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CHARACTERISTICS OF AERATION PROPERTIES OF SELECTED SOIL PROFILES FROM CENTRAL EUROPE

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A b s t r a c t. The purpose of this paper was to characterise soil structure from the point of view of its aeration properties and to verify applicability of some methods for the determination of different properties related to aeration. The studies were performed on 15 representative soil samples from Austria, Czech Republic, Hungary, Poland and Slovakia. The paper presents results of measurements of different soil aeration properties such as oxygen diffusion rate (ODR), redox potential (*Eh*), relative gas diffusion coefficient (D/D_o), air permeability (*k*), air-filled porosity (*Eg*) and activity of soil dehydrogenase and catalase. All the aeration parameters such as D/D_o, ODR, *k* were correlated with soil water content, air-filled porosity, bulk density and particle density. In most cases the aeration indicators themselves were also intercorrelated. The activity of both studied enzymes was correlated with some of the aeration parameters. Threshold values of soil physical conditions providing satisfactory aeration status in particular soil profiles were determined.

K e y w o r d s: soil aeration, air-filled porosity, ODR, *Eh*, D/D_o, air permeability, dehydrogenase activity, catalase activity, Central Europe soils

INTRODUCTION

Soil aeration status is an effect of equilibrium between biological processes of oxygen uptake combined with carbon dioxide production in soil environment and physical processes of gas transport between soil and atmosphere. Gas transport depends directly on the diffusion coefficient in the soil which is determined by the amount, tortousity and continuity of the air -filled pores, i.e., by water content and physical arrangement of soil particles, and, indirectly, by all the modifying factors (compaction, crusting, tillage, irrigation, drainage etc.). Soil oxygenation status which is closely related to soil redox transformations, plays a fundamental role in the functioning of plant and microorganisms, and influences type of respiration and kind of population of microorganisms.

Fluctuations in the enzyme activity could be influenced by the type and density of the vegetation cover, climate and soil type, and depend on the state in which the enzyme is present in the soil, i.e., either as an extracellular enzyme in the soil solution, associated with microorganisms, or sorbed to colloidal particles [6,7]. Dehydrogenases carry out a broad range of activities that are responsible for oxidation, i.e., dehydrogenation of organic matter. They give information on the influence of natural environmental conditions and xenobiotics on enzyme activities [24].

Catalases decompose hydrogen peroxide, formed as a by-product during respiration, to water and oxygen. These enzymes play an important role for microorganisms, protecting their cells from toxic H_2O_2 [20].

Recently observed changes in climate with an increase of temperature and the lowering of ground water level led to proposal of a joint project to investigate structures of some selected soil profiles in Central Europe [4,10]. The project was supported by the Austrian Federal Ministry of Sciences, Research and Art. Samples were chosen to represent a wide range of chemical and physical soil properties and different types of soil utilisation and cultivation.

The purpose of this paper was to characterise the structure of 15 representative soil samples from Central Europe from the point of view of their aeration properties such as oxygen diffusion rate (ODR), redox potential (*Eh*), relative gas diffusion coefficient (D/D_o), air permeability (*k*), air-filled porosity (*Eg*) and activity of soil dehydrogenases and catalases and to determine correlations between these properties and soil physical parameters such as: water content, bulk density (*d*) and particle density (γ).

MATERIALS AND METHODS

Soils

The soils examined came from 15 sites representing typical regions of:

Austria - two profiles typical for the agricultural production of Lower Austria (Wieselburg - Cambisol under corn and Fuchsenbigl - Phaeozem under wheat) [10,23,31].

Czech Republic - cultivated Arenic Chernozem from Central Bohemia (Tišice) [10,23,31].

Hungary - six profiles from the region of Nagykunság (Great Kúnság) representing different agricultural practices: Fluvic Gleysol (Abádszalók, A-1, A-2) cultivated and uncultivated, i.e., under natural grassland, Vertic Gleysol (Kisújszállás, K-1, K-2) under cultivation with deep loosening and without deep loosening, Orthic Solonetz (Karcagpuszta, P-1, P-2) uncultivated and cultivated with gypsum amelioration [10,22,23].

Poland - three profiles (from Nałęczów Plateau) of Orthic Luvisol representing various types of utilisation: under forest (Forest), private farming (Farm) and state farming (Exp) [9, 10,23,31,32].

Slovakia - three profiles from the South -West Slovakia: Calcaro-haplic Phaeozem (Macov 1), Fluvi-calcaric Phaeozem (Macov 2) and Calcaro-gleyic Phaeozem (Zemianska Olča) [10, 23].

Basic soil properties are presented in Table 1. A full description and characteristics have been published by Gliński [10].

Measurement methods

Undisturbed soil samples in 100 cm^3 brass cylinders were collected in late autumn of 1991 and transported to Lublin in January 1992. Measurements of all the parameters were taken at four soil water tensions: 0 (capillary saturation), 63, 159 and 500 hPa. Undisturbed soil cores after capillary saturation were brought to equilibrium at individual soil water tension levels on kaolin tension plates at room temperature. Relative gas diffusion coefficient (D/D_o) and air permeability (*k*) were measured at each equilibrium (except of Polish profiles at 0 hPa). After these measurements had been completed, the cylinders were resaturated and, after subsequent equilibrations on the tension plates, were used to determine oxygen diffusion rate (ODR), redox potential (*Eh*), the content of Fe^{+2} and the activity of dehydrogenases and catalases.

The ODR measurement method consists in determining the intensity of electric current corresponding to oxygen reduction on a platinum cathode placed in the soil and negatively polarised in respect to the reference electrode. ODR values characterise potential oxygen availability for plant roots. For the ODR measurement, a device described by Malicki and Walczak [19], with an automatic control of the effective reduction voltage was used. Four platinum wire electrodes (0.5 x 4 mm) were placed at a depth of 2 cm and polarised to -0.65 V versus saturated calomel electrode, for 4 min. The principle of the method is described in detail by Gliński and Stępniewski [17] and Gliński and Konstankiewicz [11].

The *Eh* was measured potentiometrically using four Pt electrodes of the same type as for ODR measurements; with a saturated calomel electrode as a reference electrode, and a laboratory pH-meter (Radiometer, Copenhagen). The electrodes were placed at the 2-cm depth. The measurements were taken after stabilisation of the readings [17].

The measurement of D/D_0 was performed according to an unsteady - state method of Stępniewski [28] with the sample holder modification described by Stępniewski [27]. Oxygen was used as a diffusing agent. The method is also described by Gliński and Konstankiewicz [11]. In this method the soil core is placed horizontally. The non-shrinking cores in this device are held in the cylinder, but the shrinking cores (if they are stable enough) can also be installed after their removal from the cylinder.

The measurement of *k* was performed at 10 hPa air pressure with a laboratory permeameter type LPIR-1 produced by the Experimental Department of Metallurgy in Cracow. The soil core (in the cylinder) in this device is placed vertically and the air is blown through it from the bottom [3,17].

The content of Fe^{+2} was determined in the extract in 0.05 M H_2SO_4 (2.5 g of the wet soil plus 25 ml of the sulphuric acid solution, shaken for 5 min) with the use of αα'-dipyridyl in acetate buffer solution of pH 4.5 [1].

Dehydrogenase activity was measured by the method of reduction of TTC (2,3,5-triphenyltetrazolium chloride) to formazan during incubation for 20 h at 30 °C, at pH=8.2 according to procedure of Casida *et al.* [8].

Catalase activity was measured by manganometric titration of surplus H_2O_2 under acidic conditions according to the procedure by Johnson and Temple [18].

Water content, bulk density and particle density were determined by the methods described by Turski *et al.* [30].

All analytical results were calculated on the basis of the oven-dry (105 °C) soil mass.

The 15 soil profiles studied were subjected to preincubation at controlled water content in the range from full saturation (0 hPa) through 63 and 159 to 500 hPa. The results obtained were elaborated for the individual soil profiles at 159 hPa (water easy available for plants) and also for all the horizons of the 15 profiles taken together at 4 soil water tensions.

The analysis of variance and regression analysis were used in the statistical processing of the data. A linear (y=a+bx), exponential (y=exp(a+bx)) and power law ($y=ax^b$) models were used to express the observed relationships. Statistical analyses of soil parameters were done for each soil water tension.

RESULTS AND DISCUSSION

Oxygenation indicators at 159 hPa water tension

The *Eg* (Fig. 1) varied widely for the studied soils in the range from almost 0 (P-2) to 0.333 m^3m^{-3} (Forest). It is reasonable to assume an air content of above 0.25 m^3m^{-3} to be sufficient for good aeration. In the range of air contents from 0.10 to 0.25 m^3m^{-3}, aeration may be deficient under some conditions while the air contents below 0.10 m^3m^{-3} characterise decidedly deficient aeration [17]. Figure 1 shows *Eg* values in all the investigated horizons. Among the Ap horizons of the studied soils incubated at 159 hPa, only three horizons had values above 0.25 m^3m^{-3} (Fuchsenbigl, Farm and Forest), six soils showed Eg values between 0.1 to 0.25 m^3m^{-3} (A-1, A-2, Tišice, Macov 1 and 2, Exp) and six profiles were below 0.1 m^3m^{-3}. This indicates that most of the investigated soils displayed deficient aeration conditions at 159 hPa.

The upper horizons of the four soil profiles (Wieselburg, Fuchsenbigl, Macov 1 and Zemianska Olča) showed high k values, up to about 55 μm^2 (Fig. 1). In the case of Fuchsenbigl and Macov 2 air permeability levels were higher in the underlying horizons than in the upper ones. All the Hungarian soils showed very low *k* values (between 0.2 μm^2 and 6.5 μm^2 for P-1 and P-2, respectively).

Data from literature show D/D_o=0.005 as the lower critical value corresponding to low respiration activities, and D/D_o=0.02 as the upper one for the highest respiration rates [17]. A relative gas diffusion coefficient of the upper horizons (at 159 hPa) in five investigated

Table 1. Physical and chemical soil parameters

Country	Profile	Soil type	Horizon (cm)	Particle size distribution			Bulk density, *d* ($Mg\ m^{-3}$)	pH		O.M. (%)
				Sand (2000-50 μm)	Silt (50-2 μm)	Clay (<2 μm)		H_2O	KCl	
Austria	Wieselburg	Cambisol	Ap (0-20)	20.0	46.6	33.4	1.46	7.4	6.9	2.2
			AB (20-40)	25.0	50.3	24.7	1.55	7.5	6.8	2.0
			Bv (40-80)	24.0	52.0	24.0	1.49	8.0	7.2	1.2
	Fuchsenbigl	Phaeozem	Ap (0-15)	42.0	31.5	26.5	1.34	8.5	7.3	2.5
			Ah (15-23)	43.0	34.4	22.6	1.45	8.5	7.5	2.7
			AC (23-40)	41.0	37.1	21.9	1.41	8.6	7.7	1.0
Czech Republic	Tišice	Arenic Chernozem	15-20	60.0	24.0	16.0	1.59	8.5	7.5	3.2
			40	47.0	37.0	16.0	1.24	9.0	8.3	1.2
			90	41.0	44.0	15.0	1.33	8.9	8.2	n.t.
Hungary	Abádszalók-cult. (A-1)	Fluvic Gleysol	A (0-20)	15.6	36.6	47.8	1.15	5.9	4.8	3.3
			B (21-60)	13.9	32.3	53.8	1.28	6.3	5.1	1.6
			BC (61-80)	17.6	29.8	52.6	1.39	6.7	5.4	0.8
			C (81-120)	43.6	24.6	31.8	1.45	7.2	6.1	n.t.
	Abádszalók-uncult. (A-2)	Fluvic Gleysol	A (0-20)	13.7	33.9	52.4	1.21	6.2	5.2	2.5
			B (21-60)	11.7	31.7	56.6	1.29	6.4	5.2	1.3
			BC (61-80)	19.2	28.3	52.6	1.48	6.7	5.5	1.0
			C (81-120)	41.9	23.7	34.4	1.43	6.9	6.0	n.t.
	Kisújszállás-deep loosend (K-1)	Vertic Gleysol	A (0-30)	20.2	35.2	44.6	1.32	6.4	5.8	3.2
			B (31-50)	12.2	42.8	45.0	1.41	7.5	6.7	0.3
			BC (51-80)	10.6	47.6	41.8	1.49	7.7	7.1	0.5
			C (81-130)	28.2	25.8	46.0	1.49	6.7	5.7	n.t.
	Kisújszállás-without loosening (K-1)	Vertic Gleysol	A (0-30)	18.6	35.4	46.0	1.27	6.4	5.8	3.2
			B (31-50)	15.8	32.6	51.6	1.35	6.6	5.8	1.9
			BC (51-110)	13.2	30.8	56.0	1.48	7.3	6.3	0.07
			C (91-110)	11.2	45.4	43.4	1.50	7.4	7.0	n.t.

T a b l e 1. Continuation

Country	Profile	Soil type	Horizon (cm)	Particle size distribution			Bulk density, d (Mg m^{-3})	pH		O.M. (%)
				Sand (2000-50 μm)	Silt (50-2 μm)	Clay (<2 μm)		H_20	KCl	
Hungary	Karcagpuszta-uncult.	Orthic	A (0-20)	24.2	34.0	41.8	1.41	7.4	6.9	1.5
	(P-1)	Solonetz	B (21-40)	13.4	35.2	51.4	1.58	9.0	7.4	0.6
			BC (41-70)	16.0	32.2	51.8	1.61	8.1	6.9	1.2
			C (71-85)	5.4	52.4	42.2	1.61	9.0	7.8	
	Karcagpuszta-cult.	Orthic	A (0-20)	20.8	34.0	45.2	1.42	7.8	6.9	1.4
	(P-2)	Solonetz	B (21-50)	14.0	29.2	56.8	1.53	8.4	7.1	0.5
			BC (51-70)	12.4	33.2	54.4	1.53	8.7	7.5	0.4
			C (71-95)	11.4	49.2	39.4	1.55	9.0	8.0	n.t.
Poland	Forest	Orthic Luvisol	E (11-16)	63.0	27.0	10.0	1.35	4.6	4.1	0.7
	Private farm	Orthic	Ap (0-24)	66.0	27.0	7.0	1.23	4.9	4.5	1.4
	(Farm)	Luvisol	E (25-35)	65.0	26.0	9.0	1.48	5.9	5.3	0.4
	State farm	Orthic	Ap (3-8)	65.0	29.0	6.0	1.39	6.2	5.5	1.5
	(Experimental)	Luvisol	E (30-35)	65.0	28.0	7.0	1.41	6.6	5.8	0.3
Slovakia	Macov 1	Calcarohapli	Akp (0-38)	38.0	40.7	21.3	1.46	8.3	7.8	2.0
		c	Ak (38-48)	37.3	40.6	22.1	1.30	8.4	8.1	2.0
		Phaeozem	A/Crk (48-65)	37.9	44.7	17.4	1.30	n.t.	n.t.	n.t.
			Ck (65-85)	33.4	55.2	11.4	1.31	n.t.	n.t.	n.t.
	Macov 2	Fluvical-	Akp (0-38)	42.6	39.0	18.4	1.36	8.0	7.6	2.9
		caric	Ak (38-68)	37.3	40.7	22.0	1.28	8.2	7.8	2.2
		Phaeozem	A/Ckg (68-88)	16.2	60.2	23.6	1.38	n.t.	n.t.	n.t.
	Zemianska Olča	Calcarogleyi	Agkp (0-33)	12.8	52.5	34.7	1.28	8.4	7.5	4.6
		c	A/Cgk (33-47)	5.4	69.9	24.7	1.32	8.6	7.8	0.7
		Phaeozem	Cgk (57-100)	3.7	78.1	18.2	1.37	n.t.	n.t.	n.t.
			Abgrk (100-120)	6.6	75.2	18.2	1.51	n.t.	n.t.	n.t.

O.M. - organic matter.

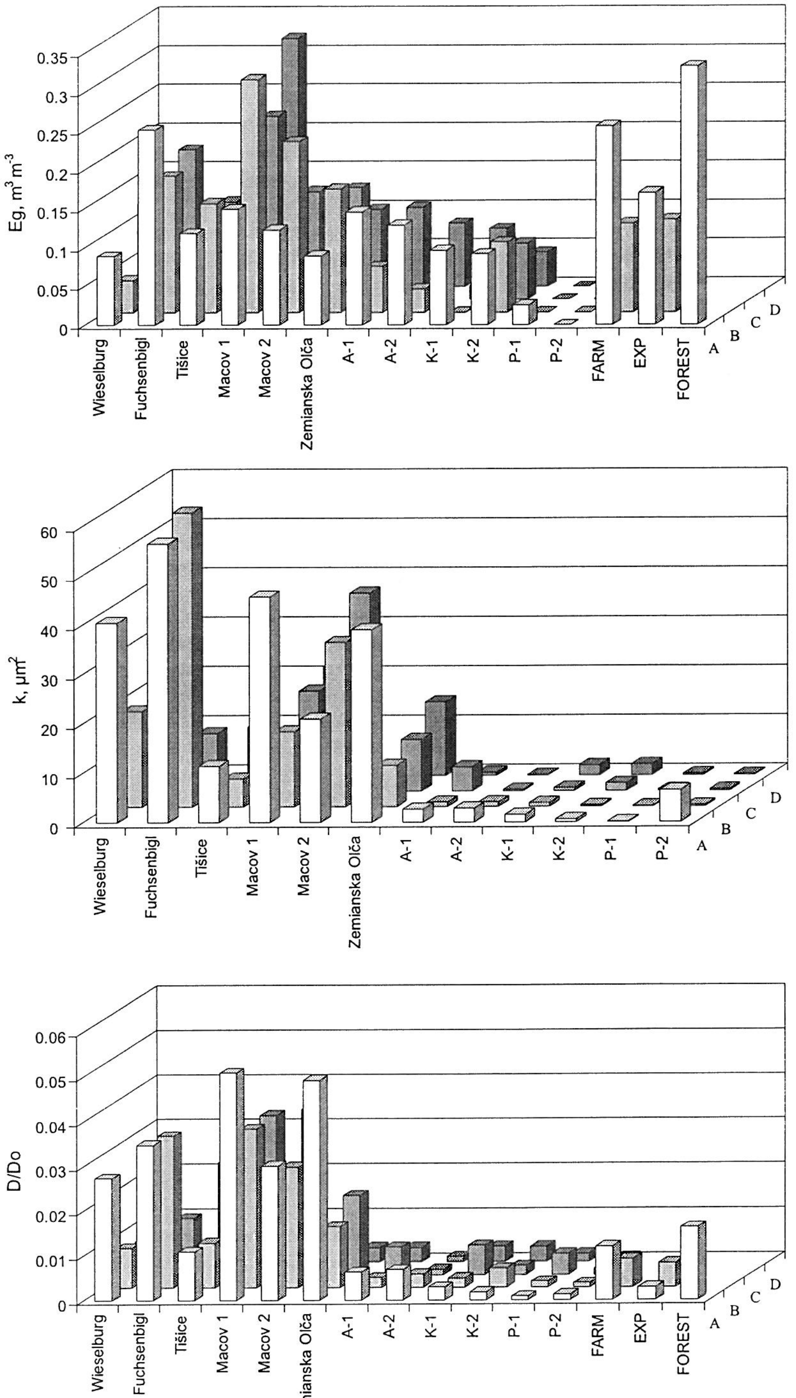
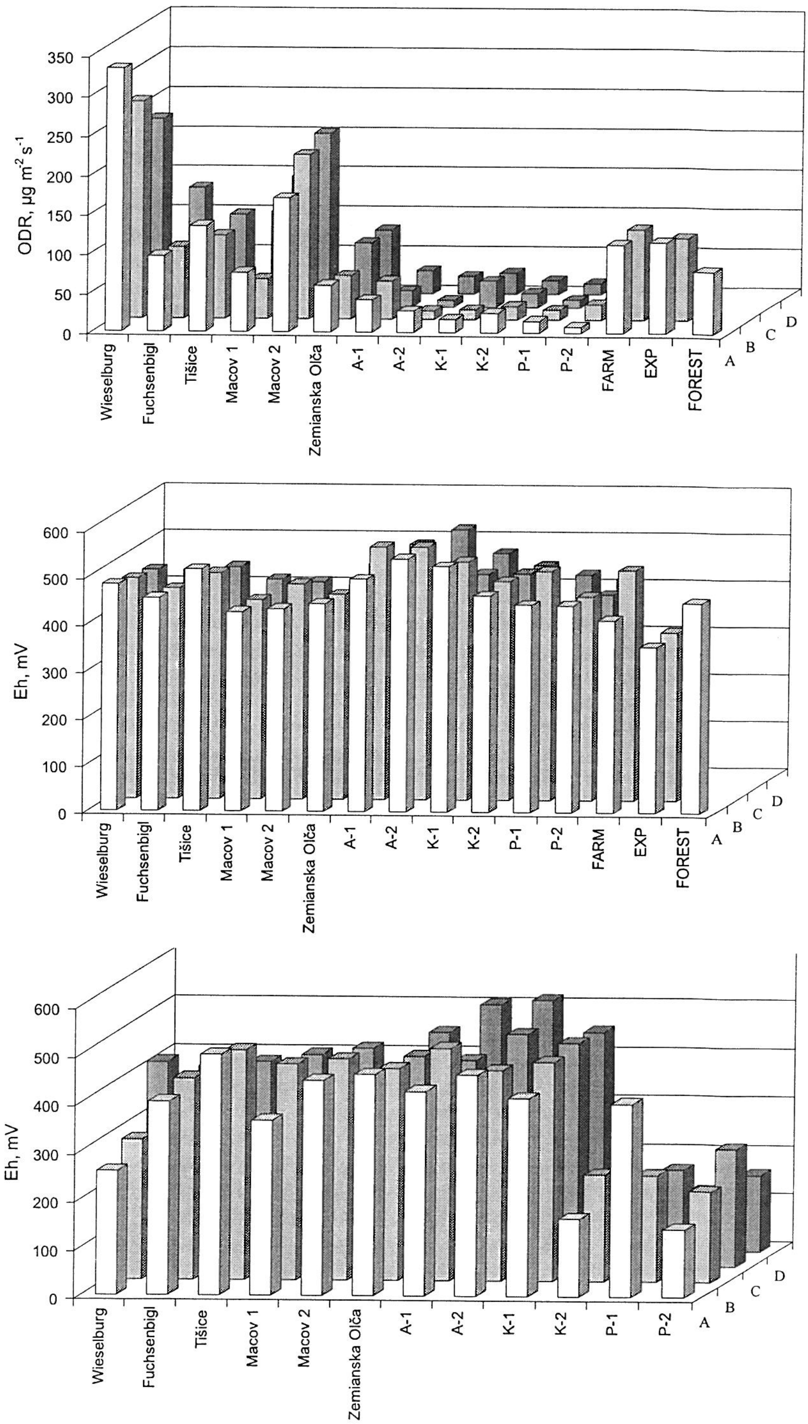


Fig. 1. Air-filled porosity (*Eg*), air permeability (*k*), diffusion coefficient (D/D_o) in individual soil profiles (incubation at 159 hPa). A,B,C,D - soil horizons from the upper A to the deepest D.



a

b

Fig. 2. Oxygen diffusion rate (ODR) (incubation at 159 hPa), redox potential (*Eh*) (incubation at 159 hPa) (a) and redox potential (*Eh*) (incubation at full saturation with water) (b) in individual soil profiles. For other explanations see Fig. 1.

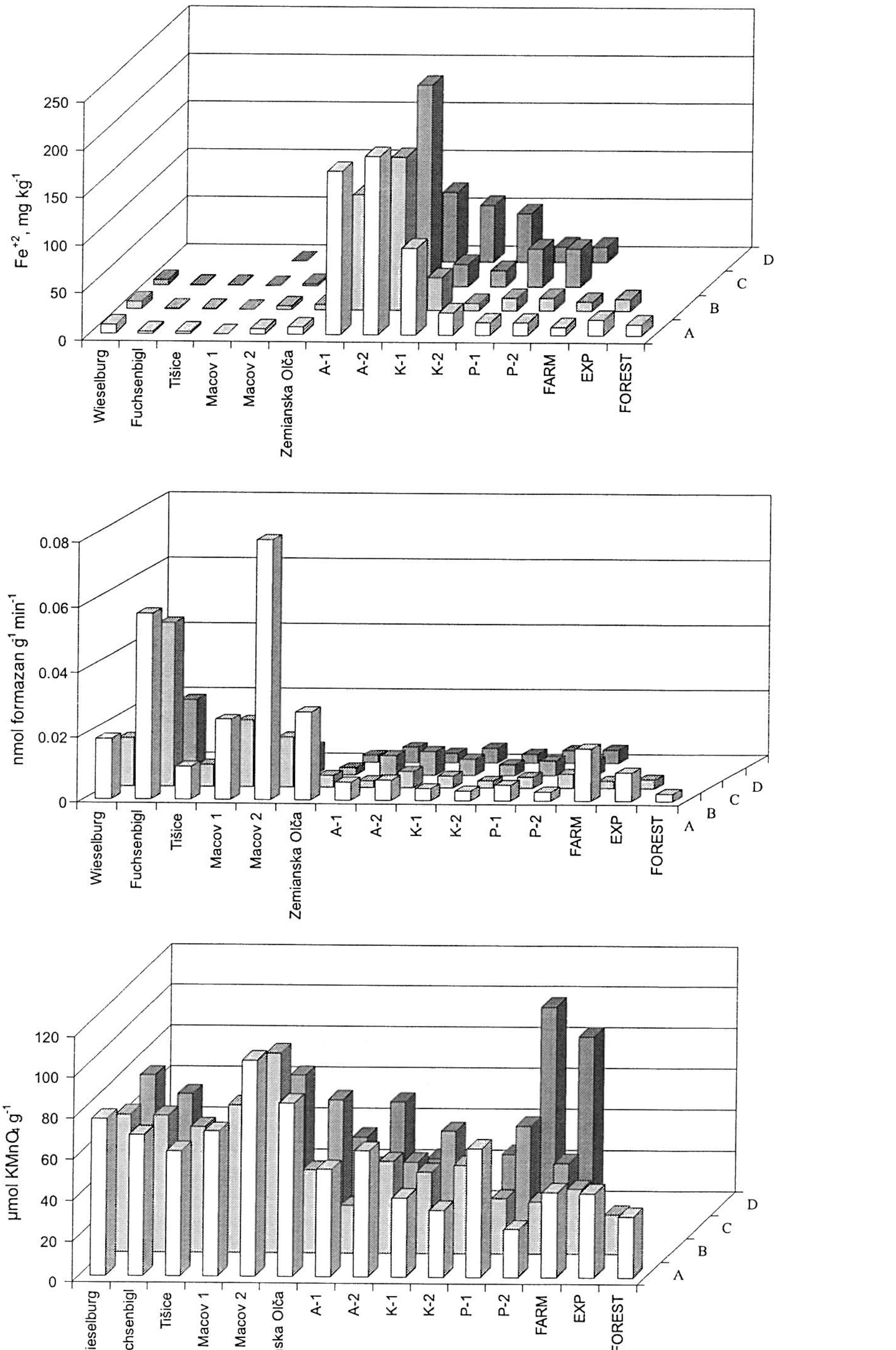


Fig. 3. Fe^{+2} content, dehydrogenase and catalase activities in individual soil profiles (incubation at 159 hPa). For explanation see Fig. 1.

profiles (P-1, P-2, K-1, K-2, Exp) was lower than that of the lower critical value and was within the range from 0.00087 to 0.003 (Fig. 1). D/D_o of the Austrian and Slovakian soil samples were above 0.02 corresponding to high respiration rates with the highest value (0.051) in the Macov 1 profile. When the above are considered for the studied soils we can conclude that there are favourable conditions for respiration in the upper and lower horizons of these five profiles.

The critical ODR value, which is usually considered to be below 30 $\mu g\ m^{-2}s^{-1}$ was found in the five Hungarian Ap horizons incubated at 159 hPa (Fig. 2). The remaining studied profiles showed relatively high levels of ODR. The highest ODR value observed in Wieselburg (332 $\mu g\ m^{-2}s^{-1}$) by far exceeded the values most frequently observed in soils, which usually range between 0 and 200 $\mu g\ m^{-2}s^{-1}$ [17].

The Ap horizons studied at 159 hPa were characterised by high *Eh* (Fig. 2), which dropped below 400 mV only in the Exp profile and did not drop below 300 mV, even at capillary saturation (0 hPa) in the most studied profiles (Fig. 2). The period of capillary saturation lasted for 7 days in the heavy Hungarian profiles and for 2 days in the other profiles. Very high *Eh* values suggested high redox buffering capacity of the soils, except in the two Hungarian profiles (K-2 and P-2) and one Austrian profile (Wieselburg). Gliński and Stępniewska [13] suggested that saturation time needed to decrease *Eh* value to 300 mV at 20°C can be used as a measure of the soil redox buffering capacity (soil redox resistance - t_{300}). It is related to many soil properties [13], among others to the presence of reducible iron content and oxidised forms of nitrogen and manganese.

The studied profiles exhibited low levels of Fe^{+2} content at the soil water tension at 159 hPa (Fig. 3). Only three of the profiles (A-1, A-2, K-1) showed Fe^{+2} content above 50 mg kg^{-1}. This low level of the reduced forms of iron was accompanied by high *Eh* values. None of the studied soils reached *Eh* below 300 mV corresponding to the initiation of iron reduction [25]. A possible reason for high *Eh* values may be the presence of nitrates. It was found out that supplementing soil with nitrates maintains soil *Eh* at a constant level for a certain period, and delays reduction of Mn(IV) and Fe(III) compounds [2,12,16].

Dehydrogenase activity varied widely in the Ap horizons of the tested soils (Fig. 3). The Hungarian soils and the Forest soil in Poland exhibited very low activities, which did not exceed 0.007 nmol formazan $g^{-1}min^{-1}$. Among the remaining profiles the highest dehydrogenase activity (0.0825 nmol formazan $g^{-1}min^{-1}$) occurred in the Macov 2 profile.

Catalase activity (Fig. 3) in the Ap horizons were the highest for the Macov 2 (up to 105 μmol $KMnO_4$ g^{-1}), the lowest for P-2 (below 24 μmol $KMnO_4$ g^{-1}) and did not show such as high differentiation as the dehydrogenase activity.

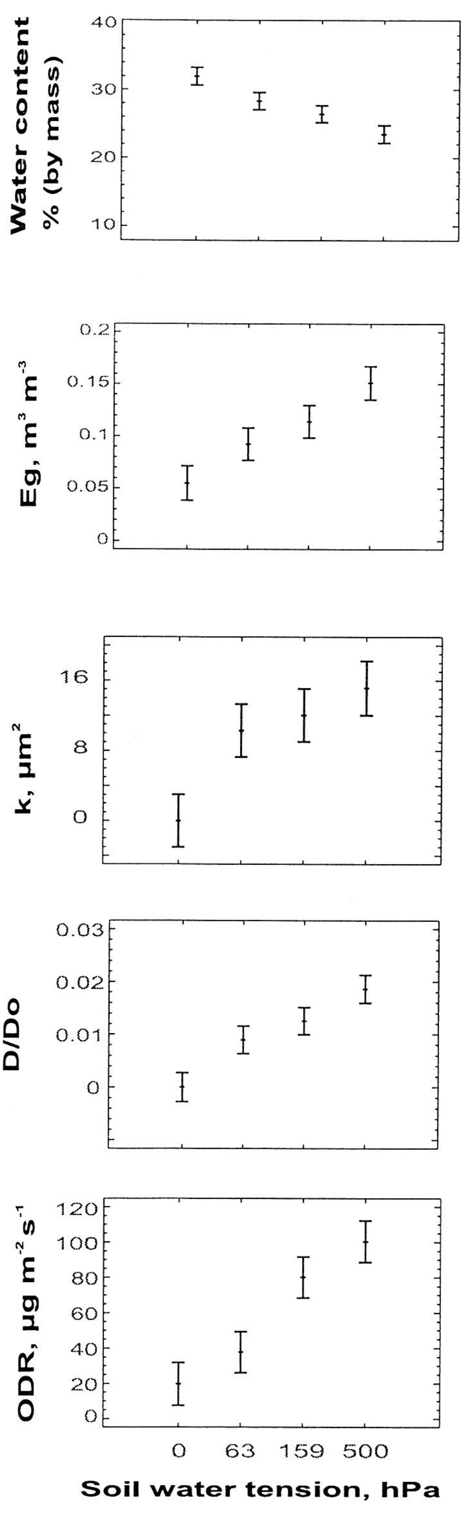
Oxygenation indicators in the range from 0 to 500 hPa water tension

A decrease of water content following changes of soil water tension from 0 to 500 hPa improved soil oxygenation (Fig. 4). This tendency was confirmed by a significant increase of soil oxygenation parameters like: *Eg*, *k*, D/D_o, ODR and *Eh* values and a significant decrease of Fe^{+2} content as well as of dehydrogenase and catalase activity in all the studied horizons (Table 2). The same tendency was found for the Ap horizons except for the dehydrogenase activity and Fe^{+2} content (Table 3).

Figure 4 shows average values of water content of the 15 investigated profiles versus soil water tension. Water content is the main factor influencing aeration state of the studied soils and modifying aeration indicators presented in this figure.

Air-filled porosity increased as the soil water tension increased in the range of 0-500 hPa. The average *Eg* values were 0.055, 0.092, 0.114, 0.151 $m^3\ m^{-3}$ at 0, 63, 159 and 500 hPa, respectively (Fig. 4).

Air permeability for the profiles studied considerably increased at 63 hPa when compared to the saturated soils and slowly increased



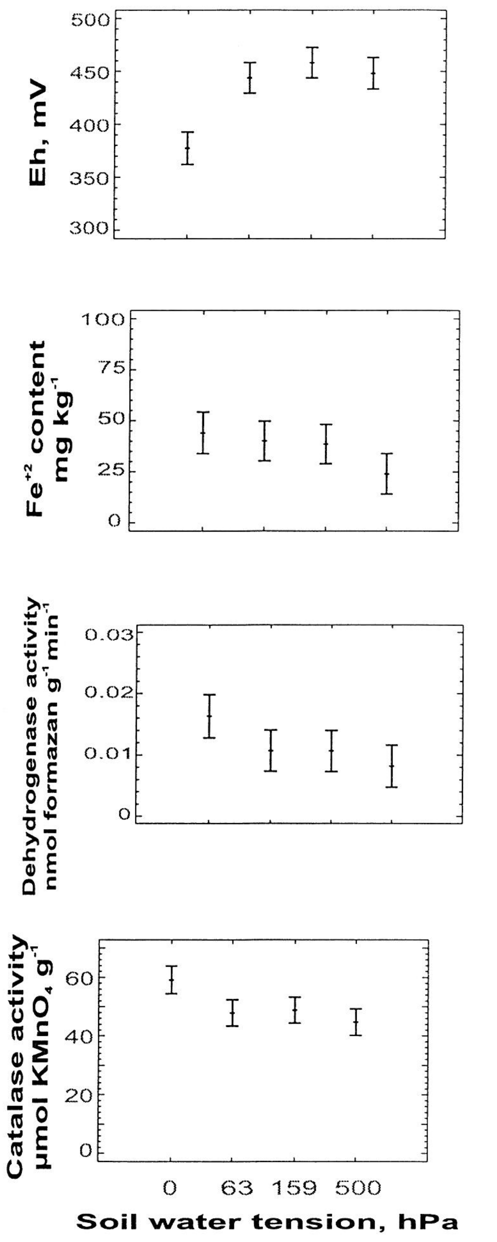


Fig. 4. Water content, Air-filled porosity (*Eg*), air permeability (*k*), diffusion coefficient (D/D_o), oxygen diffusion rate (ODR), redox potential (*Eh*), Fe^{+2} content, dehydrogenase activity and catalase activity versus soil water tension (average values of all horizons of 15 profiles taken together). The bars represent 95 % LSD confidence intervals.

at 159 and 500 hPa. The average values of k were 0, 10.3, 12.0 and 15.1 μm^2 at 0, 63, 159 and 500 hPa, respectively (Fig. 4).

A relative gas diffusion coefficient increased with a decrease of soil water content. The average D/D_o values were 0, 0.009, 0.013 and 0.018 at 0, 63, 159 and 500 hPa, respectively (Fig. 4).

ODR showed a typical tendency for changes under different air-water conditions (Fig. 4). The average values of ODR were 19.7, 37.7, 80.1, 100.4 $\mu g\ m^{-2}s^{-1}$ at 0, 63, 159, and 500 hPa, respectively.

The average Eh values in all the horizons studied ranged from 377 to 458 mV and showed a tendency to increase with increasing soil water tension. The most pronounced difference was found between soil preincubated at 0 hPa (377 mV) and 63 hPa (443 mV). Relatively small changes in the Eh values was observed at soil water tensions >63 hPa (Fig.4).

Concentration of Fe^{+2} declined with the increase of soil water tension levels. Mean values of reduced iron content were 44.0, 40.0, 38.5 and 22.9 mg kg^{-1} at 0, 63, 159 and 500 hPa, respectively (Fig. 4). Low concentration of Fe^{+2} in the soils saturated with water corresponds to a relatively high Eh value under the same conditions.

Dehydrogenase activity in general decreased with the decrease of soil water content (Fig. 4). The highest activity was observed in the soils saturated with water and the lowest in the soils preincubated at water tension of 500 hPa. The range of the average (for the 15 soils and all the horizons) values of enzyme activity was from 0.0082 nmol formazan $g^{-1}min^{-1}$ (for 500 hPa) to 0.0163 nmol formazan $g^{-1}min^{-1}$ (for 0 hPa). The phenomenon of changes in dehydrogenase activity related to soil aeration status had been observed earlier [5,14,15,21,29].

An average catalase activity in all the studied horizons ranged from 44.8 to 59.1 μmol $KMnO_4$ g^{-1} and showed a tendency to decrease with increasing soil water tension. The most pronounced differentiation occurred between soil preincubated at 0 hPa (59.1 μmol $KMnO_4$ g^{-1}) and 63 hPa (47.9 μmol $KMnO_4$ g^{-1}). Relatively small changes of catalase activity were observed at soil water tensions >63 hPa (Fig. 4).

Soil aeration parameters changed with depth. We observed a significant decrease of values of k, D/D_o, ODR, dehydrogenase activity and catalase activity, as well as a significant increase in bulk density (d) and particle density (γ) for all the studied profiles. No depth-related trends were found for Fe^{+2} content, Eg, Eh and soil water content (Table 4), although this last one showed a tendency to decrease with depth.

Results of regression analysis of the investigated parameters for the Ap horizons of the 15 profiles are shown in Table 5 and for all the horizons of the 15 profiles in Table 6. The Ap horizons were treated separately. A linear (y=a+bx), exponential (y=exp(a+bx)) and multiplicative ($y=ax^b$) model was used and a model giving the best fit were chosen for the description of the analysed relationships. High correlation coefficients were found for the relationships between the investigated parameters for both Ap horizons and all the horizons treated jointly.

Dehydrogenase activity correlated only with redox potential ($r=-0.28^{***}$ for all the horizons and $r=-0.33^{*}$ for Ap horizons only) and with air-filled porosity in the Ap horizons ($r=-0.33^{*}$), (Tables 5 and 6).

Catalase activity was positively correlated with ODR, k and D/D_o (Tables 5 and 6). The correlation coefficients were higher for the Ap horizons (from 0.34^{*} to 0.42^{**}) as compared to all the horizons treated jointly (0.25^{***} to 0.38^{***}).

The content of Fe^{+2} was negatively correlated with ODR, k, D/D_o and Eg (in this last case only for all the horizons) and positively with water content (Tables 5 and 6). The highest correlation coefficients were observed with water content ($r=0.61^{***}$).

Redox potential was correlated with ODR ($0.39^{***}<r<0.43^{**}$), Eg ($0.30^{**}<r<0.52^{***}$) and water content ($-0.27^{*}<r<-0.24^{**}$) and when all the horizons were treated together the correlation with d ($r=-0.21^{*}$), g ($r=-0.18^{*}$) and D/Do ($r=0.16^{*}$) was observed (Tables 5 and 6).

Table 2. Statistical significance of differences in the tested parameters found between soil water tension levels of the selected soil profiles from Central Europe (on the basis of 95% LSD method)

Soil water tension (hPa)	Dehydro-genase activity	Catalase activity	Fe^{2+}	*Eh*	ODR	*k*	D/D_o	*Eg*	Water content by mass
0 - 63	0	-	0	+	0	+	+	+	-
0 - 159	0	-	0	+	+	+	+	+	-
0 - 500	-	-	-	+	+	+	+	+	-
63 - 159	0	0	0	0	+	0	0	0	0
63 - 500	0	0	0	0	+	0	+	+	-
159 - 500	0	0	0	0	0	0	+	+	-

(+) - significant increase, (-) - significant decrease, (0) - no significant difference.

Table 3. Statistical significance of differences in the tested parameters found between soil water tension levels of the selected soil Ap profiles from Central Europe (on the basis of 95% LSD method)

Soil water tension (hPa)	Catalase activity	*Eh*	ODR	*k*	D/D_o	*Eg*	Water content by mass
0 - 63	0	+	0	+	0	+	-
0 - 159	0	+	+	+	+	+	-
0 - 500	-	+	+	+	+	+	-
63 - 159	0	0	0	0	0	0	0
63 - 500	0	0	+	0	0	+	-
159 - 500	0	0	0	0	0	0	0

No significant changes were found for dehydrogenase activity and Fe^{+2} content. For other explanations see Table 2.

Table 4. Statistical significance of differences in the tested parameters found between soil depths of the selected soil profiles from Central Europe (on the basis of 95% LSD method)

Soil depth	Dehydro-genase activity	Catalase activity	ODR	*k*	D/D_o	Bulk density, *d*	Particle density, γ
A - B	-	-	0	0	0	+	+
A - C	-	0	0	-	0	+	+
A - D	-	-	0	-	-	+	+
B - C	0	0	0	0	0	0	0
B - D	0	0	0	0	0	0	+
C - D	0	-	-	0	0	0	+

No significant changes were found for Fe^{+2}, *Eh*, *Eg*, and water content by mass. For other explanations see Table 2.

Table 5. Correlations between particular aeration indicators calculated for all the soil water tension levels (Ap horizons) of the soil profiles from Central Europe. No significant correlations with bulk density (*d*) and particle density (γ) were found (they are omitted in the table)

Parameter	*Eh*	ODR	*k*	D/D_o	*Eg*	Water content by mass
Dehydrogenase activity	-0.33* $y=ax^b$	n.s.	n.s.	n.s.	-0.33* $y=ax^b$	n.s.
Catalase activity	n.s.	0.38** $y=ax^b$	0.34* $y=a+bx$	0.42** $y=a+bx$	n.s.	n.s.
Fe^{+2}	n.s.	-0.43*** $y=ax^b$	-0.55*** $y=e^{(a+bx)}$	-0.49*** $y=e^{(a+bx)}$	n.s.	0.61*** $y=e^{(a+bx)}$
Eh		0.43** $y=ax^b$	n.s.	n.s.	0.52*** $y=ax^b$	-0.27* $y=a+bx$
ODR			0.67*** $y=a+bx$	0.53*** $y=a+bx$	0.62*** $y=ax^b$	-0.78*** $y=e^{(a+bx)}$
k				0.86*** $y=a+bx$	0.52*** $y=a+bx$	-0.61*** $y=a+bx$
D/D_o					0.37** $y=a+bx$	-0.45*** $y=a+bx$
Eg						-0.41* $y=a+bx$

* - significant at P<0.05, ** - significant at P<0.01, *** - significant at P<0.001, n.s. - not significant.

Table 6. Correlations between particular aeration indicators calculated for all the soil water tension levels of the soil profiles (all the horizons jointly)

Parameter	*Eh*	ODR	*k*	D/D_o	*Eg*	*d*	γ	Water content by mass
Dehydrogenase activity	-0.28** $y=e^{(a+bx)}$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Catalase activity	n.s.	0.25** y=axb	0.38** $y=a+bx$	0.38*** $y=a+bx$	n.s.	n.s.	n.s.	n.s.
Fe^{+2}	n.s.	-0.49** $y=ax^b$	-0.39*** $y=e^{(a+bx)}$	-0.40*** $y=e^{(a+bx)}$	-0.55*** $y=e^{(a+bx)}$	n.s.	n.s.	0.60*** $y=a+bx$
Eh[(1)]		0.39** $y=ax^b$	n.s.	0.16* $y=e^{(a+bx)}$	0.30** $y=ax^b$	-0.21* $y=a+bx$	-0.18* $y=e^{(a+bx)}$	-0.24** $y=e^{(a+bx)}$
ODR			0.65*** $y=a+bx$	0.59*** $y=a+bx$	0.51*** y=axb	n.s.	-0.24** $y=a+bx$	-0.71*** $y=ax^b$
k				0.85*** $y=a+bx$	0.51*** $y=a+bx$	-0.18* $y=a+bx$	-0.26*** $y=a+bx$	-0.45*** $y=a+bx$
D/D_o					0.53*** $y=a+bx$	-0.24** $y=a+bx$	-0.27*** $y=a+bx$	-0.44*** $y=a+bx$
Eg						-0.51 $y=a+bx$	-0.31*** $y=a+bx$	-0.42* $y=a+bx$

[(1)]Correlations between *Eh* and particular parameters were calculated for the soils incubated at the water content in the range of 0-159 hPa. For other explanations see Table 5.

ODR was positively correlated with air permeability (0.65^{***}<r<0.67^{***}) and D/D_o (0.53^{***}<r<0.59^{***}), *Eg* (0.51^{***}<r<0.62^{***}) and negatively with water content (-0.78^{***}<r<-0.71^{***}). Moreover, a negative correlation was observed with particle density when all the horizons were considered jointly (r=-0.24^{**}), (Tables 5 and 6).

Air permeability (*k*) was correlated positively with D/D_o (0.85^{***}<r<0.86^{***}), *Eg* (0.51^{***}<r<0.62^{***}) and negatively with water content (-0.61^{***}<r<-0.45^{***}). It showed also a negative correlation with bulk density (r= -0.18^{*}) and particle density (r=-0.26^{***}) for all the horizons considered jointly (Tables 5 and 6).

A relative gas diffusion coefficient (D/D_o) was correlated positively with *Eg* (0.37^{**}<r<0.53^{***}), negatively with water content (-0.45^{***}<r<-0.44^{***}). The negative correlation was observed with *d* and γ when all the horizons were analysed jointly (r=-0.24^{**} and r= -0.27^{***}, respectively), (Tables 5 and 6).

Air-filled porosity (*Eg*) showed an obvious, on the other hand, negative correlation with water content by weight (-0.42^{***}<r<0.41^{*}) and - when all the horizons were considered jointly - also a negative correlation with *d* (r=-0.51^{***}) and γ (r=-0.31^{***}), (Tables 5 and 6).

CONCLUSIONS

Application of the measurement methods used in this study for the characterisation of soil samples preincubated under variable water conditions (range 0-500 hPa) allowed us to characterise satisfactorily aeration properties of the 15 investigated soils from Central Europe and to draw the following conclusions (based on average values):

1. Air-filled porosity (*Eg*) increased from about 0.06 m^3m^{-3} at 0 hPa (volume of the entrapped air) to about 0.15 m^3m^{-3} at 500 hPa and was negatively correlated with soil water content, bulk density and the density of solid particles.

2. Air permeability (*k*) varied from 0 (at 0 hPa) to 15 μm^2 (at 500 hPa) and was positively correlated with D/D_o and *Eg* and negatively with soil water content, bulk density and the density of solid particles.

3. Relative gas diffusion coefficient (D/D_o) varied from 0 (at 0 hPa) to 0.02 (at 500 hPa) and was correlated positively with *Eg* and negatively with soil water content, bulk density and the density of solid particles.

4. Oxygen diffusion rate (ODR) ranged from about 20 $\mu g\ m^{-2}s^{-1}$ (at 0 hPa) to about 100 $\mu g\ m^{-2}s^{-1}$ and was positively correlated with *k*, D/D_o, and *Eg* and negatively with soil water content and particle density.

5. Redox potential (*Eh*) ranged from 377 mV (at 0 hPa) to about 460 mV (at 159 hPa) and was positively correlated with ODR, *Eg* and D/D_o, and negatively with dehydrogenase activity, bulk density, particle density, and soil water content.

6. Content of Fe^{+2} varied from 44 mg kg^{-1} (at 0 hPa) to about 24 mg kg^{-1} (at 500 hPa) and was correlated positively with soil water content and negatively with *Eg*, D/D_o, *k* and ODR.

7. Dehydrogenase activity was within the interval of 0.016 nmol formazan $g^{-1}min^{-1}$ (at 0 hPa) to 0.008 nmol formazan $g^{-1}min^{-1}$ (at 500 hPa) and was correlated only negatively with *Eh* and *Eg* in the Ap horizons.

8. Catalase activity ranged from about 60 μmol $KMnO_4$ g^{-1} (at 0 hPa) to 45 μmol $KMnO_4$ g^{-1} (at 500 hPa) and was correlated positively with D/D_o, *k*, and ODR.

9. A common feature for all the investigated soils was a highly significant correlation among indicators of soil aeration (*Eh*, ODR, *Eg*, D/D_o, *k*) and other physical soil properties (bulk density, particle density, water content).

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