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Soil compaction and fertilisation effects on nutrient content and cellular fluid pH of spring barley (*Hordeum vulgare* L.)

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Abstract. The main objective of this work was to investigate the effect of soil bulk density on nutrient (N, P, K) assimilation and on cellular fluid pH of spring barley (*Hordeum vulgare* L.) with different levels of fertilisation. Data were collected from the research fields of the Estonian University of Life Sciences (58º23´N, 26º44´E) with four different levels of soil compaction on sandy loam Stagnic Luvisol from 2001 to 2003. The soil was compacted by a tractor MTZ-82 (with loader; total weight 4.9 Mg) before spring sowing. Four levels of fertilisation ($N_0P_0K_0$, $N_{40}P_7K_{20}$; $N_{80}P_{14}K_{40}$; $N_{120}P_{21}K_{80}$) were applied using N20: P3.5: K10 fertiliser. Results of our experiments showed a high positive correlation between soil bulk density and cellular fluid pH (average r = 0.87) and negative correlation between soil bulk density and nutrient content (average r = –0.88) at highest rates of fertilisation ($N_{80}P_{14}K_{40}$; $N_{120}P_{21}K_{80}$) and positive correlation (r = 0.84) at lower rates of fertilisation ($N_0P_0K_0$, $N_{40}P_7K_{20}$) in the earing phase of barley. If the soil bulk density increased up to the level 1.56 Mg m^{-3}, there was a sudden increase of cellular fluid pH without fertiliser use. Use of fertilisers decreased the barley stress. A sudden increase of cellular fluid pH started after soil bulk density 1.61 Mg m^{-3}. The greatest impact of soil compaction was on nitrogen and potassium content in barley dry matter in all fertilisation levels. The nitrogen and potassium content in barley dry matter decreased up to 37% by high soil bulk density depending on fertilisation. The experiment showed that the higher decrease of nutrient content and the sudden increase of cellular fluid pH started at the same soil bulk density value.

Key words: soil compaction, bulk density, spring barley (*Hordeum vulgare* L.), nutrients (N, P, K), fertilisation, cellular fluid pH

INTRODUCTION

Soil compaction, caused by using heavy machinery with high inflation pressure of the tires on wet soil inevitably happens during soil tilling. Reduced soil porosity, higher penetration resistance and bulk density, caused by destruction of soil aggregates, are the results of compaction (Voorhees et al., 1979; Lipiec & Hatano, 2003). Soil sensitivity to compaction depends on soil properties, mostly on soil texture (especially clay content) and structure (Håkansson & Lipiec, 2000). However, soil water content is the most important factor in making decisions about cultural operation because of its effect on soil compaction by agricultural machines (Défossez et al., 2003). It is well established that increasing soil bulk density and penetration resistance above some threshold value due to compaction reduces root growth and may thus

reduce water and nutrient acquisition (Kuchenbuch & Ingram, 2004) and reduce crop yields (Lipiec et al., 1991). Where farmers perceive the growth of crops to be adversely affected on compacted soils, a common action is to apply additional N fertiliser. However, the growth responses obtained may be less significant than those that would accrue at lower levels of compactness, and the additional nitrogen application may be inefficient economically and detrimental to the environment (van den Akker & Soane, 2005). Soil compaction can increase fuel costs for tillage, and decrease fertiliser and water use efficiencies (Lavoie et al., 1991). As a result of that, anaerobic conditions in compacted soil and reduced plant phytomass will increase nutrient losses from soil and cause higher environmental pollution (Lipiec & Stepniewski, 1995), especially when high fertilisation rates are used. Ball et al. (1999) showed that episodic N_2O fluxes were mainly associated with the period after fertilisation and were strongly dependent on rainfall and particularly in compact soil.

Many studies have shown that the cellular responses to the environmental stresses are rather similar. In most investigations the environmental stress caused increase of intracellular (both, cytosolic and vacuolar) pH (Roos et al., 1998; Fabien et al., 1999) and of apoplastic pH (Kosegarten et al., 2001). The increase of intracellular pH is correlated in many cases with an increase of intracellular calcium for a range of abiotic stresses (Bowler & Fluhr, 2000). Bacon et al. (1998) reported that the elongation rates of barley decreased with decreasing soil water content, as the soil dried where the pH of cell fluid increased from 5.9 to 6.9. The plant hormone abscisic acid (ABA) is the major player in mediating the adaptation of the plant to stress. According to studies of Zhang et al. (2002), the optimum pH for the abscisic acid binding is about 6.5.

There has been plenty of research focused on studying machinery and vehicle effects and its modelling on different soil parameters, especially on soil bulk density, penetration resistance, water tension, structure, and porosity of soil on different soil types (reviews of Alakukku et al., 2003; Hatano & Lipiec, 2003; Hamza & Anderson, 2005; Raper, 2005). The effect of soil parameters on plant growth is mostly presented as an impact on cultural plant production (yield) (Arvidsson, 1997; Aura, 1999; Lipiec et al., 2003). There are also several investigations about root growth in compacted soils and nutrient uptake of some crop plants (Tardieu, 1988; Yamaguchi & Tanaka, 1989).

The objective of our work was to investigate the effect of soil compaction and fertilisation on nutrient (N, P, K) content and on cellular fluid pH of spring barley (*Hordeum vulgare* L.). We hypothesise that compacted soil will increase and fertilisation will decrease the cellular fluid pH of barley shoots and that compacted soil will decrease the nutrient content in barley roots and shoots independently of fertilisation.

MATERIALS AND METHODS

Field experiments

Data were collected from the Estonian University of Life Sciences research field (58º23´N, 26º44´E) with different levels of soil compaction on a sandy loam soil in Tartu County. The soil was compacted by tillage with a tractor MTZ-82 before sowing time in spring 2001, 2002, and 2003. A wheeled vehicle loaded with 2.22 Mg on the first axle and – 2.62 Mg on the rearward axle (total load is 4.84 Mg). Every autumn the soil was ploughed at 0.25 m depth. Traffic was applied uniformly to cover the entire

experimental plots. Different bulk densities were achieved by making 1, 3, or 6 tractor trips resulting in four compaction treatments, one of them being a control (without special compaction). The inflation pressures in the tractor wheels were 150 kPa. Drilling of spring barley (*H. vulgare*) was done with 450 germinating seeds per m^2 (in the middle of May). No fertilisers were used in the years 2001 and 2002. In 2003, four levels of a complex fertiliser (N20: P3.5: K10) were applied together with drilling ($N_0P_0K_0$, $N_{40}P_7K_{20}$; $N_{80}P_{14}K_{40}$; $N_{120}P_{21}K_{80}$). No herbicides and other pesticides were used.

The soil type of the experiment area is a sandy loam *Stagnic Luvisol* in the WRB 1998 (FAO, 1998) classification. Of the genetic and diagnostic horizons, the humus (32 cm), ferralic accumulation (8 cm), stagnic (10 cm) and argillic (29 cm) horizons were found in the soil of the experimental area. The soil characteristics of the humus horizon (at the beginning of the experiment in 2001) were: C 1.4%, N 0.11%, K 164 mg kg^{-1}, P 183 mg kg^{-1}, Ca 674 mg kg^{-1}, Mg 101 mg kg^{-1}, pH_{KCl} 6.2, sand (2.0–0.02 mm) 67.9%, silt (0.02–0.002 mm) 22.9%, and clay (< 0.002 mm) 9.2%.

The samples of soil and plants were taken in the earing phase of barley (July 17th). Plant samples (4 replications) from each treatment were taken for measuring nutrient content and cellular fluid pH. Soil bulk density was measured with 50 cm^3 steel cylinders in 10 cm layers up to 40 cm. Penetration resistance was measured with a cone penetrometer (cone angle 30º, stick diameter 12 mm) in every 0.05 m layer up to 0.6 m in six replications. Root samples were taken by 1131 cm^3 (h = 15 cm, Ø = 9.8 cm) steel cylinders in 15 cm layers up to 60 cm in 4 replications from two fertilisation treatments ($N_0P_0K_0$ and $N_{120}P_{21}K_{80}$). Before root washing on 0.5 mm sieve, the soil from cylinders was weighted and soil bulk density calculated.

Laboratory analyses

Determination of cellular fluid pH was carried out by using a pH-meter with microelectrodes (EVIKON, Tartu, Estonia). The plant leaves were pressed between electrodes. Determination was performed between 4 p.m. and 6 p.m., taking into account the daily rhythms of cellular fluid pH. Samples for determining cellular fluid pH were taken from the upper (younger) leaves of barley plants. From each replication (4) the pH was measured in 10 plants. After pH measurement, the plant samples were dried at 105°C temperature and milled. For the chemical analysis of plants the Kjeldhal method was used to determine the content of total nitrogen (Ryan et al., 2001). The content of phosphorus was determined colorimetrically on the basis of yellow phosphorus-molybdatic. Potassium content was determined by a flame photometer in dipping solution diluted with distilled water (Ryan et al., 2001). To find the water content in the soil, the soil samples taken from the field were weighted and dried at 105°C to a constant weight, then weighted again. After that the water content was calculated.

Air-dried soil samples were sieved through a 2 mm sieve and used for determining soil reaction (pH) in 1M KCl 1:2.5, organic carbon (C_{org}) after Tjurin (Vorobyova, 1998), calcium and magnesium in NH_4OAc at pH 7 (Soil Survey Laboratory Methods Manual, 1996) and phosphorus and potassium by the Melich-3 method (Handbook on reference methods for soil analysis, 1992), and nitrogen after Kjeldhal (Ryan et al., 2001).

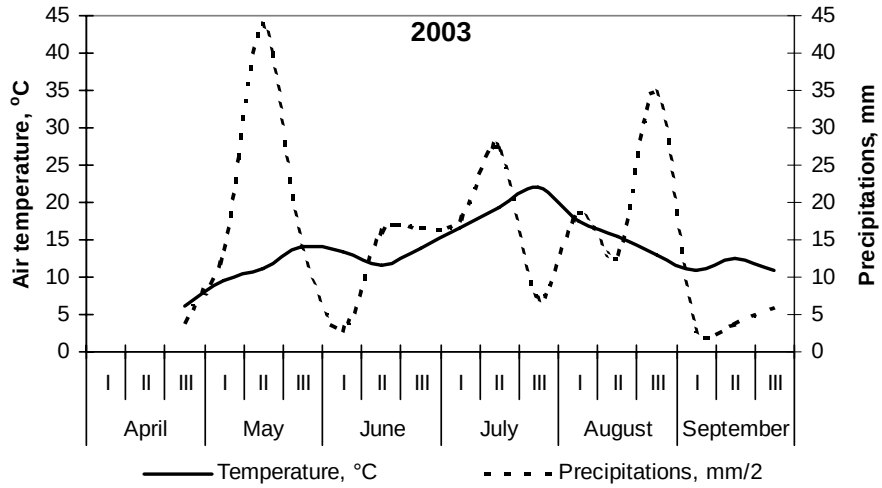

Fig. 1. Weather conditions as Walter (1955) klimagrams during the spring barley (*Hordeum vulgare* L.) growing period in 2003.

Statistics

The main data presented in the current paper were collected in year 2003 with different levels of soil compaction and fertilisation. Data of the years 2001 and 2002 (Reintam & Kuht, 2003) were used to conduct a correlation analysis between soil bulk density, cellular fluid pH of barley leaves, and nitrogen content of shoots.

Correlation analysis with 3 years data was made and the correlation coefficient *r* was calculated. As the correlation between plants' data and soil properties was highest with the average soil bulk density of upper 30 cm soil, the average was calculated and used to show correlations. The two-way analysis of variance (ANOVA) was used to process the collected data and find the impact of trial factors. The factors were soil bulk density and fertiliser rate. The significance of the experimental factors was calculated using the Fischer test. To compare the differences between values, the standard Student's *t*-test was used, and least significant differences (LSD) at significance $P < 0.05$ are given.

Weather conditions

In 2003 the growing period (from May to August) of barley was rainy and cold (Fig. 1). The precipitation totals were 450 mm. Average air temperature was 15°C during the barley growing period in 2003. More precipitation occurred in May (143 mm) and August (133 mm) and less in June (71 mm) and July (104 mm). Average air temperature was the highest in July (20.1°C) and the lowest in May (11.6°C). According to the Walter (1955) klimagram, there was less precipitation than evapotranspiration in periods where the precipitation line was under the temperature line (Fig. 1).

RESULTS

The analysis of trial factors showed a significant (at $P< 0.05$) effect of fertilisation and soil compaction and their co-effect on cellular fluid pH, potassium and phosphorus content in barley shoots (Table 1).

Table 1. Direct and co-effect of trial factors from total environmental impact on spring barley (*Hordeum vulgare* L.) cellular fluid pH (CpH), nutrient (N, P, K) content (g kg^{-1}) in shoots and roots dry mass and on shoots and roots dry weight (g m^{-2}). The effect of trial factors is calculated by Fischer test.

Trial factor	Direct and co-effect of trial factors from total impact (Cv = 100)				
	Dry weight	CpH[1]	Nutrient content		
			N	P	K
Shoots					
Fertilisation	46.6*[2]	42.8*	1.2	26.2*	9.6*
Compaction	36.9*	44.7*	11.5*	48.9*	45.7*
Fertilisation+compaction	7.6*	5.0*	61.0*	20.1*	31.1*
Roots					
Fertilisation	13.1*	nd[3]	4.6	0.3	1.7
Compaction	7.5*	nd	62.8*	48.9*	54.1*
Fertilisation+compaction	35.5*	nd	12.0*	47.2*	14.3*

[1] Cellular fluid pH
[2] Significant at level $P < 0.05$
[3] Not determined

Fertilisation had no significant effect on nitrogen content in shoots and roots and on potassium and phosphorus content in roots. Both trial factors had significant effects on barley shoots and roots dry weight.

To determine the effect of soil compaction on the nutrient content of the plants, the bulk density and penetration resistance from the soil parameters were measured. After three years of compaction, significant differences in soil bulk density and penetration resistance were detected in topsoil and also in subsoil (Fig. 2, a, b). Measuring of penetration resistance indicated thickened layers in 0.1–0.2 m and 0.3–0.4 m depth in soil, especially in 3- and 6-time passed soil. The penetration resistance was 3.6 MPa higher in treatment compacted 6 times, compared with uncompacted soil. The moisture content in compacted soil was higher than in uncompacted soil (Fig. 2, c).

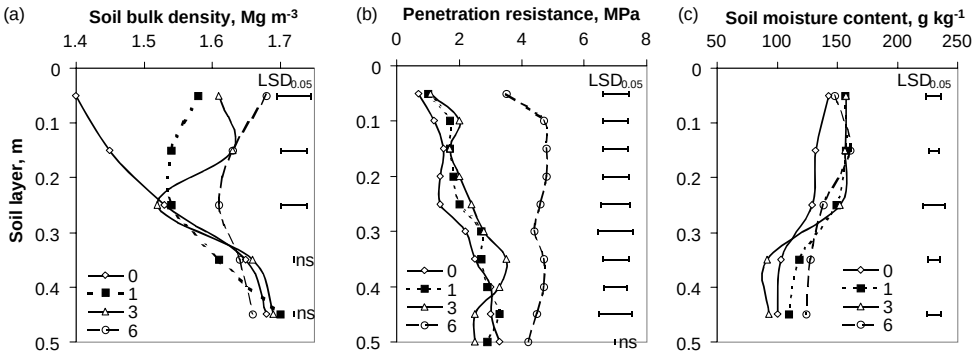

Fig. 2. Soil compaction effect on soil bulk density (a), penetration resistance (b) and moisture content (c) at the earing phase of spring barley (*Hordeum vulgare* L.) in 2003 (average of fertilisation treatments). 0 – uncompacted control; 1, 3, 6 – number of special passes; $LSD_{0.05}$ – least significant differences at level $P < 0.05$; ns – no significant differences between treatments.

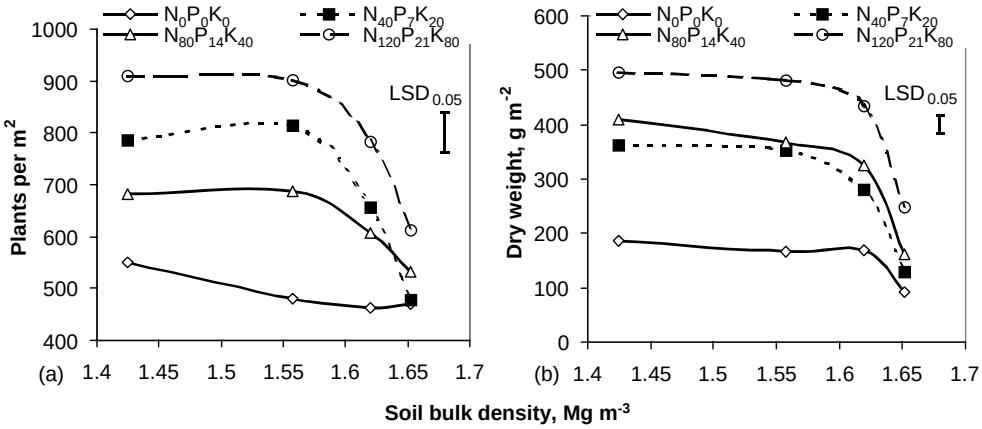

Fig. 3. Spring barley (*Hordeum vulgare* L.) shoot density (a) and dry weight depending on soil bulk density in the earing phase in 2003. $LSD_{0.05}$ – least significant differences at level $P < 0.05$.

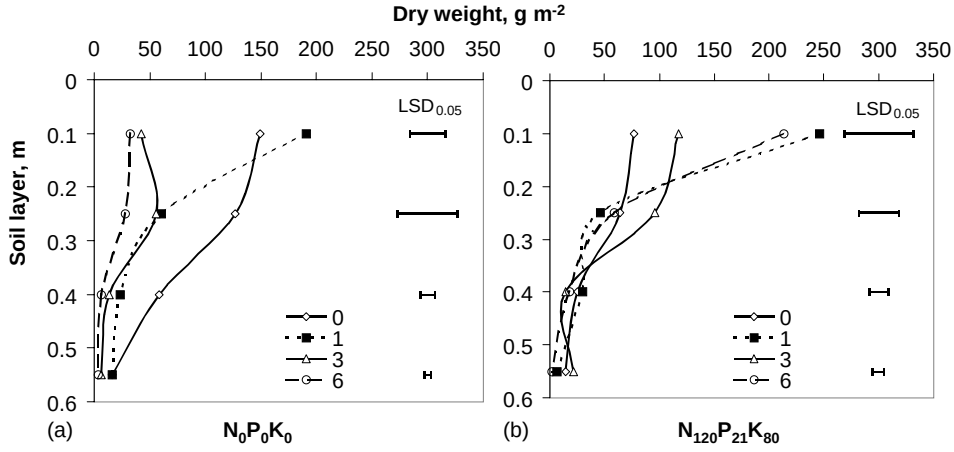

Fig. 4. Spring barley (*Hordeum vulgare* L.) roots dry weight depending on soil compaction at two fertilisation levels in the earing phase in 2003. 0 – uncompacted control; 1, 3, 6 – number of special passes; $LSD_{0.05}$ – least significant differences at level $P < 0.05$.

Soil compaction decreased the number of barley sprouts per m^2 and barley dry weight (Figs 3, a, b). There was no significant decrease of plants density and dry weight due to the one pass, where 30 cm soil average bulk density was 1.56 Mg m^{-3}. At higher soil bulk densities both density and dry weight of barley decreased significantly in all fertilisation treatments. On the fertilised plots the number of barley sprouts and barley dry weight were up to two times higher than on unfertilised plots.

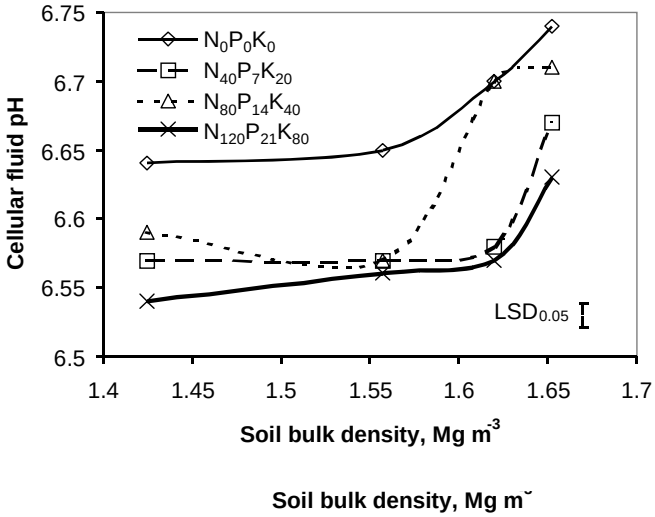

Fig. 5. Effect of soil bulk density and fertilisation on cellular fluid pH of spring barley (*Hordeum vulgare* L.) leaves in the earing phase in 2003. $LSD_{0.05}$ – least significant differences at level $P < 0.05$.

Dry weight of barley roots was affected by compaction and fertilisation. In unfertilised soil, compaction decreased mass of barley roots significantly in all measured depths (Fig. 4a). In soil passed six times, the root mass was four times lower than in uncompacted soil. Fertilisation decreased barley root mass in uncompacted and soil passed three times and increased in soil passed one and six times in upper 15 cm soil layer (Fig. 4b). However, in deeper soil layers there were more roots in uncompacted than in compacted soil.

The result of our experiments showed that soil bulk density of more than 1.55 Mg m^{-3} increased cellular fluid pH of barley leaves in all compaction treatments more than 0.1 pH unit (Fig. 5). At the same time, fertilisation caused a significant ($P < 0.05$) decrease of cellular fluid pH already at the lowest level ($N_{40}P_7K_{20}$). On uncompacted soil, the highest pH (6.64) was observed without any use of fertilisers. Even in the most compacted treatment, the pH at $N_{120}P_{21}K_{80}$ level was lower than on $N_0P_0K_0$ level on uncompacted soil. No significant differences were between fertilisation rates ($N_{40}P_7K_{20}$–$N_{120}P_{21}K_{80}$) on moderately compacted soil.

The highest increase of cellular fluid pH started at soil bulk density 1.62 Mg m^{-3} in all fertilisation variants. A correlation analysis with 3 years' data showed high positive correlation ($r = 0.87$) between soil bulk density and cellular fluid pH (Fig. 6). The sudden increase of intracellular pH started from soil bulk density 1.52–1.6 Mg m^{-3}, depending on weather conditions during the growing period. The soil bulk density level was higher in years with more precipitations and lower in drier years.

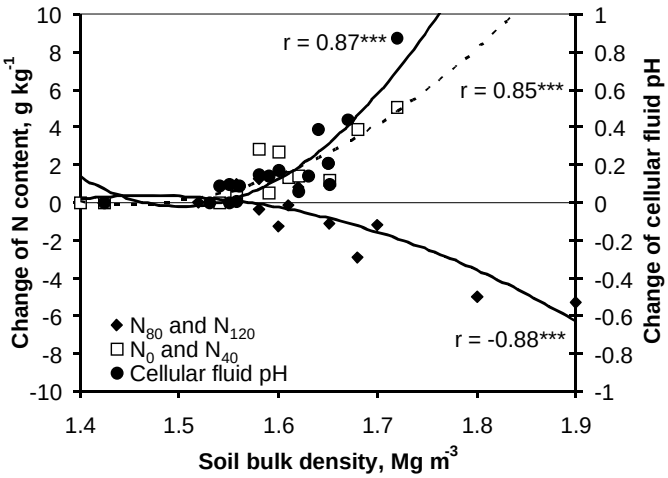

Fig. 6. Correlation between soil bulk density and changes in nitrogen content and cellular fluid pH of spring barley (*Hordeum vulgare* L.; average of 3 years' experiment; *n*=12). The correlation between changes in nitrogen content and bulk density was given in two levels of fertilisation: $N_0P_0K_0$–$N_{40}P_7K_{20}$ and $N_{80}P_{14}K_{40}$–$N_{120}P_{21}K_{80}$. *** – significant at level $P < 0.001$.

Without compaction, fertilisation with rates $N_{80}P_{14}K_{40}$ and $N_{120}P_{21}K_{80}$ increased nitrogen content in dry mass of barley plant sprouts, but were only 12.5 g kg^{-1} at $N_{40}P_7K_{20}$ (Fig. 7), this being due to a dilution effect because fertilisation with rates $N_{40}P_7K_{20}$ increased the amount of barley sprouts from 588 to 800 per m^2 (Fig. 2, a). Moderate soil compaction (1.56 Mg m^{-3}) increased nitrogen content in all fertilisation treatments, and the lowest content was in unfertilised plants. Soil bulk density of more than 1.6 Mg m^{-3} decreased barley nitrogen content in treatments where high rates of fertiliser ($N_{80}P_{14}K_{40}$ and $N_{120}P_{21}K_{80}$) were used. In $N_{40}P_7K_{20}$ and $N_0P_0K_0$ treatments bulk density of more than 1.6 Mg m^{-3} increased nitrogen content in plant dry matter because soil compaction decreased development of barley sprouts. In those treatments there were 35% less sprouts than in the highly fertilised treatments. A three years' data analysis indicated high positive correlation ($r = 0.85$) between nitrogen content and soil bulk density without use of fertilisers or with use of fertilisers at low rates and high negative correlation ($r = –0.88$) with use of fertilisers at higher rates (N80–N120; Fig. 6). The decrease of nitrogen content started at the same point of soil bulk density where cellular fluid pH started to increase. The change curves of phosphorus (Fig. 8) and potassium (Fig. 9) due to soil compaction and fertilisation were similar. The content of both nutrients increased significantly ($P = 0.05$), like that of nitrogen, due to an increase of bulk density from 1.42 to 1.56 Mg m^{-3}. Further increase of soil bulk density had a similar impact on phosphorus and potassium content as on nitrogen. The fertilisation rate $N_{40}P_7K_{20}$ caused an increase of phosphorus content from 1.2 to 1.6 g kg^{-1} in barley shoots on the most compacted soil (Fig. 8). The highest compaction areas showed no increase of potassium content in barley sprouts caused by fertilisation, and no significant differences between fertilisation treatments were detected.

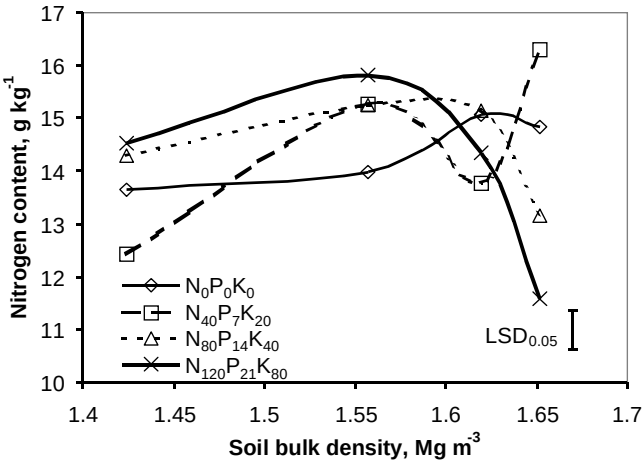

Fig. 7. Effect of soil bulk density and fertilization on nitrogen content in spring barley (*Hordeum vulgare* L.) shoots in the earing phase in 2003. $LSD_{0.05}$ – least significant differences at level $P < 0.05$.

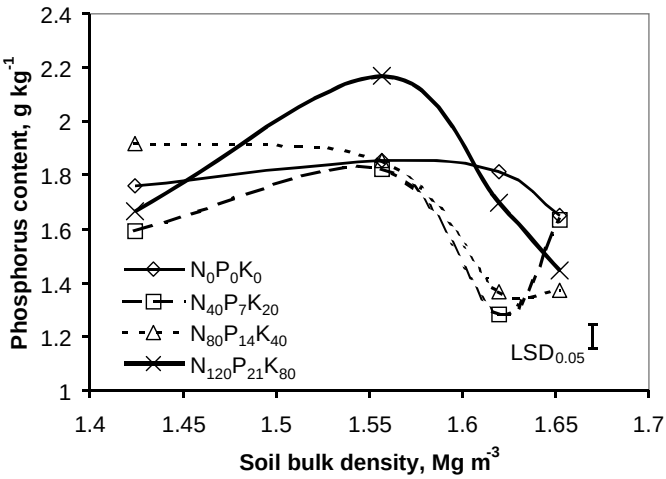

Fig. 8. Effect of soil bulk density and fertilisation on phosphorus content in spring barley (*Hordeum vulgare* L.) shoots in the earing phase in 2003. $LSD_{0.05}$ – least significant differences at level $P < 0.05$.

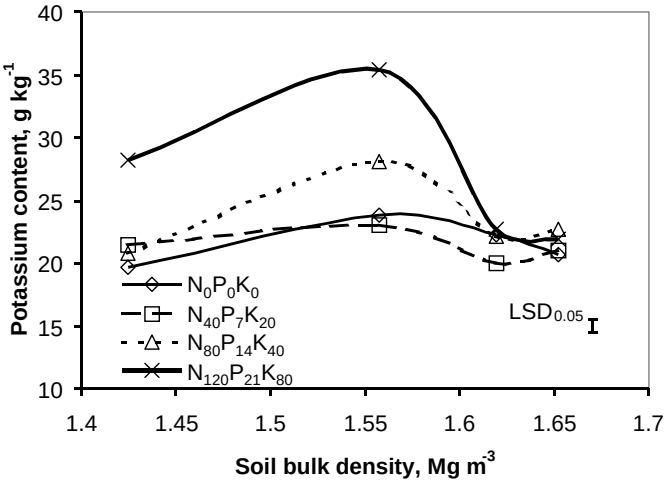

Fig. 9. Effect of soil bulk density and fertilisation on potassium content in spring barley (*Hordeum vulgare* L.) shoots in the earing phase in 2003. $LSD_{0.05}$ – least significant differences at level $P < 0.05$.

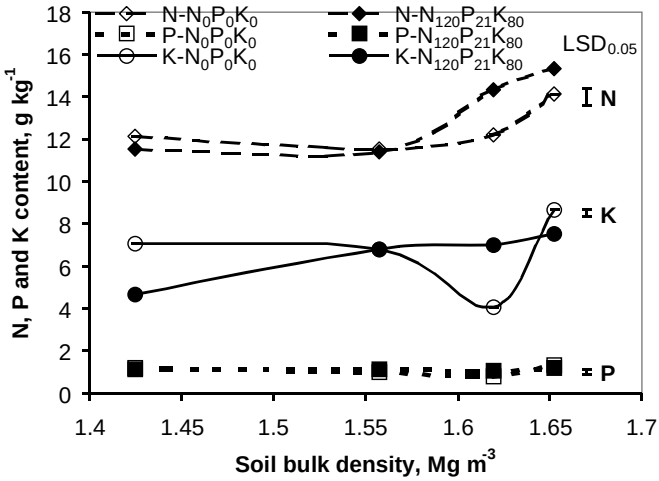

Fig. 10. Effect of soil bulk density and fertilisation on nitrogen (N), phosphorus (P) and potassium (K) content in spring barley (*Hordeum vulgare* L.) roots in the earing phase in 2003. $LSD_{0.05}$ – least significant differences at level $P < 0.05$.

Compaction caused a significant increase of phosphorus and potassium content in barley roots (Fig. 10). Fertilisation had no such a positive effect. Without any use of fertilisers, the content of phosphorus and potassium was even higher. Lowest changes due to soil compaction were in barley nutrient content without any use of fertilisers.

DISCUSSION

The barley plants felt highly the deficit of nutrient elements in compacted soils, depending on the soil bulk density level (Figs 6–9). In a more dense soil, low nutrient acquisition is mostly connected with unsuitable conditions for plant roots to develop as was the case in the current experiment (Fig. 4). Due to the reduction of pore size and increased mechanical strength of the soil, development and spreading of plant root system will be inhibited (Unger & Kaspar, 1994). Roots are growing more horizontally rather than vertically like it was in fertilised compacted soil, where most roots were in the upper 15 cm soil layer. A decreased root system results in greater distances between the neighbouring roots and affects water and nutrient uptake. Absorption of water and nutrients usually takes place in the soil adjacent to the root surface from 2 to 8 mm, depending on soil and nutrient types (Yamaguchi & Tanaka, 1989). Though compaction may increase root–soil contact and induce greater water movement towards the roots, a greater nutrient inflow rate per unit length and root soil contact area are not sufficient without additional nutrient application to compensate for reduced root size (Lipiec & Stepniewski, 1995). Tardieu (1994) and other authors showed that soil penetration resistance influenced plants and their root growth through plant hormones and, therefore, growth is inhibited even if water and nutrients are not limited. However, in the current experiment the soil compaction decreased barley roots mass and through that dry weight and nutrient content in dry weight without fertiliser use. Though the root mass in the fertilised compacted soil was higher than in the uncompacted soil, there was still decrease of barley mass and nutrient content.

The easiest detectable change due to soil compaction stress is cellular fluid pH in plants. As data of the current experiment and our earlier data (Reintam & Kuht, 2003) and data of other authors (Fabien et al., 1999; Hussain et al., 1999; Kosegarten et al., 2001) showed, the intracellular pH increased in stress conditions. Typical pH of corn cells cytosol is 7.0–7.5 and of vacuoles is 4–6 (Leigh, 2001). The plant hormone abscisic acid (ABA) is the major player in mediating the adaptation of the plant to stress. Results of Mulholland et al. (1996) showed that the ABA concentration was greatly increased 6 days after emergence when seedlings were grown in compacted soil, and root and shoot growth and leaf conductance of barley were all reduced when plants were grown in compacted soil with a bulk density of 1.7 Mg m^{-3} (relative to uncompacted control plants 1.1 Mg m^{-3}). Increased cellular pH will decrease plants nutrient acquisition through proton pumping via the H^+-ATPase and transporters (Leigh, 2001; Shabala & Shabala, 2002). On the other hand, a low level of protons will increase the intracellular pH (Marre et al., 1989) so that these two points are mostly connected. A lower content of nutrients in barley shoots and a higher content of nutrients in roots due to the soil compaction can be explained with those processes.

Fertilisation increased nutrient uptake and decreased the harmful effect of soil compaction of up to the 3 times compacted treatment and had no effect on the soil compacted 6 times (Figs 3–10), where the soil penetration resistance was over 4 MPa and bulk density were more than 1.6 Mg m^{-3} (Fig. 2). Critical value of penetration resistance on sandy loam soil is 3 MPa (Håkansson & Lipiec, 2000). It is reported that soil fertilisation with NP, farmyard manure (30 t ha^{-1}) and NP plus farmyard manure improved the root density of barley by up to 5%, 10% and 11%, respectively, in comparison with control plots (Sidiras et al., 2001). On the other hand, fertilisation

decreased nutrient content in roots in uncompacted soil (Fig. 10) probably because of quick transport of nutrients from roots to shoots. In stress conditions, namely a dense soil and a low level of nutrients, the transport of nutrients is inhibited and their content in roots increases. In fertilised treatments, also the root biomass was smaller (Fig. 4). Higher root–shoot ratio of barley due to compaction was reported also by Hussain et al. (1999). Plants growing in soil despite good nutrition and water supply have higher shoot mass and lower root mass. Bona et al. (1995) found an increase of maize root length density in deep layers with decreasing levels of N fertilisation, from 280 to 140 and 0 kg ha^{-1}. Supplying aerated nutrient solution into compacted soil, Goss (1977) gained positive effects on plant growth. Increased nutrient uptake by roots on compacted soil may be connected with higher root mass in the upper moist (Fig. 2, c) soil layer. As fertilisation was made in spring together with sowing, the nutrients were also in the upper part of the soil. A compacted soil layer, because of its high strength and low porosity, confines the crop roots in the top layer and reduces the volume of soil that can be explored by the plant for nutrients and water (Hammel, 1994).

The increase of nitrogen, phosphorus and potassium content (Figs 7–9) in barley dry matter with increasing of soil bulk density at some fertilisation levels may be explained by a decreased amount of barley sprouts per m^2 and with a bigger nutrition area and better light conditions for each plant. An important role was also played by weather conditions of the experimental year. The earing period (time of sampling) was mostly dry in the years, and in dense soil moisture was kept longer (Fig. 2, c). Mengel & Kirkby (1987) also observed that in a dry year the uptake of elements, such as nitrogen, calcium and magnesium, which are moving into the plant with water, might increase due to thicker soil. In a moist soil there are more nitrates than in a dry soil. The high pH in this period may be induced by nitrate nutrition. Kosegarten et al. (2001) showed a correlation between nitrate supply and apoplastic pH.

CONCLUSIONS

In our experiments, plant nutrient content and the intracellular pH indicated the critical level of soil bulk density for barley growth, which was 1.52–1.60 Mg m^{-3} in the sandy loam topsoil depending on soil moisture conditions and fertilisation. At this point, nutrient acquisition and total mass of barley started suddenly decrease. We can detect easily the most suitable soil condition for plant growing by using connected measurements of nutrient (N, P, K) content and cellular fluid pH. Concerning the degree of intracellular fluid pH, we concluded that the tested method is rather sensitive and allows us to find out plausible relations between the intracellular pH, soil compaction and levels of the fertilisers.

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