources oscillated between 62.4 mm and 77.7 mm, and in the 0–0.5 m layer between 96.2 mm and 115.9 mm. The highest water retention and water resources available to plants were found in gleyic vertisols (K1) (Fig. 2, 3). The share of water unavailable to plants (pF 4.2) in field water capacity was substantial, and ranged from 14.3%–22.0% v/v in humic horizons (Table 4). However, in B horizons and some parent materials (C), due to the high content of clay and high soil compaction, the water in micropores, which is unavailable to plants, prevailed. The share of water available to plants in total porosity (AWC/Tp) rarely exceeded 50%, and the share of water unavailable to plants in total porosity (Micropores/Tp) ranged from 29.3% to 64.1%. In the volume of water available to plants

(AWC), the share of water readily available to plants (RAWC) in humic horizons was higher than the content of water hardly available to plants, i.e. water in small pores (SAWC). On the other hand, in B horizons developed from heavy loam, the share of water readily available to plants was lower than water hardly available to plants and ranged from 38.2% to 45.9%. A similar RAWC/AWC ratio was found by Orzechowski and Smólczyński (2010) in black earths developed from clay and in heavy alluvial soils.

The calculated correlation coefficients showed a significantly positive relationship between the amount of clay and the volume of water unavailable to plants (r = 0.880), and negative for water available to plants (AWC, r = –0.711), including water readily available for plants (RAWC, r = –0.852). The fine silt fraction (0.02–0.002 mm) had a significant positive impact on the volume of water available to plants (r = 0.467), including water readily available to plants (r = 0.621), (Table 5).



R1, R2 – Reszel, K1 – Kętrzyn, S1 – Sępopol, L1 – Lidzbark Warmiński

Fig. 2. Water resources in 0.3 m soil layer

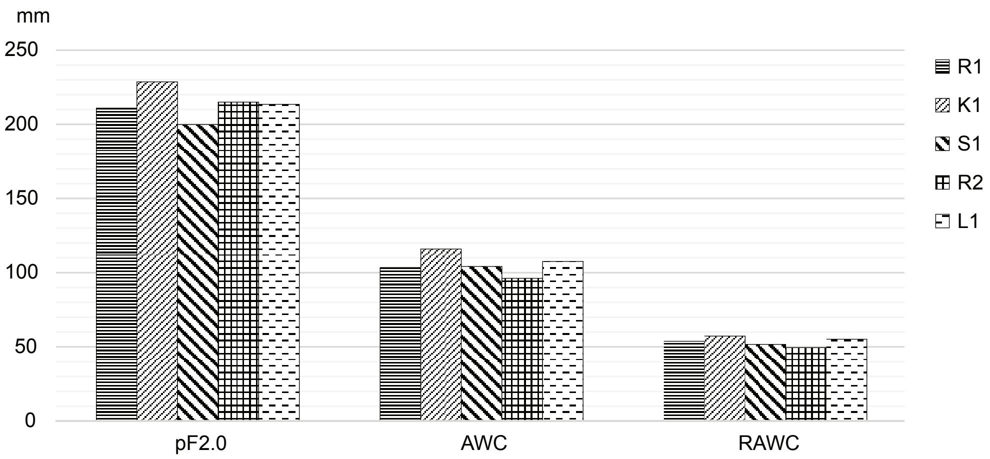


Fig. 3. Water resources in 0.5 m soil layer

Table 5
Coefficients of correlation between granulometric fractions and soil retention properties

Content of fraction with a diameter of [mm]	Total porosity	pF 2.0	Macro-pores	AWC	RAWC	Micro-pores	Eh	ODR	COLE	rH
			% v/v				mV	µg m^{-1} s^{-1}		
2.0–0.05	0.227	–0.207	0,282	0.503*	0.580*	–0.441*	0.210	0.244	–0.510*	0.232
0.05–0.02	0.488*	0.023	0,191	0.441*	0.372	–0.252	0.382	0.464*	–0.353	0.299
0.02–0.002	–0.596*	–0.769*	0.060	0.467*	0.621*	–0.789*	0.023	0.103	–0.407	0.080
< 0.002	0,223	0.683*	–0.224	–0.711*	–0.852*	0.880*	–0.211	–0.307	0.651*	–0.247

* – significance level at α=0.05

3.3. Redox properties

In the studied soils, the values of redox potential (Eh), oxygen diffusion rate (ODR) and reduction rate assessment index (rH) were low, which proves unfavorable aerobic conditions (Table 3). The values of Eh exceeded 300 mV, the threshold value for oxygenated/reduced soils, only in surface horizons of the studied vertisols. At subsurface horizons, the Eh was below 300 mV, which is associated with the reduction of manganese and iron compounds (Gliński and Stępniewska, 1986: Stępniewska, 1988). The values of ODR ranged from 53.6 to 58.8 μg m^{-2} s^{-1} in surface horizons. In deeper horizons the ODR values did not exceed 50.0 μg m^{-2} s^{-1}, which indicates the possibility of hypoxia of the root system of most cultivated crops. In parent materials of black vertisols and gleyic vertisols and some typical vertisols, the ODR values did not exceed 35.0 μg m^{-2} s^{-1}, which is the value of lower critical oxygenation limit for plants (Gliński and Stępniewska, 1986). High water content in soil and simultaneous high content of swelling clay minerals and low volume of air pores promotes gleyic processes, as indicated by redoximorphic parameters. Limited macrodiffusion in the studied vertisols may limit the oxygen supply to the plant root system, hamper its development and even cause plant dying. It is particularly important in clay soils, which have high potential fertility but unfavorable air-water relations resulting from the small volume of air popres (Stępniewski 1980). Unfavorable aerobic conditions in soils developed from glaciolimnic sediments in the Sępopol Plain were also confirmed by the studies of Orzechowski et al. (2018). The values of rH exceeded 20.0 in the studied soils, but this was mainly due to the neutral reaction of soils, which has a key impact on its value.

The values of the redox potential, oxygen diffusion rate and rH index were negatively correlated with clay content, but these relationships were not statistically significant (Table 5).

4. Conclusions

1. Vertisols in the Sępopol Plain were developed from glaciolimnic sediments and had textures of clay (C), loam (L) and heavy clay (HC).
2. The studied vertisols had high field water capacity (pF 2.0) and the content of water unavailable to plants (pF 4.2). Only in humic horizons the volume of water available to plants (AWC) was higher than the volume of water unavailable to plants.
3. Studied vertisols had low volume of air pores. The distribution of soil pores was unfavorable, and the ratio of macropores to mesopores to micropores in humic horizons was as 1:2.7–5.1:1.5–5.4.
4. The studied vertisols had unfavorable aerobic conditions, which was proved by low values of redox potential (Eh) and oxygen diffusion rate (ODR). The values of Eh exceeded 300 mV, which is a threshold value for oxygenated / reduced soil.

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Fizyczne, wodne i oksydoredukcyjne właściwości wertisoli na Nizinie Sępopolskiej w Polsce północno-wschodniej

Słowa kluczowe

Wertisole
Osady glacjolimniczne
Właściwości fizyczne
Retencja wody
Potencjał oksydoredukcyjny

Streszczenie

Wertisole występujące na terenie Niziny Sępopolskiej w Polsce północno-wschodniej charakteryzują się naturalną wysoką żyznością. Należą one do grupy gleb o dużej zawartości frakcji iłowej, które wykazują zdolności do cyklicznego kurczenia się i pęcznienia minerałów ilastych. W wyniku zmiennego uwilgotnienia w glebach tych tworzą się głębokie szczeliny i gładkie powierzchnie ślizgu na powierzchni agregatów. Celem niniejszej pracy było zbadanie właściwości chemicznych, fizycznych, powietrzno-wodnych i oksydoredukcyjnych wertisoli wytworzonych z zastoiskowych osadów glacjolimnicznych zlodowacenia bałtyckiego. Badane wertisole wytworzyły się z drobnoziarnistych osadów glacjolimnicznych o uziarnieniu iłu zwykłego (C), gliny zwykłej (L) i iłu ciężkiego (HC). Gleby te charakteryzowały się dużą polową pojemnością wodną (pF 2,0) i zawartością wody niedostępnej dla roślin (pF 4,2), a małą objętość porów powietrznych. Stwierdzono istotną dodatnią korelację pomiędzy ilością frakcji iłowych, a objętością wody niedostępnej dla roślin (pF 4.2), natomiast ujemną zależność w odniesieniu do wody ogólnie dostępnej (AWC), w tym wody łatwo dostępnej dla roślin (RAWC). Rozkład porów glebowych był niekorzystny, a stosunek makroporów do mezoporów i mikroporów w poziomach próchnicznych kształtował się jak 1 : 2.7–5.1 : 1.5–5.4. Wertisole te charakteryzowały się niekorzystnymi warunkami oksydoredukcyjnymi o czym świadczą niskie wartości potencjału redox (Eh) i natężenia dyfuzji tlenu (ODR). Wartości potencjału Eh jedynie w poziomach powierzchniowych przekraczały wielkość 300 mV, przyjętą jako granica pomiędzy glebą natlenioną, a zredukowaną.