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Effect of oxygen deficiency on the macroelement content of the soil (pot experiment with barley cv. Aramir vegetation)

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A b s t r a c t. A greenhouse experiment to test the relationship between the oxygen status of soil and the macroelement content was conducted. N-NH_4^+, N-NO_3^-, P and K content in the soil under oxygen stress conditions depend on the stage of barley development. It seems that the more preferable mineral form of nitrogen during the shooting stage was nitrate. Oxygen stress (flooded conditions) distinctly decreased the uptake of all the elements, but two higher densities of soil combined only with a flooded condition, significantly lowered the rate of the decrease of concentrations as well as of N-NH_4^+ and P and in the case of the highest density also that of K.

A decrease of all nutrient concentration was lower under conditions of high water content accompanied by low-redox potential and oxygen availability. The most sensitive element with respect to water content was phosphorus (r=-0.380***), the least sensitive was N-NO_3^- (r=-0.14**). The influence of redox potential and oxygen diffusion rate on absorption of NH_4^+, NO_3^-, P and K showed a positive correlation in all the cases investigated. The highest correlation was observed in the P uptake. The critical ODR value (about 35 μg $m^{-2}s^{-1}$) was confirmed under investigated conditions by the supposed uptake of all the elements studied.

K e y w o r d s: oxygen, deficiency, macroelements, soil

INTRODUCTION

Water stress is a ubiquitous limiting factor in agriculture. Contrary to other factors that may limit crop yields (e.g., acid, alkaline or saline soils) water availability is highly variable within a given growing season and from year to year [5]. On the other hand one of the most important factors of soil conditions is soil oxygen availability even during short period of flooding, which can severely limit plant development and nutrient uptake [21]. Nitrogen, P and K are the most frequently deficient nutrients in crop production. In the biosphere N is available for plants in different forms, which includes molecular N_2, volatile ammonia (NH_3) or nitrogen oxides (NO_x), mineral N (NO_3^- and NH_4^+) and organic N (amino acids, peptides etc). The utilisation of these N sources is determined strongly by environmental and particularly soil conditions [23]. In well-aerated soils, mineral N especially NO_3^- is the most abundant form of available N, while NH_4^+ predominates in soils in which nitrification is inhibited, for example under waterlogging or in a cold [13]. Phosphorus is considered important because the high P fixation by most soils requires the addition of a large excess of P fertiliser to meet crop requirements for good production [9]. Chen *et al*. [2] have observed that K application on K-deficient soils reduced the content of active reducing substances and ferrous iron in the soil, raised the soil redox potential in the rhizosphere, increased the Eh value of rice roots and lowered the content of iron in rice plants.

We conducted a greenhouse experiment to test the relationship between the oxygen status and macroelement content in soil.

MATERIALS AND METHODS

A pot experiment was conducted in a polyethylene foil tunnel. Brown soil, developed from loess (Orthic Luvisol) containing 1.54% organic matter, 25% of the 1-0.05 mm fraction, 70% of the 0.05-0.002 mm fraction and 5% of the <0.005 mm fraction. Manipulating two physical parameters that usually change in field conditions, i.e., soil moisture and soil bulk density differentiated soil oxygen conditions. The bulk densities used were 1.20 (d_1), 1.35 (d_2) and 1.50 (d_3)

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$Mg\ m^{-3}$. An equal level of moisture content, corresponding to a soil moisture tension between 80-15 kPa (w_3) was maintained up to the beginning of oxygen stress. Except during oxygen stresses, the same control soil water content was maintained in all pots.

In order to differentiate oxygen conditions during oxygen stress lasting for 14 days, that is to alternate ODR values, two additional moisture levels were applied along with the control level. They were a medium-level moisture, corresponding to a soil moisture tension 2-5 kPa (w_2), and a maximum moisture content (moisture tension equal 0 kPa - w_1), when during the whole stress time there was a 2-5 mm layer of water on the soil surface.

The experiment consisted of one NPK level and one barley species cv. Aramir. Nutrients were added to each pot before sowing in the following doses (in g per 1 kg soil): 0.1 g N (NH_4NO_3), 0.125 g K (2/3 dose in K_2SO_4 and 1/3 dose in KCl), and 0.066 g P ($CaHPO_4 \cdot 2H_2O$).

Barley plants thinned to 25 per pot were subjected to oxygen stress in the three following stages of their development:

Stress I - at the tillering stage.
Stress II - at the shooting stage.
Stress III - at the commencement of flowering stage.

Thus the experimental design comprised 3 soil moistures and 3 soil bulk densities with 4 replications. This gave 108 pots (each 6 dm^3 in volume containing 6.5 kg of soil).

Platinum electrodes, 4 mm long and 0.5 mm in diameter, were used for the ODR measurements. The measurements were made with an ODR meter having an automatic polarisation voltage control [10]. The electrode polarisation time was 4 min, and the polarisation voltage was -0.65V versus a saturated calomel electrode.

The Eh of soil samples was measured potentiometrically using four Pt electrodes (of the same type as for ODR) the saturated calomel electrode as a reference, and a portable pH-meter (Orion).

$N\text{-}NO_3^-$ in soil was determined potentiomertrically after extraction in 1 M CH_3COONH_4 using nitrate selective electrode [17]. Ammonium-N was extracted from the soil with 1 M KCl according to the Nessler method [6]. Exchangeable P was measured using the Egner method as modified by Riehm [15]. K was determined in the calcium lactate extract with ASA method [15].

Water content, bulk density and particle destiny were determined by methods described by Turski *et al.* [22].

Each measurement was taken four times during each stress (3-rd, 7-th, 10-th and 14-th day).

RESULTS AND DISCUSSION

Figure 1a showed the average values of $N\text{-}NH_4^+$ content under oxygen stress conditions depending on the stage of barley development. During the first stages (tillering and shooting) there are no significant differences in the uptake of $N\text{-}NH_4^+$ by plants and microbes. A strong decrease of $N\text{-}NH_4^+$ content was observed during the third oxygen stress (about 65% compared with the second stress). The average content of $N\text{-}NO_3^-$ at the end of three oxygen stresses is shown in Fig. 1b. The $N\text{-}NO_3^-$ content was reduced about 50% after the second oxygen stress and a significant increase of $N\text{-}NO_3^-$ content was observed during the beginning of flowering stage. It seems that the more preferable mineral form of nitrogen during the shooting stage under experimental conditions was nitrate. Marschner [11] found that the NH_4^+ concentration under agricultural conditions is many times lower than the NO_3^- concentration. On the other hand, this difference in soil concentrations does not reflect the uptake ratio of both N forms, since most plants preferentially take up NH_4^+ when both forms are available and N is limited [24]. Bassirirad *et al.* [1] observed that loblolly pine showed an increased preference for NO_3^- versus NH_4^+ at elevated CO_2 levels. Nitrate uptake is tightly controlled by the N nutritional status of the plant. In several plant species preculture under N deficiency resulted in increased NO_3^- uptake rates once NO_3^- is supplied a few hours before measuring transport [3]. This induction of NO_3^- transport reached the maximum after 12 to 24 h in barley [16], whereas NH_4^+ did not induce this uptake system [7]. During the third oxygen stress, the decrease in the $N\text{-}NH_4^+$ content was accompanied by an increase in the $N\text{-}NO_3^-$ content. This phenomenon might be connected with the nitrification process under investigation conditions, especially after the shooting stage when the uptake of nitrogen by the plant is lower and the microbial processes can dominate.

P and K transformation under oxygen stress showed a similar tendency. Those two elements showed a statistically significant decrease of content (about 20 and 10% compared with first oxygen stress, respectively) during the second growing stage (Figs 1c, d).

The influence of the combination of the two physical parameters, which differentiated soil oxygen conditions, i.e. soil moisture and soil bulk density on NH_4^+, NO_3^-, P and K content, is presented in Fig. 2. The concentration of the elements investigated was highest in flooded soil (w_1) in all the experimental treatments (except one) with a tendency to decrease with the decrease in the water content (w_2, w_3). Oxygen stress (flooded conditions) distinctly lowered the uptake in all elements under investigated conditions. Analogically phosphorus absorption decreased with water stress [5]. The combination of soil moisture and soil bulk density differentiated the elements with respect to their content in the soil. There were no significant differences in NH_4^+, NO_3^-, P and K content between all water contents (w_1, w_2, and w_3) at the lowest bulk density (d_1). That tendency was maintained for the next two densities (d_2 and d_3) in the case of $N\text{-}NO_3^-$ content and medium density (d_2) for K content (Figs 2a, b). The other results were noted for the $N\text{-}NH_4^+$ and P content. There were significant differences in the concentration of those elements between the two lower water

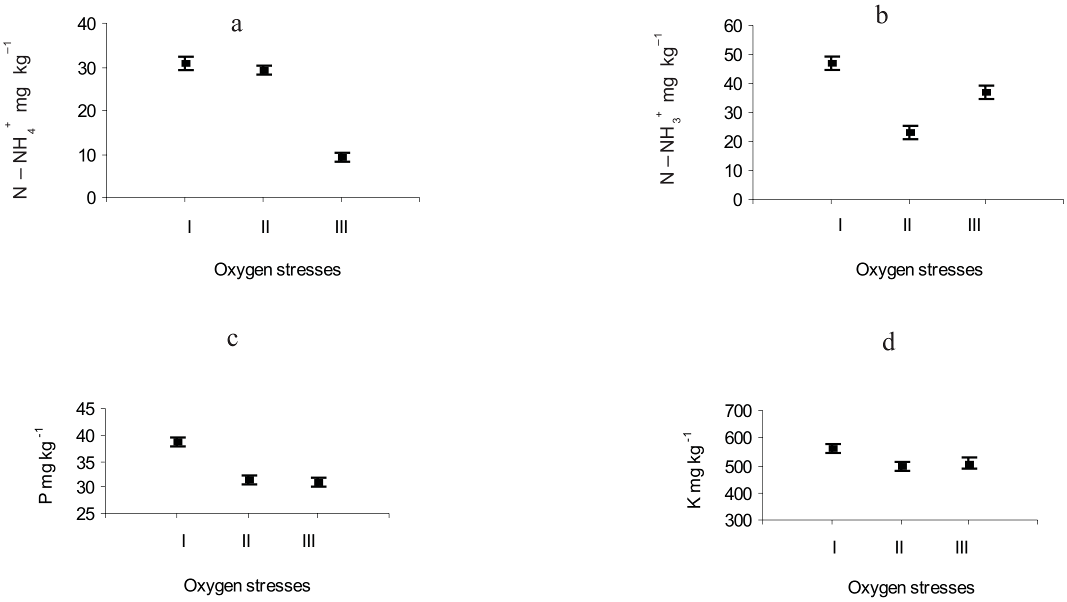
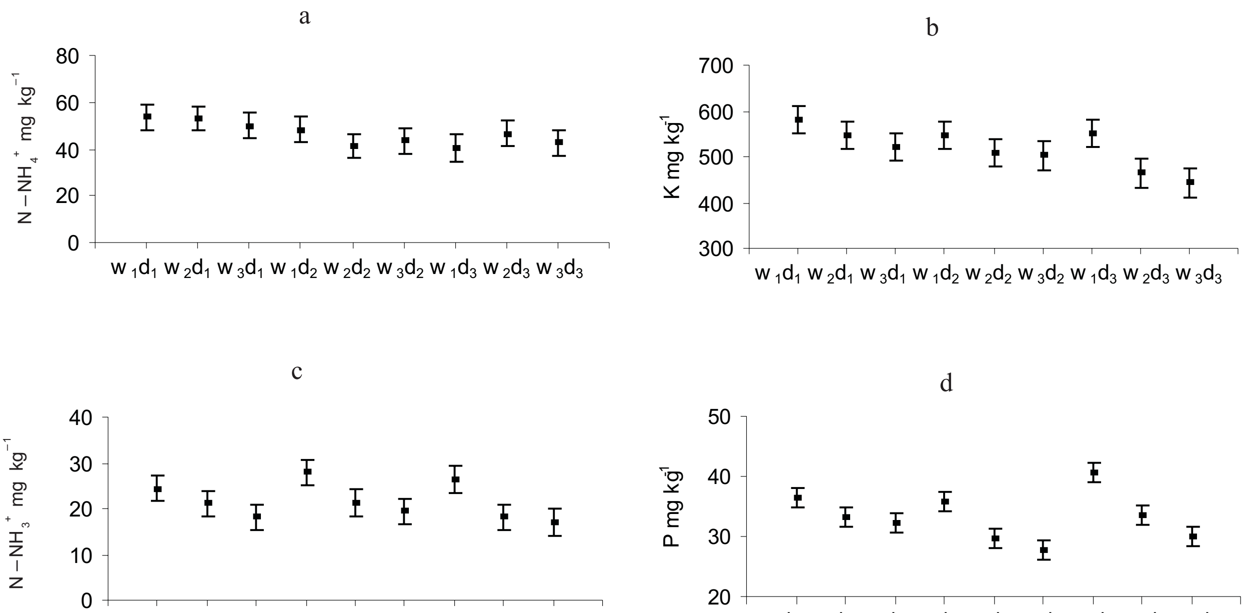


Fig. 1. Average N-NH_4^+ (a), N-NO_3^- (b), P (c), and K (d) contents in the soil during three oxygen stresses.



w_1 - flooded soil 0 kPa, w_2 - soil moisture tension 2-5 kPa, w_3 - soil moisture tension 80-15 kPa, d_1 - bulk density = 1.2 Mg m^{-3}, d_2 - bulk density = 1.35 Mg m^{-3}, d_3 - bulk density = 1.50 Mg m^{-3}.

Fig. 2. N-NO_3^- (a), K (b), N-NH_4^+ (c) and P (d) contents in the soil at three soil moisture contents and three bulk densities (average value of entire time of growing).

contents (w_2 and w_3) and the two higher densities (d_2 and d_3) and the highest moisture (w_1). Our results showed that the two higher densities of soil combined only with flooded conditions significantly elevate the content of N-NH_4^+, P (Figs 2c, d) and K (Fig. 2b) in the case of the highest density.

Relation between soil moisture (a), aeration status (b, c) and NH_4^+, NO_3^-, P and K decrease (Δ value) is shown in Figs 3-6. This decrease was calculated from the difference of the initial content of the nutrients, and the content at the given time of experiment. In the case of the lack of transformation of a given nutrient under experimental

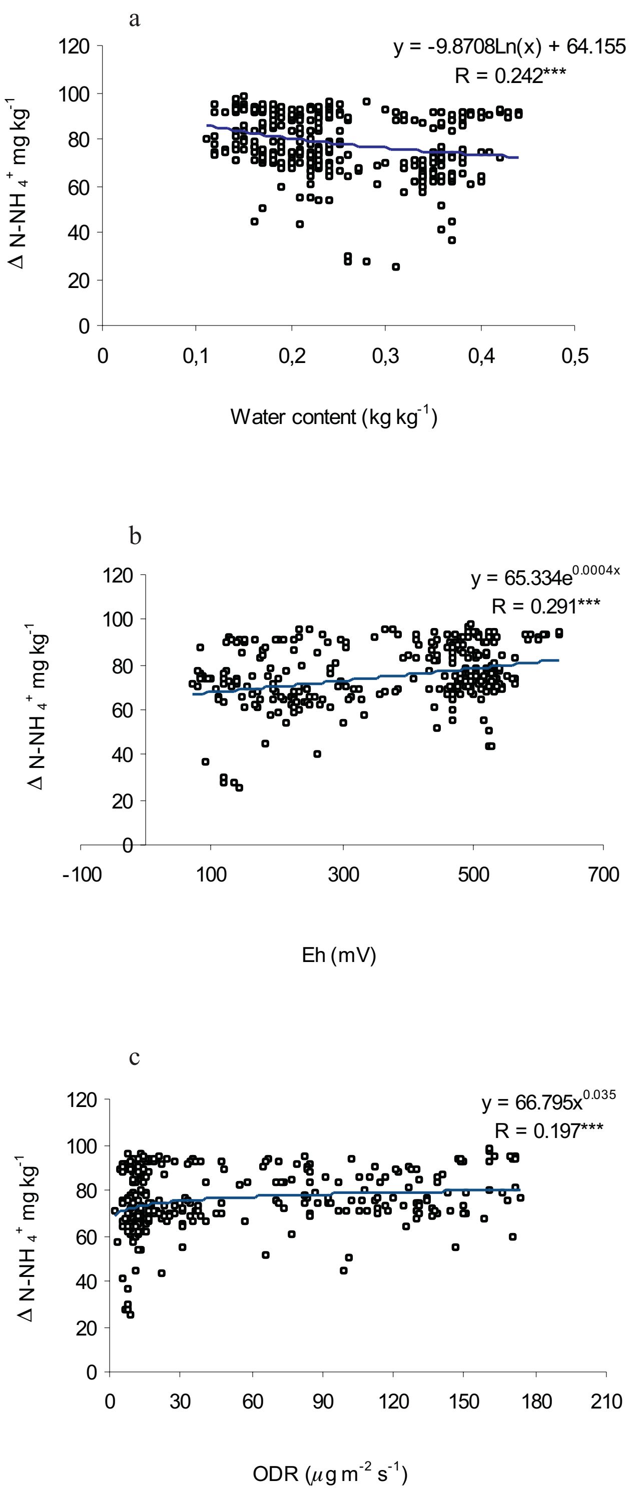


Fig. 3. Dependence of ΔN-NH_4^+ on soil moisture content (a), Eh (b) and ODR (c) in the soil (the results for all the soil moisture contents and bulk densities are put together) (ΔN-NH_4^+ is a difference between initial N-NH_4^+ in the sample and the N-NH_4^+ concentration under given conditions).

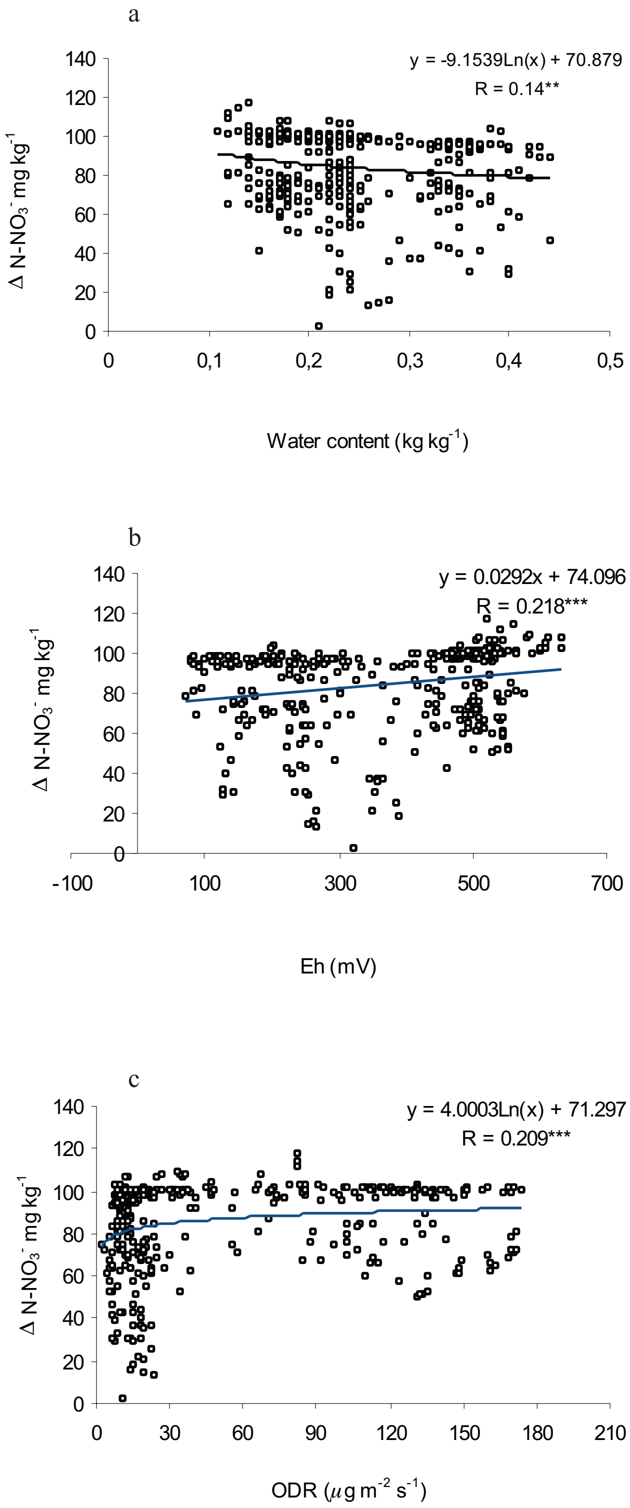


Fig. 4. Dependence of ΔN-NO_3^- on soil moisture content (a), Eh (b) and ODR (c) in the soil (the results for all the soil moisture contents and bulk densities are put together) (ΔN-NO_3^- is a difference between initial N-NO_3^- in the sample and the N-NO_3^- concentration under given conditions).

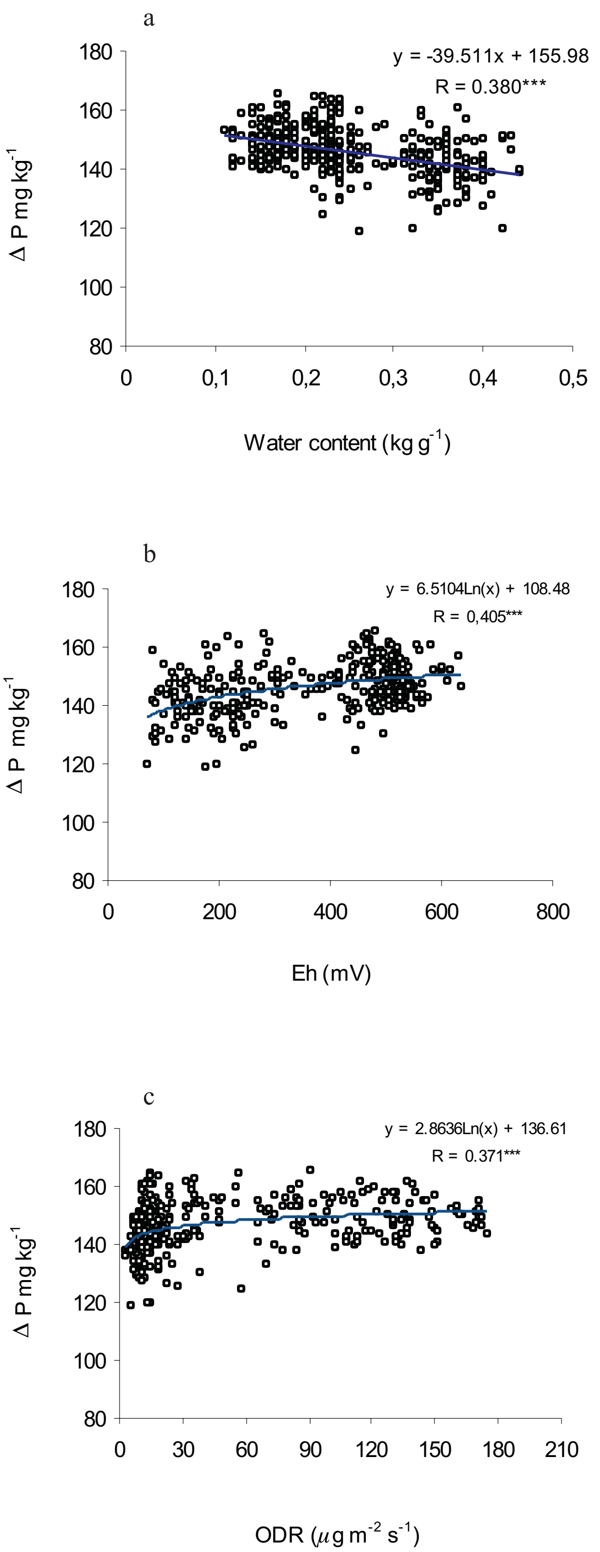


Fig. 5. Dependence of ΔP on soil moisture content (a), Eh (b) and ODR (c) in the soil (the results for all the soil moisture contents and bulk densities are put together) (ΔP is a difference between initial P in the sample and the P concentration under given conditions).

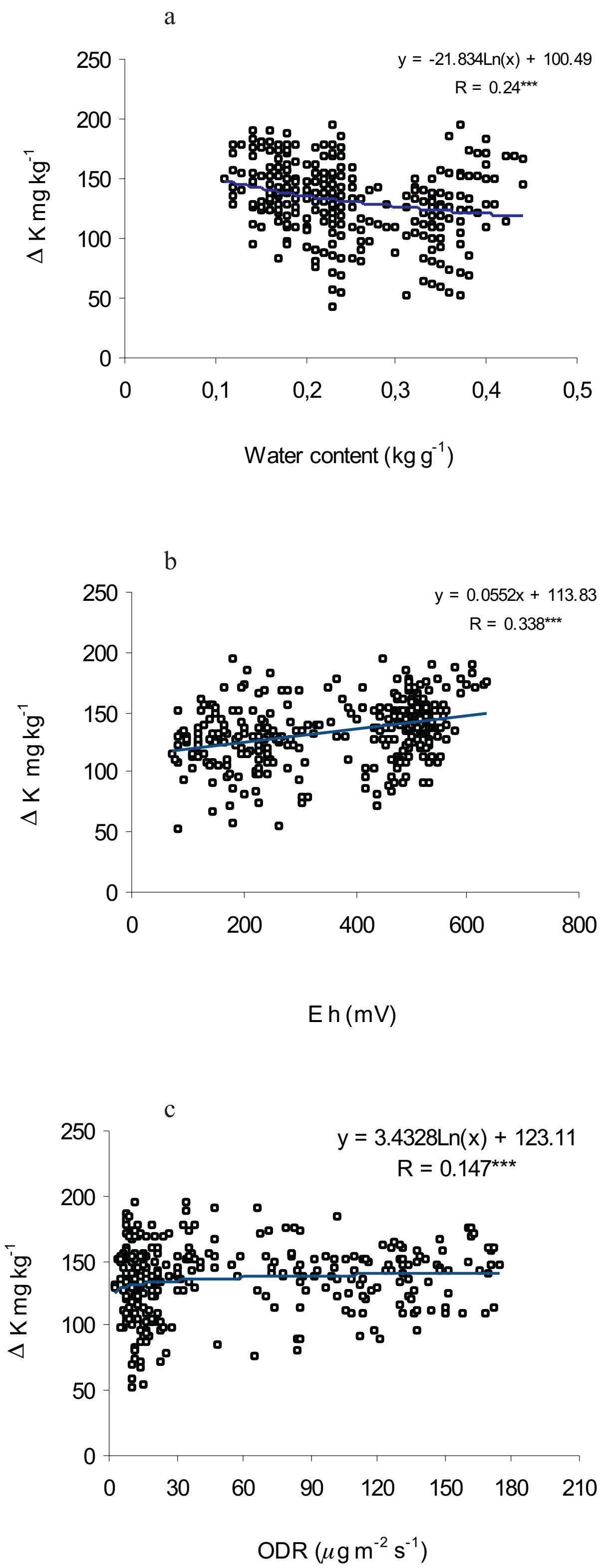


Fig. 6. Dependence of ΔK on soil moisture content (a), Eh (b) and ODR (c) in the soil (the results for all the soil moisture contents and bulk densities are put together) (ΔK is a difference between initial K in the sample and the K concentration under given conditions).

conditions (as supposedly for P and K) the difference can be treated as the uptake by plants and microbes. A significant negative correlation occurred between the soil moisture content and the decrease of the content of a particular nutrient. The most sensitive element with respect to water content was phosphorus (r=-0.380***) and the least N-NO_3^-.

The influence of redox-potential on the decrease of NH_4^+, NO_3^-, P and K content was positive in all the cases investigated (Figs 3b-6b). The highest correlation was observed in the case of P. Most of the processes connected with the nitrogen pool in the soil and its chemical transformation are linked to the oxygen status of the soil. They are denitrification, nitrification, processes of microbial fixation of atmospheric nitrogen, and ammonification [4]. Flooding the soil increases the availability of both native and added P, whether judged by solubility in different extractants or uptake by rice plants [8,12]. Due to this a negative correlation between Eh and P solubility has been recorded [14].

The parameter of oxygen availability in the soil - ODR (Figs 3c-6c) showed a typical tendency for changes under differentiated air-water conditions [4]. Statistical analysis showed a significant relation between the oxygen diffusion rate and NH_4^+, NO_3^-, P and K content. The critical ODR value, which is usually considered to be below 35 $\mu g\ m^{-2}\ s^{-1}$ [4,18,19], was confirmed here by the supposed uptake of all the elements studied. Stępniewski and Przywara [21] found that the uptake of N, P, K, Ca, Mg and Na by winter rye was decreased at low oxygen availability. Stępniewski and Łabuda [20] studied the influence of the flooding of spring barley on its growth, yield, and N, P, K content and uptake and found that oxygen stress caused reduction and irreversible blocking of N, P, and K uptake.

CONCLUSIONS

1. The average values of N-NH_4^+, N-NO_3^-, P and K content in the soil under oxygen stress conditions depend on the stage of barley development.

2. Our results showed that the two higher densities of soil combined only with a flooded condition significantly lowered the rate of decrease of concentrations as well as of N-NH_4^+ and P and in the case of the highest density also of K.

3. A decrease of all nutrient concentration was lower under conditions of high water content accompanied by low Eh and oxygen availability. The most sensitive element with respect to water content was phosphorus (r= -0.380***), the least sensitive was N-NO_3^- (r=-0.14**).

4. The influence of Eh on NH_4^+, NO_3^-. The P and K content showed a positive correlation in all the cases investigated. The highest correlation was observed in the P uptake.

5. Statistical analysis showed a significant relation between the ODR and the NH_4^+, NO_3^-, P and K content. The critical ODR value (about 35 $\mu g\ m^{-2}\ s^{-1}$) was confirmed under investigated conditions by the supposed uptake of all the elements studied.

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