Int. Agrophysics, 2000, 14, 327-339

AERATION STATUS OF SOME SLOVAKIAN SOILS

Z. Stępniewska[1,2], M. Brzezińska[1], J. Gliński[1], W. Stępniewski[1,3], T. Włodarczyk[1], J. Čurlik[4], B. Houšková[4]

[1]Institute of Agrophysics, Polish Academy of Sciences, Doświadczalna 4, P.O. Box 201, 20-290 Lublin 27, Poland
[2]Catholic University of Lublin, Kraœnicka 102, 20-551 Lublin, Poland
[3]Department of Environmental Protection Engineering, Technical University of Lublin, Nadbystrzycka 40, 20-618 Lublin, Poland
[4]Soil Science and Conservation Research Institute, Roznavská, 827 13 Bratislava, Slovak Republic

Accepted April 13, 2000

A b s t r a c t. Aeration related properties of individual soil layers of three Slovakian soil profiles (Calcaro-haplic Phaeozem, Fluvi-calcaric Phaeozem and Calcaro-gleyic Phaeozem) were characterised with the use of undisturbed soil samples preincubated on water tension plates at 0, 63, 159 and 500 hPa at room temperature. The experiment included measurements of air-filled porosity (*Eg*), relative gas diffusion coefficient (*D*/*Do*), air permeability (*k*), oxygen diffusion rate (ODR), redox potential (*Eh*), content of Fe^{+2} as well as soil dehydrogenase and catalase activities.

The soils under investigation showed high resistance to reduction processes. Despite O_2 depletion following 2-days water saturation (expressed by the low values of ODR, *k*, *D*/*Do* and *Eg*), the redox potential was still maintained on a high level and concentration of the reduced iron was relatively low. A close relationship between aeration parameters was found.

K e y w o r d s: agrophysics, soil aeration status, *D*/*Do*, air permeability, *Eh*, ODR, dehydrogenase activity, catalase activity, water tension, Slovakian soils

INTRODUCTION

Soils are inhabited by a vast array of microbes, which are responsible for the breakdown of organic matter and mobilisation of nutrients. Thus, they play an important role in the cycling of nutrients in nature [14]. Air-water conditions strongly influence soil ecosystem, changing its physical and physicochemical status and, as a consequence, regulating the size of microbial populations and their activities [13]. Soil enzyme activity is often used as an index of microbial activity in the soils as well as their fertility. Dehydrogenases are key enzymes in the oxidation of soil organic matter. Catalases play a function of protection of microbial cells against toxic H_2O_2 [5].

The aim of the work was to characterise aeration properties of three Slovakian soil profiles and to find interrelationships among them. The study was performed in the frame of the multilateral Austrian-Czech-Hungarian-Polish -Slovak project on the "Assessment of Structure in Agricultural Soils" sponsored by the Austrian Ministry of Science and Research [3].

MATERIAL AND METHODS

Soils

The experiments were carried out with three soils from   itny ostrov region (Slovakia). Basic soil properties are presented in Table 1; full description of soil profiles were published by Čurlik and Houšková [7] and Gliński [8]. The studied soils (with calcareous alluvial sediment - medium textured - as the parent material) are:

1. Calcaro-haplic Phaeozem (Macov 1),
2. Fluvi-calcaric Phaeozem (Macov 2),
3. Calcaro-gleyic Phaeozem (Zemianska Olča = Z. Olča).

T a b l e 1. Soil parameters

Profile	Soil unit	Horizon (cm)	Particle size distribution			Bulk density, d (Mg m^{-3})	Particle density, γ (Mg m^{-3})	Total porosity (%)	$CaCO_3$ (%)	O.M. (%)	pH	
			Sand (2000-50 μm)	Silt (50-2 μm)	Clay (<2 μm)						H_2O	KCl
Macov 1	Calcaro-haplic Phaeozem	Akp (0-38)	38.0	40.7	21.3	1.46	2.69	45.7	15	2.0	8.3	7.8
		Ak (38-48)	37.3	40.6	22.1	1.30	2.72	52.2	40	2.0	8.4	8.1
		A/Ck (48-65)	37.9	44.7	17.4	1.30	2.62	50.3	n.d.	n.d.	n.d.	n.d.
		Ck (65-85)	33.4	55.2	11.4	1.31	2.74	52.1	n.d.	n.d.	n.d.	n.d.
		Cgk (85+)	63.8	32.6	3.6	1.44	2.75	47.6	n.d.	n.d.	n.d.	n.d.
Macov 2	Fluvi-calcaric Phaeozem	Akp (0-38)	42.6	39.0	18.4	1.36	2.62	48.1	12	2.9	8.0	7.6
		Ak (38-68)	37.3	40.7	22.0	1.28	2.67	52.0	35	2.2	8.2	7.8
		A/Cgk (68-88)	16.2	60.2	23.6	1.38	2.70	48.8	n.d.	n.d.	n.d.	n.d.
Zemianska Olča	Calcaro-gleyic Phaeozem	Agkp (0-33)	12.8	52.5	34.7	1.28	2.62	51.1	10	4.6	8.4	7.5
		A/Cgk (33-47)	5.4	69.9	24.7	1.32	2.75	52.0	33	0.7	8.6	7.8
		Cgk (57-100)	3.7	78.1	18.2	1.37	2.76	50.4	n.d.	n.d.	n.d.	n.d.
		Abgrk (100-120)	6.6	75.2	18.2	1.51	2.73	44.7	n.d.	n.d.	n.d.	n.d.

n.d. - not determined

Soils were cultivated by a cooperative farm (Macov 1 and Z. Olča) or as a research station of Soil Science and Conservation Research Institute in Bratislava (Macov 2). All the soil profiles were calcareous. The last vegetation before sampling was wheat (Macov 1) and maize (Z. Olča). Macov 2 site was without vegetation (soil after tillage).

Measurement methods

The study included aeration related soil properties such as: air-filled porosity (*Eg*), oxygen diffusion coefficient (*D*/*Do*), air permeability (*k*), redox potential (*Eh*), concentration of reduced iron (Fe^{2+}) as well as dehydrogenase and catalase activities under controlled air-water conditions.

The undisturbed soil samples in 100 cm^3 brass cylinders were collected in October 1991. Aeration parameters were measured at soil water tension (Ψ) corresponding to 0 hPa (capillary saturation), 63 hPa (pF 1.8), 159 hPa (pF 2.2) and 500 hPa (pF 2.7). Four of the 5 undisturbed soil cores representing each horizon after two-days capillary saturation were equilibrated with individual soil water tension levels on the kaolinite tension plates at room temperature. *D*/*Do* and *k* values were measured at each equilibrium. The fifth cylinder was used before each subsequent equilibrium to determine ODR, *Eh*, Fe^{2+} content and the activity of dehydrogenases and catalases. The *D*/*Do* measurement method was performed according to the unsteady - state method, using oxygen as a diffusing agent [21-23]. The measurement of air permeability was performed at 10 hPa air pressure with a laboratory permeameter of the LPIR-1 type manufactured by the Experimental Department of Metallurgy in Cracow [13]. ODR was measured by an amperometric method with four 0.5x4 mm Pt wire electrodes placed at the depth of 2 cm and polarized to -0.65 V versus saturated calomel electrode for 4 min [16]. *Eh* measurements were performed using four Pt electrodes of the same type, saturated calomel electrode and a pH-meter as described previously [13]. The content of Fe^{+2} was determined in the extract of 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 α, α'- dipyridyl in acetate buffer solution of pH 4.5 [1].

Dehydrogenase activity was measured by the method of TTC (2,3,5-triphenyltetrazolium chloride) reduction to formazan during incubation for 20 h at 30 ^oC, at pH=8.2, according to procedure of Casida *et al*. [6]. Catalase activity was determined by manganometric titration of surplus H_2O_2 under acidic conditions according to Johnson and Temple [15].

Water content (w/w) and all the analytical results (triplicate samples) were calculated on the basis of the oven-dry (105 ^oC) soil mass.

Statistical analysis

The analyses of variance and regression were used in the statistical data processing. Linear (y=a+bx), exponential ($y=e^{a+bx}$), logarithmic (y=a ln(x) +b) or multiplicative ($y=ax^b$) models were used for the description of individual relationships. The best fit model was selected on the basis of the correlation coefficient.

RESULTS AND DISCUSSION

The results showing relationship between soil water tension and the measured parameters are presented in Figs 1-8.

Air-filled porosity values increased with soil water tension in all the soil horizons (Fig. 1). The maximum *Eg* values (about 0.30 m^3 m^{-3}) occurred in the Ak and Ck horizons of the Macov 1 profile (at 159 hPa water tension) and in the Ak horizon of the Macov 2 profile (at 500 hPa water tension). The lowest value (about 0.02 m^3 m^{-3}) was exhibited in the Akp horizon of the Macov 2 and Agkp of Z. Olča at water saturation (0 hPa). Generally, the surface horizons showed lower air-filled porosity than the deeper ones.

Gas diffusion coefficient versus soil water tension is shown in Fig. 2. The highest *D*/*Do*, equal to 0.09 was found for Z. Olča (Agkp horizon at 500 hPa water tension) and about 0.06 for Macov 1 (Akp horizon) and Macov 2

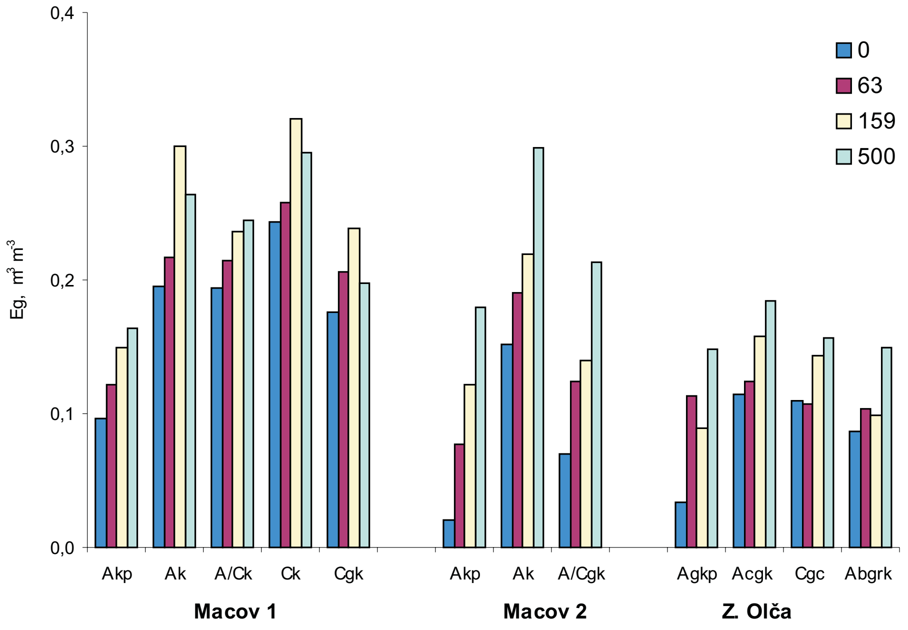

Fig. 1. Air-filled porosity of the examined soil horizons of the profiles at different soil water tension levels (Ψ).

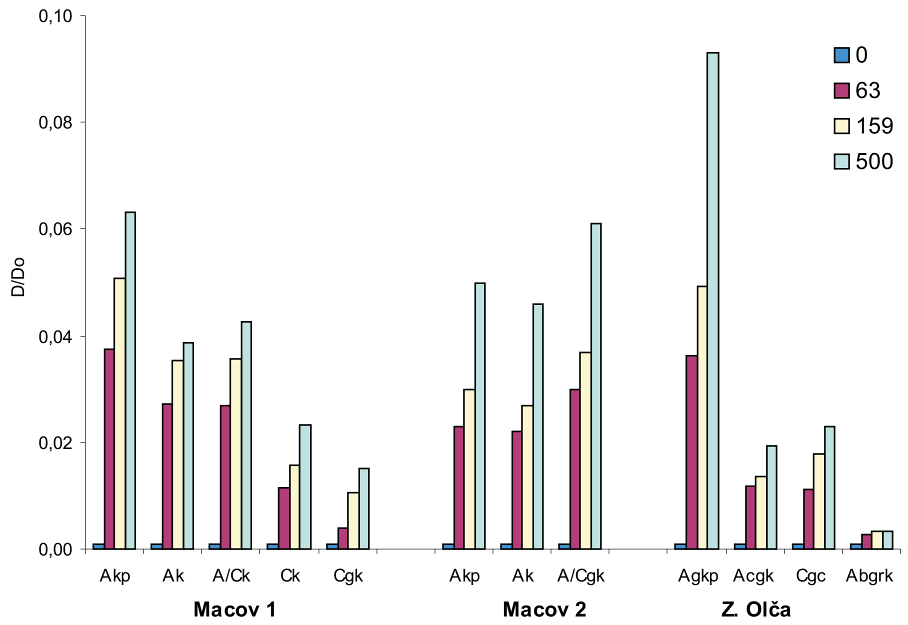

Fig. 2. Gas diffusion coefficient of the examined soil horizons at different soil water tension levels (Ψ).

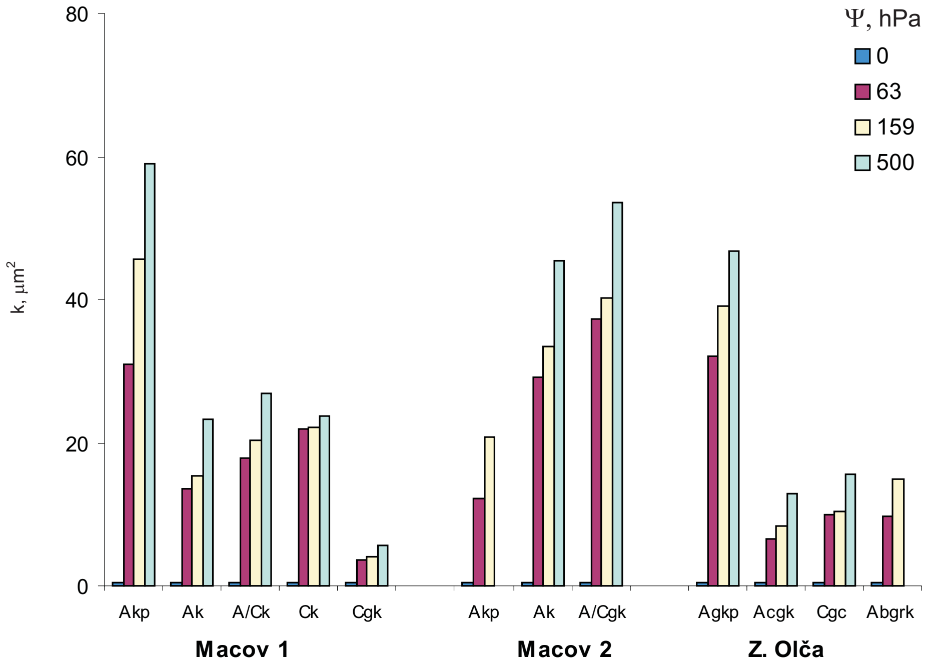

Fig. 3. Air permeability of the examined soil horizons at different soil water tension levels (Ψ).

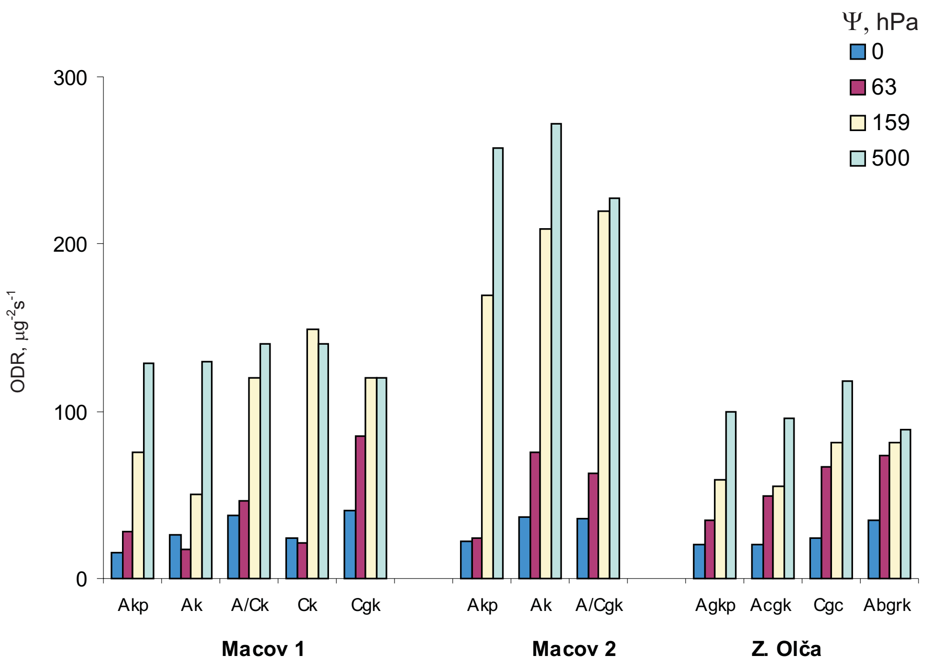

Fig. 4. Oxygen diffusion rate of the examined soil horizons at different soil water tension levels (Ψ).

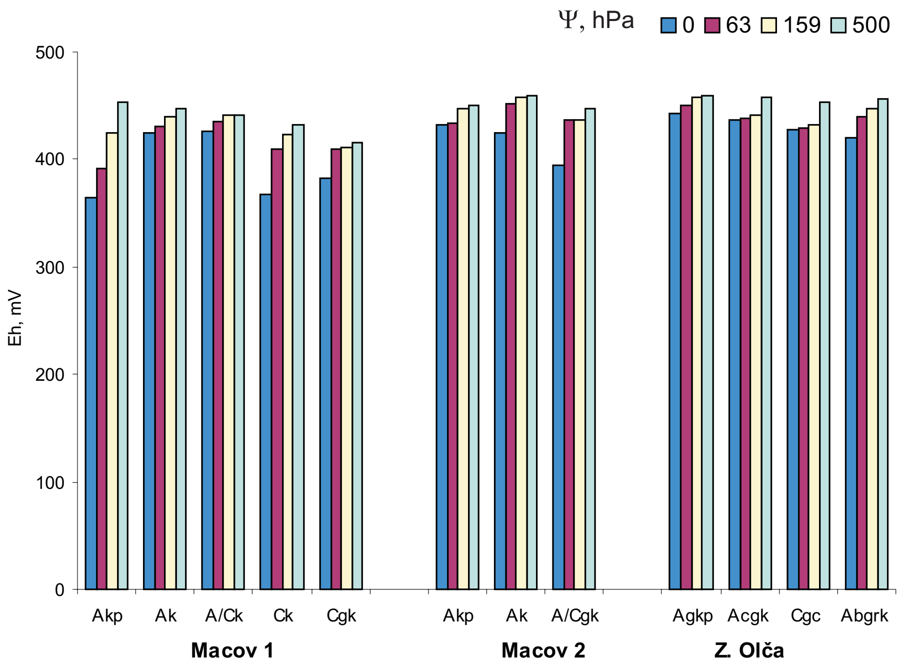

Fig. 5. Redox potential of the examined soil horizons at different soil water tension levels (Ψ).

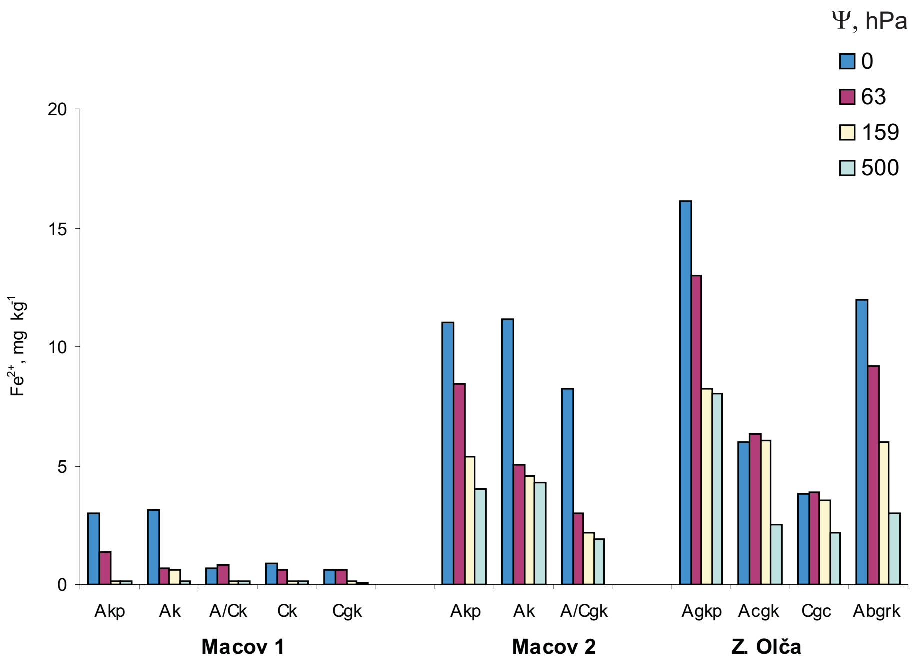

Fig. 6. Fe^{+2} content of the examined soil horizons at different soil water tension levels (Ψ).

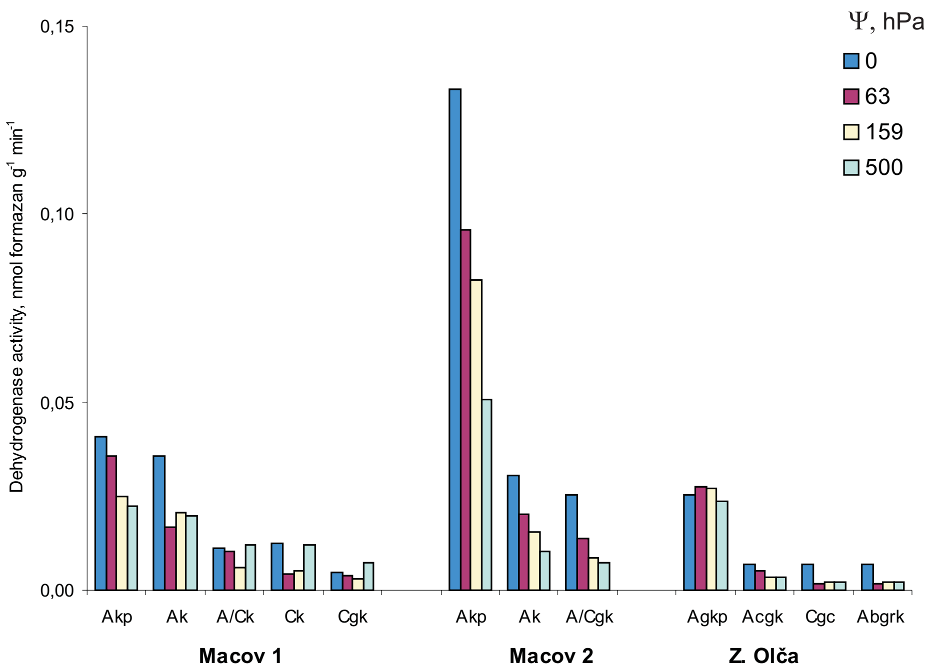

Fig. 7. Dehydrogenase activity of the examined soil horizons of the profiles at different soil water tension levels (Ψ).

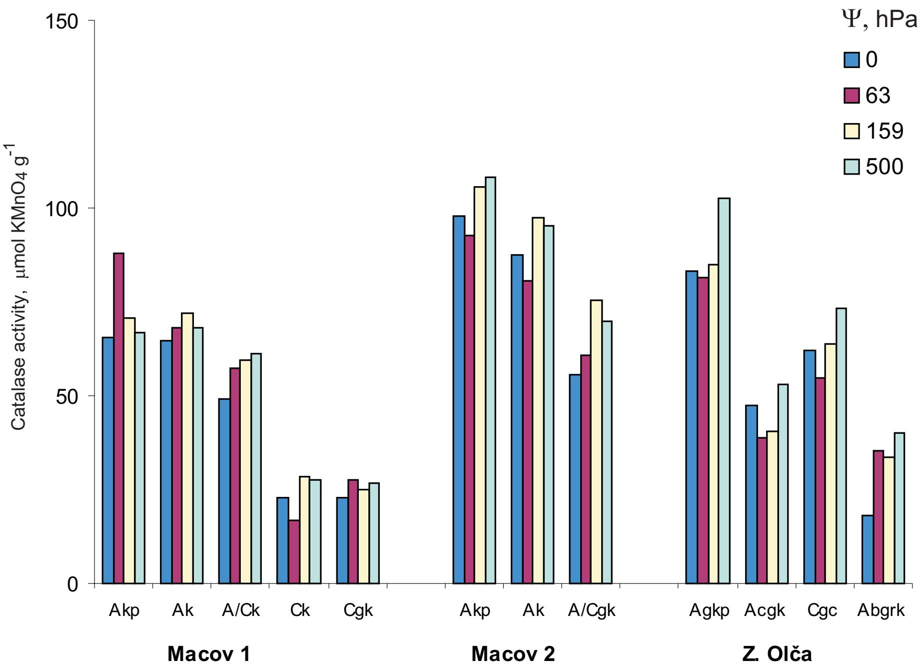

Fig. 8. Catalase activity of the examined soil horizons of the profiles at different soil water tension levels (Ψ).

(A/Cgk horizon at 500 hPa water tension). Differentiation of the diffusion properties within particular horizons was the highest in the Z. Olča profile and the smallest - in the Macov 2 profile. It should be emphasised that in the Macov 1 and Z. Olča profiles the highest diffusion coefficient values characterise surface horizons and they decrease with depth. Different situation was observed in the Macov 2, where the highest diffusion coefficient values were observed in the deepest soil horizon. There is not a definite *D*/*Do* value, which is considered critical for aeration of the soil as it depends on the soil respiration rate. Data from literature quote *D*/*Do* = 0.005 as a lower critical value corresponding to low respiration activities, and *D*/*Do* = 0.02 as an upper one for the highest respiration rates [13]. Applying those criteria here we can conclude that the two deepest horizons of the Macov 1 (Ck and Cgk) and the three deepest horizons of the Z. Olča profile (Acgk, Cgc, Abgrk) were characterised by the *D*/*Do*<0.02 in the entire water tension range, while in the Macov 2 such values occurred only at the soil water tension below 50 hPa. In turn, lower critical value *D*/*Do* = 0.005, which seems more realistic for these profiles, occurred only at water saturation. The deepest (Abgrk) horizon of the Z. Olča was characterised by *D*/*Do*<0.005 in the entire water tension range.

Air permeability versus soil water tension, presented in Fig. 3, shows the highest *k* values in the range of 30-60 μm^2 only for the upper horizons of the Macov 1 and the Z. Olča profiles and in two deeper horizons of the Macov 2 profile. It should be also noted that in two horizons (Akp from Macov 2 and Abgrk from Z. Olča profiles) it was not possible to measure the *k* value due to shrinking of the soil cores at the highest soil moisture tension, which caused falling of the cores out of the cylinders.

In the three profiles values of oxygen diffusion rate versus soil water tension (Fig. 4) show a sharp decrease of ODR at soil water tension below 63 and increase above 159 hPa, reaching maximum value (280 $\mu g\ m^{-2}s^{-1}$) for the Macov 2 profile at 500 hPa water tension. The critical ODR value which is usually considered to be about 30 $\mu g\ m^{-2}s^{-1}$ [13,20,22] occurred in the upper horizons of all the profiles at the soil water tension below 63 hPa.

In all the horizons of three profiles the values of redox potential for soil water tension >50 hPa were above 400 mV (Fig. 5). Only for Akp, Ck and Cgk horizons, i.e., Macov 1 and A/Cgk horizon of the Macov 2 profile a decrease of *Eh* below 390 mV at capillary saturation after two days was observed. This suggests a quite high redox buffering capacity of the soils. It should be noted that the *Eh* values at full saturation are related to a 2-day period of keeping the cores at capillary saturation, and that would decrease with the extension of that period. A similar situation was observed for some Hungarian alluvial soils in which 7-day saturation of the soil with water was not sufficient to cause a decrease of redox potential below 400 mV [24]. The intensity of reduction processes of the soil under condition of oxygen depletion is connected with the t_{300} index, defined by Gliński and Stępniewska [10] as the time needed to lower soil redox potential under flood conditions at fixed temperature to a level of 300 mV. For Polish mineral soils t_{300} ranged from 0.1 to 18 days [19].

Reduced iron content (Fig. 6) increased under conditions of excess of water. The highest Fe^{2+} concentration showed Z. Olča profile in the upper (Agkp) and deepest (Abgrk) horizons (about 16 mg kg^{-1} and 12 mg kg^{-1}, respectively). All the three horizons of the Macov 2 profile showed lower Fe^{+2} concentration at the same level of water saturation (8-11 mg kg^{-1}). Macov 1 profile showed lowest concentration of Fe^{2+}, also at full soil saturation with water.

Dehydrogenase activity (Fig. 7) decreased in all the profiles with an increase of soil water tension. This increase was drastically high for the Macov 2 profile, which surface horizon (Akp) showed higher activity (0.133 nmol formazan $g^{-1}\ min^{-1}$). It is a general tendency in decreasing dehydrogenase activity with the depth of all soil profiles.

Catalase activity (Fig. 8) was not so differentiated in the investigated soils as dehydrogenase activity. It tended to show a slight increase with the soil moisture tension for all the three soil profiles. The maximum activity was about 100 µmol $KMnO_4$ g^{-1} in the surface horizons of the Z. Olča (Agkp) and the Macov 2 (Akp) profiles, and about 90 µmol $KMnO_4$ g^{-1} for the Macov 1 (Ak) profile. Catalase activity decreased with soil depth similarly to dehydrogenase activity.

The influence of soil water tension on the air-water status is summarised in the form of the analysis of variance in Fig. 9 where the average values of the tested parameters of all the horizons of the three soil profiles are presented against soil water tension. A decrease of water in the soil improved soil aeration status by increasing the air-filled porosity available for the diffusion of gases, thus contributing to an increase of aeration parameters as compared to the initial saturated conditions. Consequently, the values of *Eg*, *k*, *D*/*Do*, ODR and *Eh* significantly increased with an increase in water tension from 0 to 500 hPa. Enzyme activity showed a insignificant tendency to decrease (dehydrogenases) or to increase (catalases) with an increasing soil water tension (Fig. 9).

Application of the methods used in this study allowed to characterise satisfactorily aeration related properties of the tested Slovakian soils. Aeration parameters followed typical changes in the soil water content at particular tension levels and, as a consequence, individual indices correlated with others. Table 2 shows correlation coefficients calculated for adequate relationships (all the data included). Some of the relations were not significant statistically, especially when they were calculated against water content or a simple aeration parameter like air-filled porosity.

Oxygen diffusion rate, characterising microdiffusive oxygen [20], was positively correlated with air permeability (Fig. 10), *D*/*Do* and *Eg*, but negatively with water content (Table 2), as excess of water evidently makes the flow of O_2 in the soil system difficult.

In turn, redox potential reflects the consequences of water excess, as the measure of electron activity in the soil solution. It is a very useful parameter of soil aeration after oxygen depletion, when the values of other indices drop down to zero but *Eh* can also take on negative values. A high level of redox potential of the studied soils, as well as a narrow range of the *Eh* values (about 100 mV only) for the entire range of water tension levels (0-500 hPa) indicates that a two-day period of keeping the cores at the capillary saturation was insufficient to reduce these levels in the soils. The ODR values dropped down to 15 µg $m^{-2}s^{-1}$ (Fig. 10), suggesting depletion of oxygen in the soil conditioned at 0-63 hPa water tension, but the corresponding values of *Eh* were relatively high (above 360 mV). Other Phaeozems studied by the authors [4] showed redox potential as low as - 50 mV after 14-day conditioning at water saturation at 20 ^{o}C and even - 150 mV when preincubated at 30 ^{o}C.

The range of redox potential values, observed for the Slovakian soils (360-460 mV) is considered to reflect the well aerated soil state, assuming the *Eh* equal to 300 mV (indicating Fe^{+3} reduction) is a border between oxygenated and reduced soil [13,19]. In fact, the studied soils showed a relatively low level of reduced iron content (Fig. 10). Fe^{2+} concentration of increased (up to 18 mg kg^{-1}at the maximum) with increasing water content (in the range of 15-38 % H_2O, by mass). A possible explanation of this phenomenon would be the presence of oxygenated nitrogen and manganese forms in the soils, as nitrates and Mn (IV) are the first steps of soil reduction [2,9,13,18] (neither of these forms was not established in this study).

The values of *Eh* showed a significant positive relations also with *k* and *D*/*Do* while Fe^{+2} correlated only with water content and *Eg* (Table 2).

Gas diffusion expressed by *D*/*Do* coefficient characterises soil ability to exchange gases on a macroscale [21,22]. It can be observed (Fig. 10) that the higher the *D*/*Do* value, the higher catalase activity. Catalases are enzymes related to aerobic respiration and are not produced by anaerobic microorganisms. This fact is one of the reasons why anaerobes are not capable to exist in the presence of oxygen. A positive

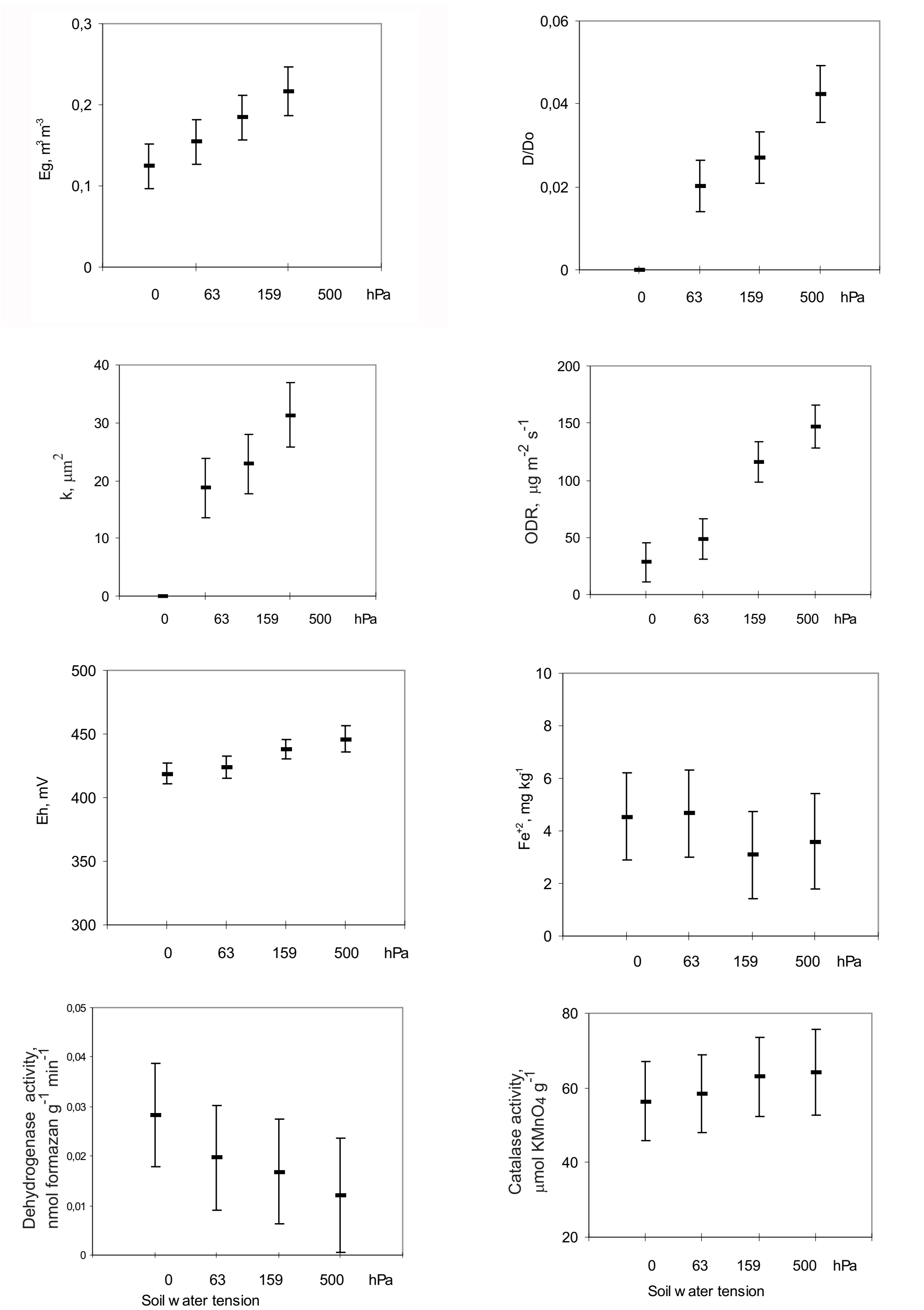

Fig. 9. Aeration parameters against soil water tension (average values of all horizons of three profiles taken together). The bars represent 95% LSD confidence intervals.

T a b l e 2. Correlations between the indicators of aeration status under study

	Catalases	Fe^{2+}	*Eh*	ODR	*k*	*D/Do*	*Eg*	Water content	d	γ
Eg								-0.83*** L	-0.35* L	n.s.
D/Do							n.s.	n.s.	n.s.	-0.39** L
k						0.90*** L	n.s.	n.s.	n.s.	-0.31*
ODR					0.61*** L	0.53*** E	0.46** L	-0.49*** E	n.s.	n.s.
Eh				0.36** Ln	0.32** L	0.38** L	n.s.	n.s.	-0.31* L	n.s.
Fe^{2+}			n.s.	n.s.	n.s.	n.s.	-0.48*** L	0.49*** L	n.s.	-0.36* L
Catalases		0.37** L	0.49** E	n.s.	0.42** L	0.49*** L	n.s.	0.44** L	-0.36* L	-0.66*** L
Dehydro-genases	0.66*** E	0.37** L	n.s.	-0.29* M	n.s.	n.s.	-0.57*** Ln	0.41** L	n.s.	-0.68*** E

n.s. - not significant, *, ** and *** - significant at P=0.05, 0.01 and 0.001, respectively. L, E, Ln and M - model linear (y=a+bx), exponential (y=exp(a+bx), logarhytmic (y=a ln(x)+b) and multiplicative ($y=ax^b$), respectively.

relation between catalase activity and aeration status, expressed by ODR and *Eh*, were found by Gliński *et al.* [11,12]. It is evident that the relations between catalase activity and Fe^{+2} concentration (as well as between catalase activity and water content) for the highly reduced soils would be negative. However, these relations were positive since the tested Slovakian soils were not completely reduced and their conditions were still appropriate for facultative anaerobes to exist even at short saturation.

Dehydrogenases are enzymes active in aerobic and anaerobic microorganisms [5]. However, energetic efficiency of anaerobic respiration is much lower than that of aerobic respiration. This is probably the main reason for a close relations between dehydrogenase activity and soil aeration status found by Gliński *et al.* [11,12], Okazaki *et al.* [17], Brzezińska *et al.* [4]. Table 2 shows that dehydrogenase activity of the Slovakian Phazeozems was significantly and positively correlated with such aeration parameters as Fe^{+2} concentration and water content, but negatively with ODR and *Eg* (Fig. 10). Correlation between this activity and redox potential was not significant probably because of the specific redox status of the studied soils.

Similar high redox potential was observed for the six Hungarian soils [24]. Eh values did not drop there below 300 mV even in the soils saturated with water for 2-7 days. However, the range of *Eh* in these Hungarian soils was broader (from 300 to 560 mV) and the corresponding reduction of iron was more advanced than in the case of the Slovakian soils (Fe^{+2} content reached values up to 200 mg kg^{-1}).

Air permeability correlated only with *D/Do*, and air-filled porosity - with water content (Table 2, Fig. 10). Some of aeration indices, used in this experiment, showed a significant relationship with physical parameters such as bulk and particle densities (Table 2).

Summarizing, it should be stated that the investigated soils showed high resistance to reduction processes. This property is beneficial for agricultural soils. Despite O_2 depletion (at 63 hPa or a 2-day water saturation), expressed by low values of ODR, *k*, *D/Do* and *Eg*, the redox potential was maintained still on a high level and the concentration of reduced iron was relatively low. The experiment showed that complex analysis of the soil could satisfactorily characterise its aeration status, even if the soil reduction was incomplete.

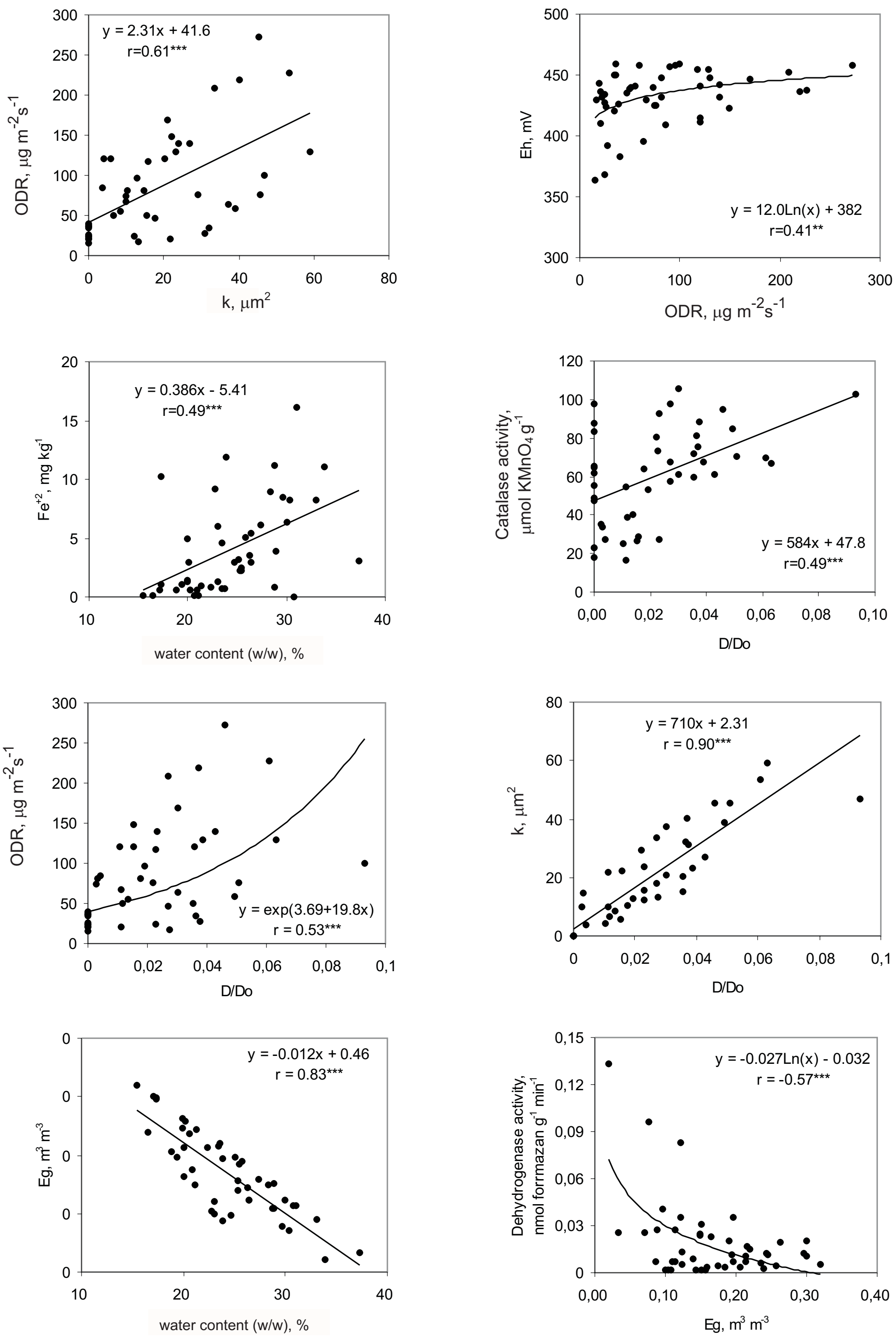

Fig. 10. Some examples of the relation between aeration parameters of the examined soil profiles (all the horizons of the three profiles were treated jointly): ODR against *k*; *Eh* versus ODR; Fe^{+2} content against water content; catalase activity against *D*/*Do*, ODR and *k* versus *D*/*Do*; *Eg* versus water content; dehydrogenase activity against *Eg*.

CONCLUSIONS

Aeration related properties of the representative Slovakian soils (Calcaro-haplic Phaeozem, Fluvi-calcaric Phaeozem and Calcaro-gleyic Phaeozem) allow us to draw the following conclusions:

1. Values of aeration parameters such as *Eg*, *k*, *D*/*Do*, ODR and *Eh* significantly increased with an increase of water tension from 0 to 500 hPa.

2. Close interrelationships between aeration parameters were found.

3. The studied soils showed high resistance to reduction processes.

REFERENCES

1. **Aleksandrova L.J., Najdenova O.A.:** Laboratory analyses of soils (in Russian). Kolos, Leningrad, 1967.
2. **Bailey L.D., Beauchamp E.G.:** Nitrate reduction and redox potentials measured with permanently and temporarily placed platinum electrodes in saturated soils. Can. J. Soil Sci., 51, 51-58, 1971.
3. **Blum W.E.H., Rampazzo N.:** Assessment of structure in agricultural soils. Results of a multilateral cooperation project between Austria, Czech-Republic, Hungary, Poland and Slovak-Republic. Int. Agrophysics, 7, 93-97, 1993.
4. **Brzezińska M., Stępniewska Z., Stępniewski W.:** Soil oxygen status and dehydrogenase activity. Soil Biol. Biochem., 30, 1783-1790, 1998.
5. **Burns R.G.:** Soil Enzymes. Academic Press, London, 1978.
6. **Casida L.E., Klein D.A., Santoro T.:** Soil dehydrogenase activity. Soil Science, 98, 371-376, 1964.
7. **Čurlik J., Houšková B.:** Physical parameters and micromorphological description of sandy Slovak soil. Int. Agrophysics, 11, 129-146, 1997.
8. **Gliński J.:** General characteristics of soils included to the multilateral program. Int. Agrophysics, 7, 99-116, 1993.
9. **Gliński J., Stahr K., Stępniewska Z., Brzezińska M.:** Changes of redox and pH conditions in a flooded soil amended with glucose and manganese oxide under laboratory conditions. Z. Pflanzenernähr. Bodenk., 159, 297-304, 1996.
10. **Gliński J., Stępniewska Z.:** An evaluation of soil resistance to reduction processes. Pol. J. Soil Sci., 19, 15-19, 1986.
11. **Gliński J., Stępniewska Z., Brzezińska M.:** Characterization of the dehydrogenase and catalase activity of the soils of the two natural sites with respect to the soil oxygenation status. Pol. J. Soil Sci., 19, 47-52, 1986.
12. **Gliński J., Stępniewska Z., Kasiak A.:** Soil enzyme activity under different conditions of oxygen and water content. Roczn. Glebozn., 34, 53-59, 1983.
13. **Gliński J., Stępniewski W.:** Soil Aeration and its Role for Plants. CRC Press, Boca Raton, Florida, 1985.
14. **Jha D.K., Sharma G.D., Mishra R.R.:** Soil microbial population numbers and enzyme activities in relation to altitude and forest degradation. Soil Biol. Biochem., 24, 761-767, 1992.
15. **Johnson J.L., Temple K.L.:** Some variables affecting measurements of catalase activity in soil. Soil Science Society Proc., 28, 207-209, 1964.
16. **Malicki M., Walczak R.**: A gauge for the redox potential and the oxygen diffusion rate in the soils with an automatic regulation of cathode potential. Zesz. Probl. Post. Nauk Roln., 220, II, 447-452, 1983.
17. **Okazaki M., Hirata E., Tensho K.:** TTC reduction in submerged soils. Soil Sci. Plant Nutr., 29, 489-497, 1983.
18. **Patrick W.H, Jr.:** The role of inorganic redox systems in controlling reduction in paddy soils. Proc. Symp. Paddy Soils. Nanjing, China 1980, Institute Soil Sci., Acad. Sinica ed., 107-117, 1981.
19. **Stępniewska Z.:** Redox properties of Polish mineral soils (in Polish). Problemy Agrofizyki, 56, 1988.
20. **Stępniewski W.:** Oxygen diffusion and strength as related to soil compaction. I. ODR. Polish J. Soil Sci., XII, 3-13, 1980.
21. **Stępniewski W.:** Gas diffusion and strength as related to soil compaction. II. Oxygen diffusion coefficient. Polish J. Soil Sci., XIV, 3-13, 1981.
22. **Stępniewski W.:** Oxygen diffusion and strength as related to soil compaction. IV. Choice of optimum parameters. Pol. J. Soil Sci., XIV, 2, 89-95, 1981.
23. **Stępniewski W.:** Gas diffusion in a silty brown soil. Zesz. Probl. Post. Nauk Roln., 220, 559-567, 1983.
24. **Stępniewski W., Stępniewska Z., Gliński J., Brzezińska M., Włodarczyk T., Przywara G., Varallyay G., Rajkai K.:** Dehydrogenase activity of some Hungarian soils as related to their water and aeration status. Int. Agrophysics, 14, 341-354, 2000.