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Weed Responses to Soil Compaction and Crop Management

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1. Introduction

Soil compaction first affects physical properties, as compaction occurs when soil particles are pressed together, reducing pore space between them and increasing the soil bulk density (Lipiec & Hatano, 2003; Raper, 2005; Reintam, 2006; Reintam et al., 2009). Soil compaction also influences chemical and biological processes, such as decreasing organic carbon (C) and N mineralization, the concentration of CO_2 in the soil (Conlin & Driessche, 2000), nitrification and denitrification, and activity of earthworms and other soil organisms (Ferrero et al., 2002). At high soil moisture, the difference in soil resistance between non-compacted and compacted soil is low and may be smaller than the value that limits root growth (>2 MPa). But as the soil dries, soil compaction is more observable (Hamza & Anderson, 2005). Further soil compaction effects are decreased root size, retarded root penetration, smaller rooting depth (Unger, and Kaspar, 1994), decreased plant nutrient availability and uptake (Kuchenbuch & Ingram, 2003; Reintam, 2006), and greater plant stress (Reintam et al., 2003), which are among the major reasons for reduced plant productivity and yield (Arvidsson, 1999; Reintam et al., 2009).

When estimating the decreased plant productivity in agro-ecosystems due to compaction, the greatest attention is usually paid to cultivated plant yields. On arable land, different weed species communities exist not only due to the different type of soil, but also because of cultivated plant diversity in agro-ecosystem, in response to different cultures, management intensity, and agro-ecosystems isolation from natural vegetation (van Elsen, 2000). Changing tillage practices consequently changes plant species composition, vertical distribution, and density of weed seed banks in agricultural soils (Buhler, 2002; Carter & Ivany, 2005). Pollard and Cussans (1981) reported that most weeds showed no consistent response to tillage and Derksen et al. (1993) suggested that composition changes in weed communities were influenced more by environmental factors (location and year) than by tillage systems. However, many weed species are more tolerant to poor soil conditions than cultivated plants. Because weeds are more efficient in nutrient uptake, the nutrient content of a crop decreases when competition with weeds increases (Koch & Köcher, 1968).

The composition of weed community is widely reported in intensive management systems. In experiments in Norway, there were no changes in the weed community during five years, even at the highest herbicide intensities (Fykse & Wærnhus, 1999). However, changing tillage or management intensity and soil physical parameters, following compaction, caused changes in weed flora. Without regular ploughing, selection for annual weeds decreases and selection for perennial weeds increases. On the other hand, in the experiments of Carter and Ivany (2005), direct seeding did not reduce the soil weed seed bank, but mouldboard ploughing for 14 years did reduce the weeds seed bank. Soil compaction caused by traffic (Jurik & Zhang ShuYu, 1999), or soil compaction in a first year's no-tillage system (Lampurlanés & Cantero-Martínez, 2003) changes dominant weed species in the community due to higher soil bulk density and penetration resistance. Many investigations have compared conventional tillage to reduced- or no-tillage systems and reported increasing numbers of perennial weed species, such couch grass (*Elytrigia repens* L.), Canadian thistle (*Cirsium arvense* L.), perennial sow thistle (*Sonchus arvensis* L.), and decrease of cultivated plant production (Blackshaw et al., 2001; Reintam et al., 2008) under no-tillage systems. Stevenson *et al*. (1998) reported that the reduction in midseason dry weight of 36% and seed yield of 59% of barley whole plant weight due to the chisel plough relative to the mouldboard plough treatment. Yield loss in this experiment was associated with interference from broadleaf plantain (*Plantago major* L.) and dandelion (*Taraxacum officinale* Weber in Wiggers). In central Iowa, a single wheel-tracking pass at crop sowing increased the cumulative number of seedlings of giant (*Setaria faberi* L.) and yellow foxtails (*S. glauca* L. [*S. pumila*]) by 187%, common water hemp (*Amaranthus rudis* L.) by 102% and common lambsquarter (*Chenopodium album* L.) by 30%. Researchers have suggested that compaction from wheel traffic apparently did not create a physical impediment to emergence; rather, it altered micro-environmental conditions in ways that stimulated weed germination and emergence (Jurik & Zhang ShuYu, 1999). Tillage effect on soil properties influences both number and diversity of weed populations (Hooker et al., 1997).

Most weeds have higher dry matter nutrient content than crops. Certain weed species have a lower optimal N requirement than crops, giving those weeds a competitive advantage in some situations (Di Tomaso, 1995). When growing with cereal crops, weeds can benefit from fertilizers (Bischoff & Mahn, 2000) irrespective of fertilizer placement (Salonen, 1992). On the other hand, many emerging weeds gain little advantage from fertilization when competing with established crops because of light competition. Nitrogen application rate weakly influences the weed flora (Andersson & Milberg, 1998); soil tillage influenced weeds more than the source of nutrients (McCloskey et al., 1996). Corn spurry (*Spergula arvensis* L.) is reported to be dominant on sandy soils and also clay soils where soil fertility and the competition with other plants are low (Mahn & Muslemanie, 1989). In addition, dry matter of corn spurry grown alone increased with increasing N up to 60 kg ha^{-1}. Competition from rye (*Secale cereale* L.) severely reduced dry matter production of corn spurry and the weed itself was only weakly competitive under increasing N rates. Furthermore, common lambsquarter is reported to dominant in biomass where N was applied, while corn spurry and shepherds-purse (*Capsella bursa-pastoris* L.) dominated on experimental plots without N (Mahn & Muslemanie, 1989). Common lambsquarter and wild mustard (*Sinapis arvensis* L.) are the most widespread weed species on mouldboard ploughed, nutrient rich, neutral soil (Zanin et al., 1997). However, common lambsquarter and wild mustard are not the major species present in cases of low fertility and dense soil (Shrestha et al., 2002).

Plant age plays an essential role on nutrient uptake by weeds. Some weed species, such as corn mayweed (*Matricaria inodora* L.) and common chickweed (*Stellaria media* (L.) Vill.), grow during vegetation period 2–3 generations, but the young plants have a higher mineral content than more mature plants (Bockholt & Schnittke, 1996). Chickweed emerges continually from spring to autumn and starts flowering within one or two months after emergence. Chickweed seed germinate in response to soil disturbance rather than seasonal cues (Miura & Kusanagi, 2001). Both species, corn mayweed and chickweed, tolerate compacted soil (Reintam et al., 2006). Walter et al. (2002) found that chickweed was positively cross-correlated with clay and negatively cross-correlated with pH and potassium (K) content.

The objective of our experiment was to investigate continuous soil compaction effects on plant community composition and nutrient content in some of the most widespread weed species found in barley (*Hordeum vulgare* L.) production.

2. Material and methods

Data presented in current chapter were collected from the research field at the Estonian University of Life Sciences (58º23´N, 26º44´E) on a sandy loam soil, *Stagnic Luvisol*, at Tartu County in 2001–2004.

2.1 Experiment design

Soil compaction was accomplished using a 4.9 Mg tractor MTZ-82 before sowing time in spring 2001, 2002, 2003 and 2004. Passes of one, three and six passes with a wheeled vehicle loaded with 2.22 Mg on the first axle and 2.62 Mg on the rear axle (total load was 4.84 Mg) uniformly covered the entire experimental plot area. The inflation pressures in the wheels of the tractor were 150 kPa. An area without applied compaction served as the control, thus four compaction treatments were established on the experimental field. The compaction treatments were split to four replications and the size of each experimental plot (16 plots) was 12 x 9 m (108 m^2). Direct seeding of barley utilizing a drill (crosswise to compaction treatments) in rate of 450 germinating seeds per m^2 was accomplished in the middle of May. No fertilizers and herbicides were applied to decrease interactions during the compaction investigation on weed species and barley. Every autumn (in September) the soil was ploughed to the 0.21– 0.22 m depth.

2.2 Soil description

Soil was classified a sandy loam *Stagnic Luvisol* according to the WRB 1998 classification. From the genetic and diagnostic horizons the humus (32 cm), ferralic accumulation (8 cm), stagnic (10 cm) and argillic (29 cm) horizons were defined in the soil. The soil characteristics of the humus horizon (in beginning of experiment in 2001) are presented as follows: 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 investigated soil formed on bisequal-textured reddish-brown till and is sensitive to soil compaction. This type of soil covers 5.9% of the total area, and 15.1% of the arable land in Estonia, mostly in southern and south-eastern part (Reintam& Köster, 2006).

2.3 Field sampling

The sampling of soil and plants were accomplished in the earing phase of barley in growth stage 75–79 by numeric code description according by BBCH Growth Scale of plants. All barley fruits reached final size in the middle of July in all experimental plots. Data regarding the content of the plant community were obtained from taking vegetation samples from a 0.25 m^2 plot (*n*=4). Partitioned plant part components (barley and observed weed species) were determined, counted, measured and weighed (wet weight). Parts of plants were taken to dry them in oven at 60°C temperature to calculate dry matter content and dry weight. Homogenised plant part samples from each treatment were taken for measuring nutrient content. Root samples were taken by 1131 cm^3 (h=15 cm, Ø=9.8 cm) steel cylinders in 15 cm layers down to 60 cm in 4 replications in years 2002–2004. Before root washing on 0.5 mm sieve, the soil from cylinders was weighted and soil bulk density calculated. No root measures were made in 2001. The soil bulk density was also measured with 50 cm^3 (h=5 cm, Ø=3.5 cm) cylinders in 0.1 m layers down to 0.4 m in four replications. At the each layer depth, samples were taken for measuring soil moisture, pH_{KCl} and nutrient (C_{org}, N_{total}, plant available P, K, Ca, Mg) content. Penetration resistance was measured with a cone penetrometer (cone angle 60°, stick diameter 12 mm) in every 0.05 m layer down to 0.6 m in six replications from every experimental plot. Soil moisture and penetration resistance was measured also every spring after compaction.

2.4 Laboratory analyses

Soil and plant analyses were carried out at the laboratories of the Department of Soil Science and Agrochemistry, Estonian University of Life Sciences. The plant samples (aboveground and root parts separately) were dried at 60°C temperature and milled after removing the plants from a field. The Kjeldahl method was used to determine the content of total N of plants. The content of phosphorus (P) was determined colorimetrically on the basis of yellow phosphorus-molybdatic. Potassium content was determined by flame photometer in dipping solution diluted with distilled water. Air–dried soil samples were sieved through a 2 mm sieve and used to determine: soil reaction (pH) in 1M KCl 1:2.5, organic carbon (C_{org}) after Tjurin, calcium, magnesium, sodium in NH_4OAc at pH 7 and phosphorus and potassium after Melich-3 method. To determine water content in the soil, the soil samples taken from the field were weighted and dried at 105 °C to the constant weight and weighted again. After that the water content was calculated. Samples for the particle size determination were treated with sodium pyrophosphate to break down aggregates. Sands were sieved and fractions finer than 0.05 mm were determined by pipette analysis.

2.5 Weather conditions

In 2001 and 2003 the barley growing period (from May to August) was relatively rainy and cold. The precipitation totals were 373 mm and 450 mm, respectively. Average air temperature was 15.8°C in 2001 and 15°C in 2003 during the barley growing period. More precipitation occurred in May and August and less in June and July. Average air temperature was highest in July (20.1°C) and lowest in May (11.6°C). In 2002 the growing period was relatively warm and dry. During the vegetation period only 163 mm of rain fell and the average air temperature was 17.4°C. More precipitation occurred in June and in end of July, less in May and August. Average air temperature was highest in July (20.1°C) and lowest in May (13.9°C). The rainiest year was 2004, when 475 mm total precipitation fell during the growing period; average air temperature was 16.2°C. More precipitation occurred in June and less in May. Average air temperature was highest in August (17.1°C) and lowest in May (12.1°C).

2.6 Statistics

The one-way, two-way and three-way analysis of variance (ANOVA) was used to determine the impact of trial factors based on the collected data. Soil bulk density (soil compaction), and fertilization rate were considered fixed effects while year was considered random. The significance of experiment factors was calculated using the Fischer test and the level of significance $P<0.05$ was used. To compare the differences between values the standard Student's *t*-test was used and least significant differences (LSD) at significance $P<0.05$. Correlation analysis was also used to process the data. The program Statistica 7.0 was used for data analysis.

3. Results and discussion

3.1 Compaction effect on soil properties

The values of soil bulk density and penetration resistance (Fig. 1 and 2) changed among the experiment years due to the different weather conditions during sampling. The values of both, penetration resistance and bulk density depend on the soil moisture content (Fig. 3). However, the effect of traffic on the soil properties was significant in every experimental year between the non-compacted and the six times compacted soil. The differences in soil penetration resistance between one and three times compacted soil were significant after four years of soil compaction (Fig. 2). In average of the four years data there were no significant differences between those treatments. However, the six passes increased the soil penetration resistance by 2.0–3.0 MPa compared with to non-compacted soil.

Soil compaction did not caused significant ($p<0.05$) differences in soil nutrient uptake in first year (Table 1). After four years with continuous compaction and without fertilizers use, significant positive effects of soil compaction on organic carbon, total nitrogen, available phosphorus and potassium content were detected in soil. Compaction by one pass, three and six passes increased organic carbon content 13%, 32% and 39%, respectively, compared to non-compacted soil. Three and six passes increased total nitrogen content 16% and 9%, available phosphorus content 17% and 7%, and potassium 16% and 66%, respectively, compared to non-compacted soil. One pass compaction did not cause significant changes in nitrogen and phosphorus content. Without fertilizer use, the carbon phosphorus and potassium content decreased with four years in the control by one time and three pass compacted treatments. The highest decrease by was in non-compacted soil, where the decrease was 28% in case of carbon, 13% in case phosphorus and 41% in case of potassium. In six times compacted soil the content of carbon was 4%, content of nitrogen 23% and content of phosphorus 15% higher than in first year.

Compaction effect on soil properties depended on the machinery weight and number of passes, but also from soil moisture and weather conditions during compaction treatment application and vegetation period. Moist soil is more sensitive to soil compaction than dry. Low impact of soil compaction on soil bulk density and penetration resistance in the first year was caused by dry soil (110 g kg^{-1}) at the application of compaction and the subsequent rainy growing season following application. In following years, at the time of compaction application the soil was moist (200 g kg^{-1}) and compaction had a higher effect. Soils with higher clay and moisture content are more sensitive to soil compaction. Dry summers after a rainy spring make soil more susceptible to compaction.

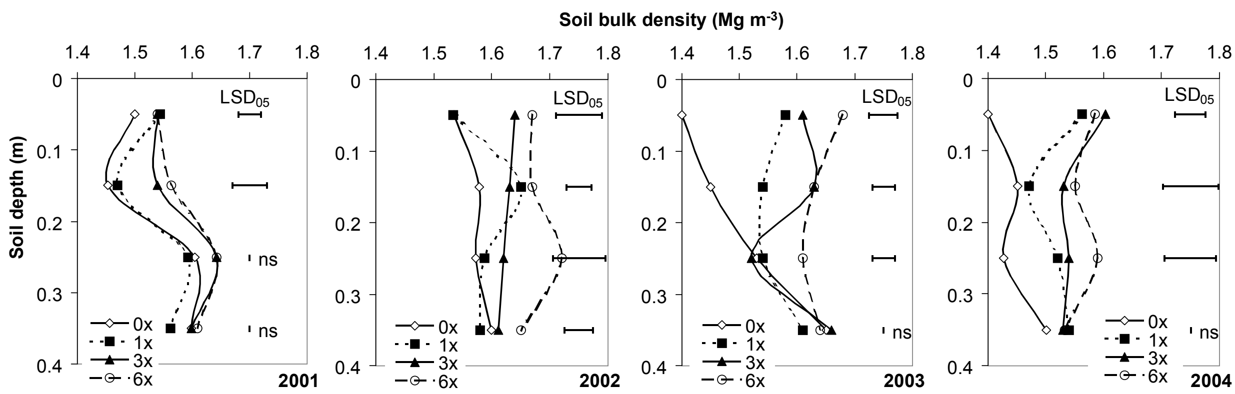

Fig. 1. Effect of soil compaction on soil bulk density in earing phase of spring barley (*Hordeum vulgare* L.) in years 2001—2004; 0x – non-compacted control, 1, 3, 6 – number of passes; $LSD_{0.05}$ – least significant differences at significance at $p<0.05$; ns – differences are not significant

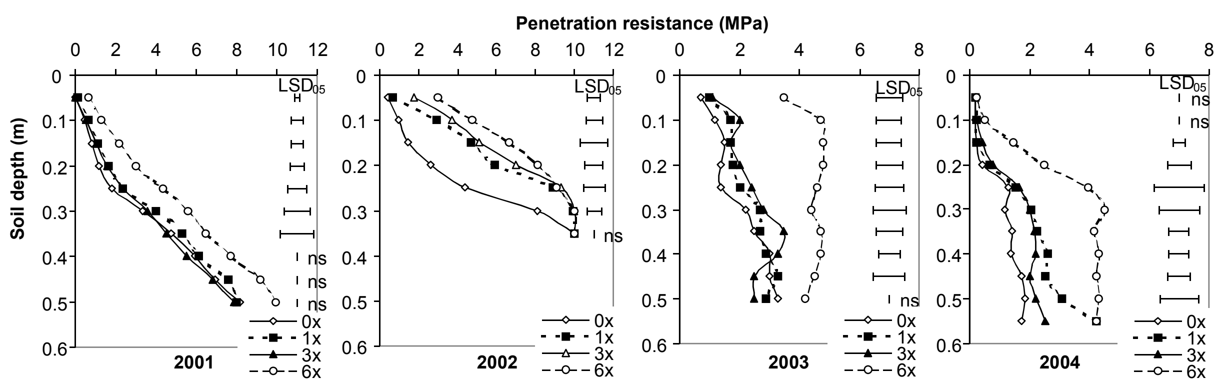

Fig. 2. Effect of soil compaction on soil penetration resistance in earing phase of spring barley (*Hordeum vulgare* L.) in years 2001—2004; 0 – non-compacted control, 1, 3, 6 – number of passes; $LSD_{0.05}$ – least significant differences at significance at $p<0.05$; ns – differences are not significant

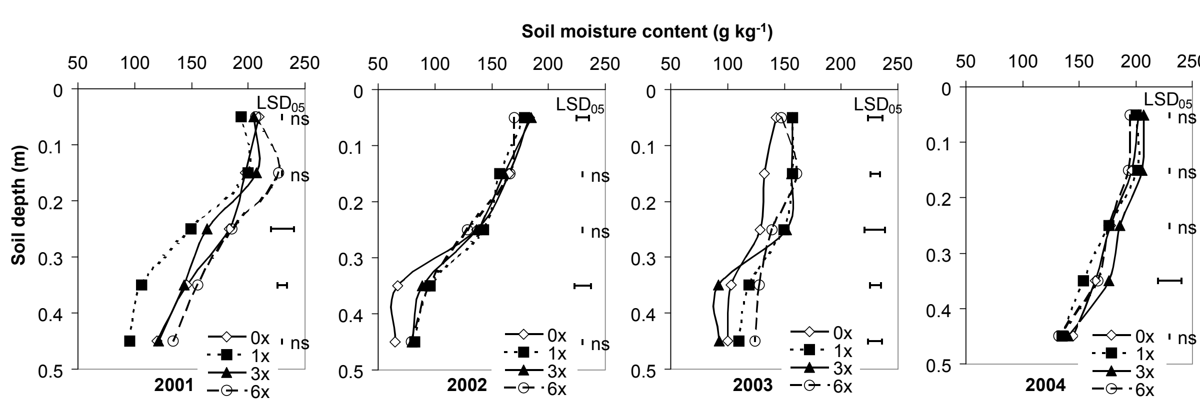

Fig. 3. Effect of soil compaction on soil moisture content in earing phase of spring barley (*Hordeum vulgare* L.) in years 2001—2004; 0 – non-compacted control, 1, 3, 6 – numbers of passes; $LSD_{0.05}$ – least significant differences at significance at $p<0.05$; ns – differences are not significant

Year/ Compaction variant	C_{org} (g kg^{-1})	N_{tot} (g kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})
2001				
Control	13.95	1.29	217.7	181.3
1 time compacted	14.20	1.21	238.5	156.0
3 times compacted	13.32	1.27	252.2	149.0
6 times compacted	13.37	1.20	176.4	217.2
$LSD_{0.05}$[a] (comp.)	ns[b]	ns	ns	ns
2004				
Control	10.02	1.36	189.5	107.7
1 time compacted	11.33	1.36	188.3	130.5
3 times compacted	13.25	1.58	220.8	125.2
6 times compacted	13.88	1.48	203.7	178.9
$LSD_{0.05}$ (comp.)	1.04	0.14	35.9	3.1
$LSD_{0.05}$ (year)	0.81	0.15	16.2	27.0

[a] Least significant difference at $p<0.05$
[b] No significant differences between variants

Table 1. Changes in soil organic carbon (C_{org}), total nitrogen (N_{tot}), available phosphorus (P) and potassium (K) content due to soil compaction and experiment year of upper soil layer (0–0.3 m) in earing phase of spring barley (*Hordeum vulgare* L.)

Compaction by a 4.9 Mg tractor with tire inflation pressure 150 kPa increased soil bulk density and penetration resistance in the first and second year. However, no hardpan was formed in subsoil, likely due to deep-freezing (up to 0.5 m) in those years and because of the moderate tractor weight. However, after the third year of continuous direct compaction, a hardpan formed below the plough layer even after one tractor pass. The soils of the experiment area have a medium fine texture. They are moderately susceptible to soil compaction when moist but not particularly vulnerable when dry. The recommended maximum tire inflation pressure for medium fine textured soils is 120 to 160 kPa (van den Akker, 2002). Significant compaction has commonly been observed to a depth of about 30 cm at an axle load of 4 Mg. The natural processes of freezing/thawing, wetting/drying and bioactivity alleviate topsoil compaction. In Sweden, one pass by a 5.4 Mg tractor brought resulted in little compaction, but repeated passes led to over-compaction. In the same time one pass by the wheel-loader (9.9 Mg) increased the degree of compaction almost as much as three passes by the tractor (Etana & Håkansson, 1996). When the plough layer is severely compacted, however, the recovery of heavy clay soils may take five years in spite of annual ploughing and frost heaving. In our experiment, the highest values of soil bulk density occurred in 2002 in all compaction treatments. In other experiment years, the highest values of soil bulk density were caused from low soil moisture content (110 g kg^{-1}) and the lowest soil bulk density values occurred in 2001 and 2004 when high soil moisture content (210 g kg^{-1}) was present at compaction application. In experiments of Pickering and Veneman (1984), soil dry density increased to the soil moisture content 0.11–0.12 kg kg^{-1} and started to decrease at higher moisture contents.

Changes in soil nutrient availability due to compaction were reflected in both reduced plant growth (see Tables 3 and 4) and changed soil physical parameters (Fig. 1 and 2). Soil compaction influences both physical properties and chemical and biological processes in the soil (Ferrero et al., 2002). Higher amounts of free P and K in six times compacted soils were directly correlated with reduced nutrient removal. As the nutrient acquisition by plants was reduced, there were higher amounts of free nutrients in the soil. Phosphorus and K ions are more sensitive to soil compaction than N ions. In a rainy year the nutrients, especially P, were leached to deeper soil layers. Phosphorus is more mobile than K. The less mobile K tended to concentrate near the soil surface. A compacted soil layer, because of its high strength and low porosity, confines the crop roots to the top layer and reduces the volume of soil that can be explored by the plants for nutrients and water (Lipiec et al., 2003). There is also an interaction between compaction and soil water content. Carbon mineralization increases with increasing water content in loose soil but decreases in compact soil (Ball et al., 2000) and may increase the total amount of nutrients in soil. There is an increased the amount of total N in the compacted soil, as total N content in soil is connected with organic C content. Also Lipiec and Stepniewski (1995) found reduced N mineralization in compacted soil and Motavalli et al. (2003) reported N recovery efficiency from 290 to 140 g kg^{-1} by compaction of the soil. However, De Neve and Hofman (2000) concluded that rates of N and C mineralization may or may not be affected by compacted conditions.

3.2 Compaction effect on plant growth

Twenty-eight weed species were identified from the experimental area during four years of the experiment. In the 2001, 24 weed species were described, mostly annual weeds. The amount of perennial weed species increased from 3 species in the first year to 7 species in fourth year due to repeatedly growing barley in monoculture without herbicides and fertilizers. Only 13 weed species emerged on six-times passed soil in 2004. The most widespread weed species were common lambsquarter, field pennycress, common fumitory and common chickweed. After four years without fertilizer use, the dominating annual weed species were field pennycress and common chickweed (Table 2).

Though the changes in soil bulk density (Fig. 1) and penetration resistance (Fig. 2) due to compaction were exiguous in 2001, there was still a decrease of plant shoot dry weight and number of plants (Table 3, 4,). Significant barley dry weight decrease was observed following the six passes treatment and also on barley plants density following the one and six pass treatments, respectively (Table 3, 2001). Compaction had higher effect on annual weeds than perennial weeds. In 2001 weeds formed 6.5% from the total plant shoot dry weight and 23.4% from plants density in non-compacted and 2.8% and 17.2% in six times passed soil, respectively. Compaction decreased common lambsquarters dry weight, but did not affect density (Table 4). Common lambsquarters weed mass was 15.3% to 32.5% of the total weed mass and comprised 25.3% to 44.4% of the weed density, depending on compaction treatment. The most sensitive weed to the soil compaction was common fumitory; its mass decreased 53%–86% and density 20%–76%, depending on compaction level. Compaction affected also other investigated weed species, but the differences were not biologically significant.

In 2002, compaction increased weed shoot mass from 12% in the control up to 52% in the six times pass treatment and decreased significantly barley yield (Table 3). Changes in perennial weed density and weight were not statistically significant. In 2002, one, three and six pass treatments had positive effect on annual weed shoot dry weight. This was mainly caused by changes in weight and density of common lambsquarters, which comprised more than 50% of the weed community (Table 4).

Weed species Common name	Scientific name	2001				2004			
		Number of passes[a]							
		0	1	3	6	0	1	3	6
Annual weeds									
Common lambsquarters	*Chenopodium album* L.	+[b]	+	+	+	+	+	+	+
Field pennycress	*Thlaspi arvense* L.	+	+	+	+	+	+	+	+
Corn bindweed	*Polygonum convolvulus* L.	+	+	+		+		+	+
Hairy tare (vetch)	*Vicia villosa* Roth.	+	+	+	+	+	+	+	+
Common chickweed	*Stellaria media* (L.) Vill.	+	+	+	+	+	+	+	+
Wall speedwell	*Veronica arvensis* L.	+	+	+	+	+	+	+	+
Field pansy	*Viola arvensis* Murr.	+	+	+	+	+	+	+	+
Red dead nettle	*Lamium purpureum* L.	+	+	+	+	+	+	+	+
Common hemp nettle	*Galeopsis tetrahit* L.		+						
Common fumitory	*Fumaria officinalis* L.	+	+	+	+		+	+	
Corn bugloss	*Lycopsis arvensis* L.	+	+		+		+		
Cleavers	*Galium aparine* L.	+	+	+	+	+	+		
Shepherds-purse	*Capsella bursa-pastoris* (L.) Med.	+	+	+	+	+	+		+
Corn spurry	*Spergula arvensis* L. (coll.)	+				+	+		+
Common scorpion grass	*Myosotis arvensis* (L.) Hill	+	+						
Wild mustard	*Sinapis arvensis* L.	+	+	+	+	+		+	+
Corn mayweed	*Matricaria inodora* L.	+	+				+		
Storks-bill	*Erodium cicutarium* (L.) L´Her.	+			+				
Sun spurge	*Euphorbia helioscopia* L.							+	
Peachwort	*Polygonum persicaria* L.	+							
Perennial weeds									
Canadian thistle	*Cirsium arvense* (L.) Scop.					+	+	+	
Coltsfoot	*Tussilago farfara* L.					+		+	
Perennial sowthistle	*Sonchus arvensis* L.				+		+	+	
Corn mint	*Mentha arvensis* L.					+			
Mugwort	*Artemisia vulgaris* L.	+	+	+	+	+	+	+	+
Great (broadleaf) plantain	*Plantago major* L.		+			+	+	+	+
Field horsetail	*Equisetum arvense* L.		+						
Knotgrass	*Polygonum aviculare* L.					+			

[a] 0 – control plot without special compaction; 1, 3, 6 number of special passes
[b] Presence (+) or absence of weeds

Table 2. Presence of weed species depending on soil compaction and year in earing phase of spring barley (*Hordeum vulgare* L.) in the first (2001) and last (2004) year of the experiment

Treatment	Dry weight (g m^{-2})				$LSD_{0.05}$[a]	Density (plants m^{-2})				$LSD_{0.05}$
	0[b]	1	3	6	(comp.)	0	1	3	6	(comp.)
2001										
Spring barley	797	632	758	551	190	883	778	859	738	104
Annual weeds	54	31	21	15	18	245	236	187	146	86
Perennial weeds	1.4	1.2	1.2	1.0	ns[c]	24	14	13	7	ns
Total biomass	855	674	780	567	215	1151	1028	1059	890	169
2002										
Spring barley	302	262	169	61	78	450	228	266	137	132
Annual weeds	33	39	58	60	22.6	213	148	182	80	73
Perennial weeds	8.3	16	2.2	5.5	ns	6	32	5	7	19
Total biomass	344	317	230	126	68	669	408	453	224	119
2003										
Spring barley	186	167	169	91	21	550	466	463	475	58
Annual weeds	21	17	27	9	7.2	462	350	344	181	107
Perennial weeds	0.3	1.2	2.6	0.8	1.7	15	34	19	19	15
Total biomass	208	185	199	101	19	1028	850	825	791	100
2004										
Spring barley	151	164	132	92	18	573	496	429	462	97
Annual weeds	9	11	12	19	2.4	264	264	210	464	101
Perennial weeds	19	4.5	15	15	ns	88	38	74	22	22
Total biomass	180	179	159	125	20	920	781	669	1043	179
$LSD_{0.05}$ (year)										
Spring barley	161	124	143	55		134	99	112	100	
Annual weeds	44.2	20.2	34.1	24.0		120	72	59	112	
Perennial weeds	8.6	16.5	3.7	6.5		24	19	18	7	
Total biomass	196	134	144	53		175	165	134	184	

[a] Least significant difference at $p<0.05$
[b] Number of passes
[c] No significant differences between treatments

Table 3. Soil compaction effect on spring barley (*Hordeum vulgare* L.) and weed dry mass and density in community in earing phase of spring barley during experiment

Common fumitory did not emerge following the six pass compaction treatment. However, compaction had no strongly positive or negative effect on pennycress and chickweed.

After three years of soil compaction without fertilizer use, the total shoot dry weight and barley yield was only ¼ from first year shoot dry mass on non-compacted soil (Table 3). Changes in barley shoot dry weight were similar to earlier years, one and three pass treatments decreased barley density; however, six passes increased it. Weeds formed 9.7% to 14.9% from total shoot mass, depending on treatment and year. There was significant increase of perennial plant dry weight and density, mostly great plantain, which composition increased from 0.5% on non-compacted soil to 12.2% on six pass compacted soil in the weed community (Table 4). Again, the dominating weed species was common chickweed, with a shoot mass of 43.2% in the control and 17.6%, 36.1% and 38.8% in one, three and six pass compacted treatments, respectively. Field pennycress increased in dry weight with compaction. Again, common fumitory was not found following the six pass treated soil in the earing phase of barley.

Treatment	Dry weight (g m⁻²)				LSD0.05[a]	Density (plants m⁻²)				LSD0.05
	0[b]	1	3	6	(comp.)	0	1	3	6	(comp.)
2001										
Chenopodium album L.	8.5	9.8	7.2	5.2	2.1	68	88	71	68	ns[c]
Fumaria officinalis L.	5.8	0.8	2.7	1.4	4.7	25	12	20	6	14
Lamium purpureum L.	2.6	5.5	1.0	0.6	ns	23	10	9	14	9
Thlaspi arvense L.	2.0	1.4	0.3	0.8	ns	16	18	8	14	ns
Stellaria media (L.) Vill.	4.8	4.3	1.5	1.7	ns	43	63	35	24	ns
Plantago major L.	0	0.1	0	0	ns	0	3	0	0	ns
Weeds total	58	42	22	16	19	285	250	200	153	ns
2002										
Chenopodium album L.	21.8	30.6	32.7	36.0	8.4	91	95	68	36	25
Fumaria officinalis L.	1.0	1.0	1.1	0.1	ns	14	8	6	1	7
Lamium purpureum L.	0.5	0.6	0.7	0	ns	9	6	4	0	6
Thlaspi arvense L.	0.7	0.2	1.9	1.5	ns	11	4	7	8	ns
Stellaria media (L.) Vill.	1.0	0.3	5.8	1.7	ns	26	3	19	10	16
Plantago major L.	1.6	0	0.2	1.8	ns	4	0	1	2	ns
Weeds total	42	55	61	65	21.3	219	180	187	87	73
2003										
Chenopodium album L.	1.8	3.3	3.7	1.2	0.7	91	97	109	56	20
Fumaria officinalis L.	0.3	0	0.2	0	0.1	16	0	13	0	5
Lamium purpureum L.	2.4	3.3	1.6	0.1	0.3	66	66	31	3	7
Thlaspi arvense L.	0.6	1.7	0.6	1.1	ns	22	38	9	19	ns
Stellaria media (L.) Vill.	9.2	3.2	10.7	3.8	5.8	109	50	63	41	45
Plantago major L.	0.1	2.4	0.2	1.2	0.1	3	3	6	13	7
Weeds total	22	18	30	10	5	477	384	363	200	95
2004										
Chenopodium album L.	0.4	0.3	0.6	0.4	0.2	25	21	17	33	3
Fumaria officinalis L.	0	0.8	0.3	0	0.3	0	22	9	0	9
Lamium purpureum L.	0.1	0.2	0.1	0.2	0.08	4	20	14	24	5
Thlaspi arvense L.	3.0	2.4	5.1	3.1	1.7	66	34	40	48	11
Stellaria media (L.) Vill.	1.0	1.4	0.8	3.7	1.4	50	25	30	150	86
Plantago major L.	0.02	0.3	0.6	25.2	0.4	1	2	3	6	1
Weeds total	28	16	27	33	4	342	302	284	486	97
$LSD_{0.05}$ (year)										
Chenopodium album L.	9.8	11.4	20.4	18.5		25	31	19	28	
Fumaria officinalis L.	4.3	ns	2.4	1.3		14	11	ns	2	
Lamium purpureum L.	1.8	ns	ns	0.3		7	8	11	11	
Thlaspi arvense L.	ns	ns	2.3	1.7		10	15	12	20	
Stellaria media (L.) Vill.	ns	3.2	6.9	ns		ns	38	ns	81	
Plantago major L.	ns	0.1	0.1	0.6		ns	ns	5	2	
Weeds total	24.7	17.2	32.1	22.3		128	81	69	102	

[a] Least significant difference at $p<0.05$
[b] Number of passes
[c] No significant differences between treatments

Table 4. Soil compaction effects on the most abundant six weed species dry mass and density in weed community in earing phase of spring barley (*Hordeum vulgare* L.) during experiment

In 2004, due to persistent rain and lower penetration resistance (Fig. 2), the impact of soil compaction on barley dry weight and density was lower than in previous two years (Table 3). The lowest barley weed dry weight and density were recorded following one time passed soil, where their share from total shoot dry weight was 8.6% and from total plant density 37.9%. Following six times passed soil weeds formed 27% total shoot dry weight and 51.2% total plant density. Perennial weed dry weight was 29% to 67% of total, depending on treatment. Also in 2004, annual weed mass increased with increasing soil bulk density; however, this was likely due to higher plant density on compacted soil and not likely due to higher plant shoot mass like in 2002 (Table 4). Compaction had significant effect on all investigated weed species dry weight and density. In six pass treated soil the most widespread weed species was great plantain by comprising 74.1% of the weed community. No common fumitory plants were detected on non-compacted and six times compacted soil in earing phase of barley after four years. Year had less impact on field pennycress shoot mass and common chickweed shoot mass and density (Table 4). Again, the most affected weed species were common lambsquarters and common fumitory.

The visible result of soil compaction on plant growth is plants height reduction. Compaction had more effect on barley stalks length than weed density (Fig. 4). One compaction pass reduced barley height by 0.02 to 0.04 m, three passes 0.03 to 0.06 m and six passes 0.08 to 0.2 m depending on experiment year. In the same level of vegetation mixture with barley we observed wild mustard, corn bindweed and common lambsquarters plants. Most of the observed weed species were shorter than barley, except in 2002, when weeds over-topped barley. Compaction also reduced average weed height, but increased the differences of plant height for only common lambsquarter. Although compaction affected common fumitory mass and density, there was no impact on common fumitory height.

As compaction changes soil properties, the direct effect will be on plant root growth. Our results showed that moderate compaction (one and three compaction passes) might increase root mass in the upper part of soil compare to non-compacted soil (Fig. 5). In the draughty year 2002, the highest root mass in the top 45 cm depth was detected in three times compacted soil, two times higher than in non-compacted soil. One time and six times compaction decreased root mass by 37% and 13%, respectively, especially in deeper soil layers. In 2003, one compaction pass increased root mass in the upper 15 cm soil layer by 50 g m^{-2}, but decreased in deeper layers to 54%. Following three and six compaction passes total root mass decreased 66% and 80% respectively. In 2004, compaction decreased root mass relative to the increase of soil bulk density. Still the highest root mass was detected in three and six pass compacted soil in 15–30 cm depth likely due to high composition of perennial weed roots. In the very rainy year 2004, total root mass was four times higher than in the droughty year 2002, and two times higher than in year 2003.

Changes of dominant weed species in plant community during the four year experiment were likely caused by changes in soil conditions: decrease of available nutrients in soil, higher soil penetration resistance and soil bulk density. Low availability of major nutrients such as N, P and K play an essential role in maintaining species richness in weed communities. Like cultivated plants, weeds have different advantages depending on environmental parameters. In this experiment, decrease of common lambsquarters dry weight was due to nutrient availability and high soil resistance to root growth, conditions where it thrived compared to other species. Common lambsquarters has been shown to grow well in a wide range of climates and soils, especially those with high organic matter content (Mitch, 1988). It possesses a prolific rooting system, which allows it to resist adverse environmental conditions, such as soil compaction. Common lambsquarters emergence rate has been reported to increase with temperature and decreases with increasing soil penetration resistance and depth (Vleeshouwers, 1997).

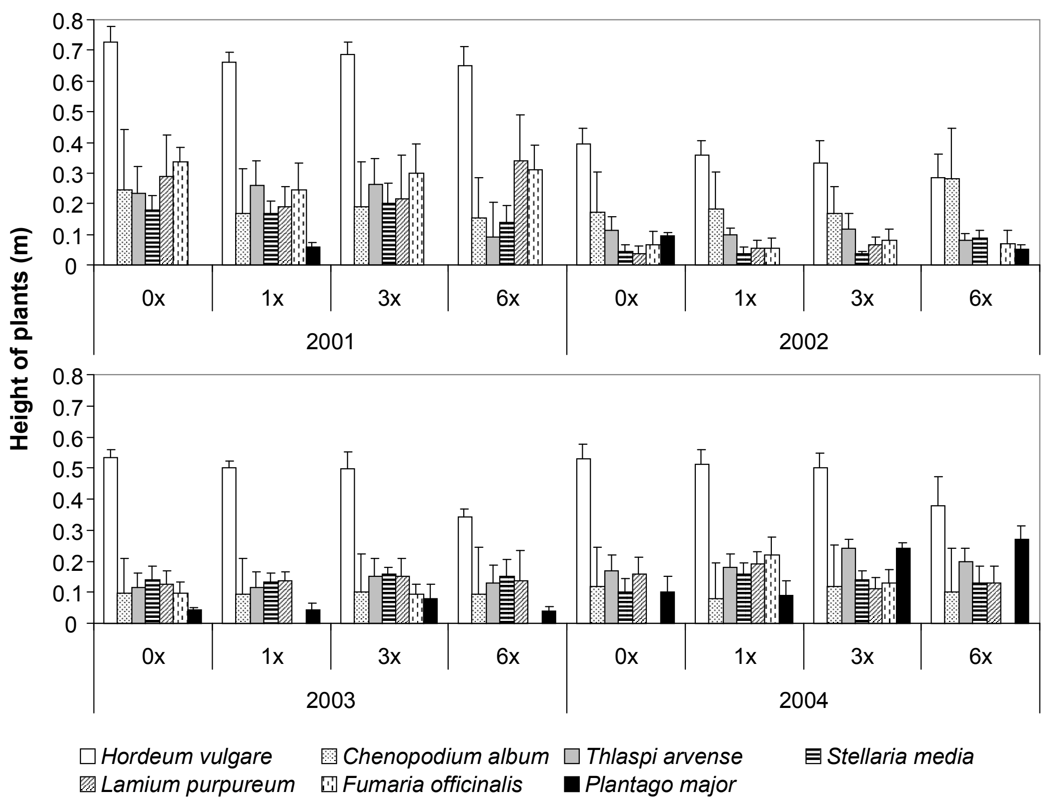

Fig. 4. Effect of soil compaction on the height of the most common seven weeds observed in earing phase of spring barley (*Hordeum vulgare* L.) in years 2001—2004; 0 – non-compacted control, 1, 3, 6 – number of passes; bars indicates the standard deviation

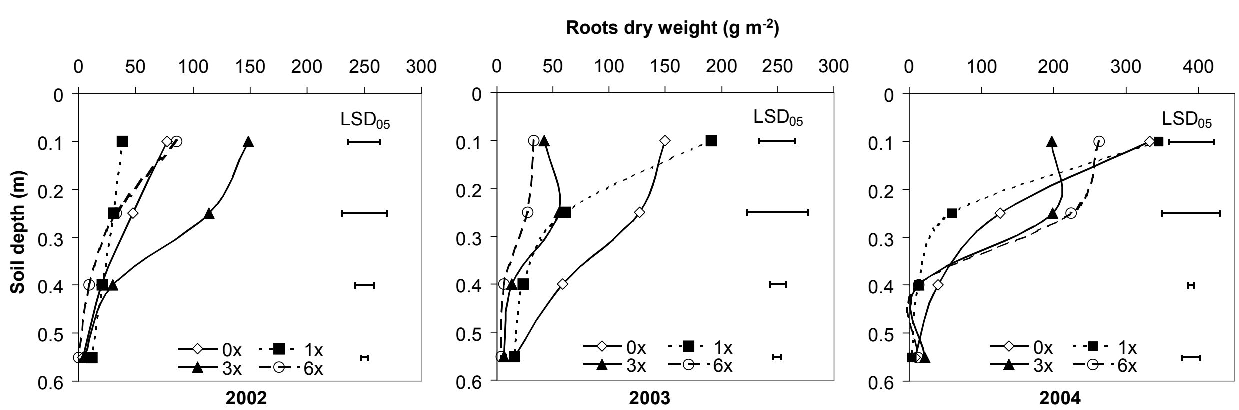

Fig. 5. Effect of soil compaction on plant roots (barley and weeds) dry weight in earing phase of spring barley (*Hordeum vulgare* L.) in years 2002, 2003 and 2004; 0 – non-compacted control, 1, 3, 6 – number of passes; $LSD_{0.05}$ – least significant differences at significance at $p<0.05$; ns – differences are not significant

Common fumitory favours well-drained soil. The plant is suited to sandy and medium loamy acid, neutral and alkaline soils (Mitch, 1997). In this respect, common fumitory has only limited ability to compete with other weeds and suffers strongly from intraspecific competition. We observed some common fumitory in tillering phase of barley, but they did not survive in competition with other weeds on compacted soil until the earing phase of barley. Field pennycress also thrives on fertile soils but the plant can also tolerate dense soils. If the intensity of tilling is reduced, the field pennycress composition density in weed community increases (Stevenson et al., 1998).

Great plantain and corn mayweed are commonly observed on edges of field and waysides, while corn spurry is observed on soils with low fertility (Trivedi & Tripathi, 1982). Great plantain is characteristic of relatively fertile, disturbed habitats and where its root system is restricted by compaction (Whitfield et al., 1996). Few great plantain plants were observed in the weed community at the beginning of this experiment but were likely out competed by other weed species. Following, compaction, soil strength inhibited establishment of most of other existing weed species and great plantain started to dominate in weed flora (Photo 1). Species which increase in abundance under changed soil properties or low nutrient conditions (Liebman, 1989) may do so due to their intolerance of earlier conditions or high nutrient levels, or they may be suppressed by other species which respond better.

Common chickweed is a cosmopolitan species, common in cereal and broad-leaved cultivated crops (Lutman et al., 2000). Walter et al. (2002) found that chickweed was positively cross-correlated with clay and negatively cross-correlated with pH and potassium content. In our experiment common chickweed tolerated moderately compacted soil more than severely compacted soil in most years of our investigation.

A B

Photo 1. Differences in great plantain (*Plantago major* L.) abundance on compacted and non-compacted soil after two years of continuous compaction (A) and great plantain on field edge likely indicating compaction problems (B)

Heterogeneous occurrence of some weed species, such common hemp nettle, common scorpion grass, storks-bill, spun spurge and peachwort, was caused by their heterogeneous seed distribution in the experimental area soil (Table 2). Increase of perennial weed species after four years was the result of herbicides free management and reduced tillage intensity (no additional tillage or cultivation operations, except ploughing, were made to control weeds). Without herbicides use also weed density increased in all compaction treatments (Table 3). While specific soil conditions have been associated with weed infestations, it should also be recognized that these same soil conditions may reduce the vigour of the crop, making the crop less competitive with weeds. Therefore, the weeds associated with a specific soil condition may be a secondary effect related to crop vigour rather than a weed response to soil conditions (Buhler, 2003). However, the soil physical properties and the position of weed seeds within the soil matrix play an important role in seedling emergence and seed survival. Grundy et al. (2003) found that the weed species with smaller seeds, such corn mayweed and wall speedwell showed a sharp decline in emergence when burial depth exceeded 1 cm, but some species (common chickweed and common lambsquarter) have the physical reserves to emerge from a wider range of burial depths and soil densities than normally observed in the field, suggesting an ability to exploit opportunities when they occur.

3.3 Compaction effect on plant nutrition

Most of the observed weed species had higher nitrogen content in their shoots than barley, especially common chickweed and common lambsquarters (Fig. 6). Nitrogen content in common chickweed and common lambsquarters dry matter reached 27 g kg^{-1}. Only in 2001, barley had higher nitrogen content than common lambsquarters, common fumitory and field pennycress and lower nitrogen content than common chickweed. In droughty 2002, the nitrogen content in weeds was more than 2 times higher than in barley. Also in 2003 and 2004, barley contained the lowest nitrogen content. Plant root (barley and weeds) nitrogen content was similar to barley in 2002 and 2003, while barley had the most roots mass. In 2004, the nitrogen content was higher in barley roots than in observed weed species. The lowest nitrogen contents during experiment were measured in 2004. Compaction did not cause any significant changes in plant nitrogen content after first year of soil compaction (Fig. 6). There was some decrease due to one and six pass compaction in case of barley, common chickweed and common lambsquarters. In 2002 and 2003, soil compaction decreased nitrogen content in most investigated weed species while three the pass compaction and six pass compaction treatments increased nitrogen content again, except in case of common chickweed (Fig. 6, 2002 and 2003). Nitrogen content in barley dry matter increased with increasing of soil bulk density. In 2004, compaction had only negative effect on plant nitrogen content regardless of compaction intensity (Fig. 6). Nitrogen decrease was detected regardless of species. Changes in root nitrogen content due to the compaction were similar to aboveground plant parts in 2002 and 2003. In 2004 increasing amount of perennial weed roots in compacted soil also increased the root nitrogen content.

Phosphorus content in plant dry matter was highest in common chickweed (3 to 4.5 g kg^{-1}) in all years (Fig. 7). Lowest phosphorus content was detected in barley in all years (1.0 to 1.7 g kg^{-1}). Changes in phosphorus content in plants due to compaction were similar to nitrogen changes in 2001. In 2002, soil compaction in most cases decreased phosphorus content. Increase of phosphorus content due to the six pass compaction treatment was observed only for common fumitory in 2002. Compaction had the highest negative effect on common lambsquarters and barley phosphorus content. In 2004, one pass compaction increased while three and six times compaction decreased phosphorus content in barley, common lambsquarters and common chickweed. Compaction had no significant impact on roots phosphorus content. However, the six pass compaction treatment increased roots phosphorus content in all years.

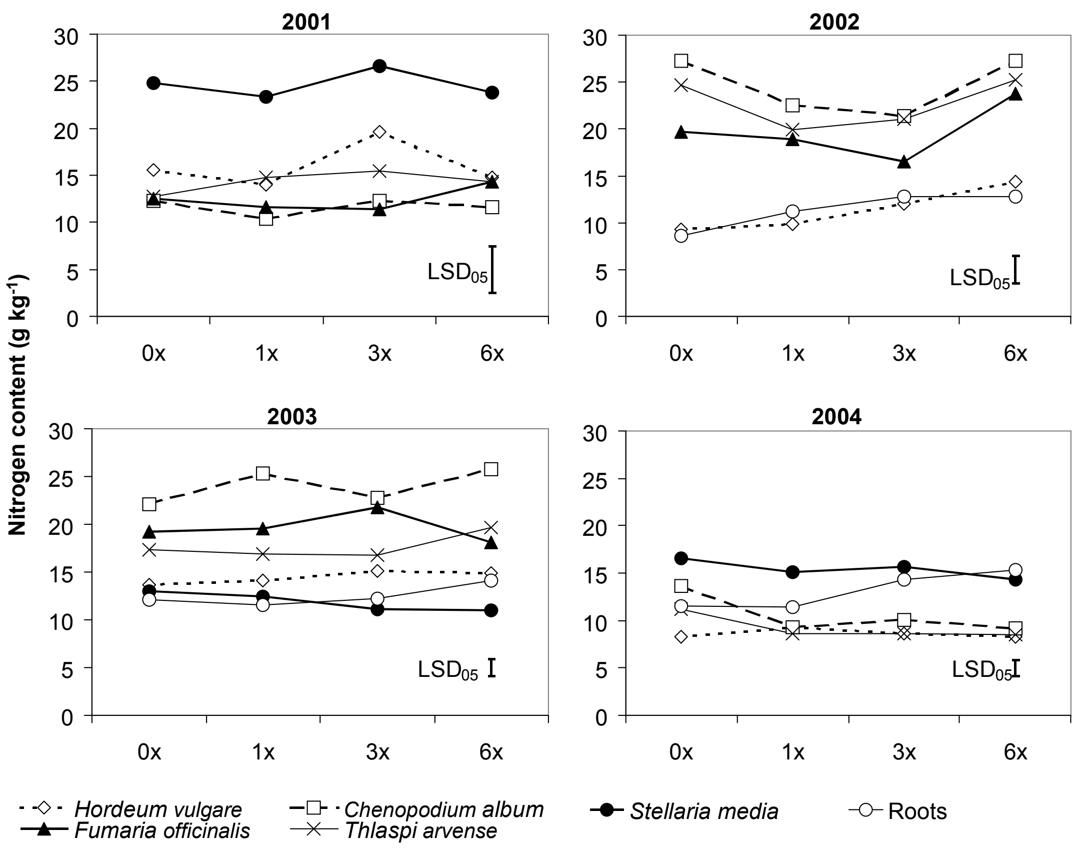

Fig. 6. Effect of soil compaction on plants and roots nitrogen content in earing phase of spring barley (*Hordeum vulgare* L.) in years 2001—2004; 0 – non-compacted control, 1, 3, 6 – number of passes; $LSD_{0.05}$ – least significant differences at significance at $p<0.05$

The weeds highest in potassium were common chickweed and common lambsquarters in all years of experiment (Fig. 8). The potassium content in common chickweed ranged from 55 g kg^{-1} to 80 g kg^{-1} and in common lambs quarters from 25 to 62 g kg^{-1}, depending on soil compaction and year. Stabile low potassium content was observed in barley and field pennycress dry matter with 12 to 20 g kg^{-1} and in roots with 5 to 12 g kg^{-1}, depending on compaction and year. No positive correlation between nutrient content and soil compaction was observed in case of potassium in plants aboveground parts. Compaction inhibited potassium uptake of all investigated species and the differences between compaction treatments were significant in 2001. The six pass compaction treatment caused highest decrease on common fumitory by 50%, on common lambsquarters and common chickweed by 21% in 2003, and on common lambsquarters and common chickweed by 33% and 35%, respectively, in 2004. Significant increase of roots potassium content was observed in 2003 due to the six pass compaction treatment and in 2004 due to one, three and six pass compaction treatments.

Similar to this experiment, our earlier investigations (Reintam & Kuht, 2004) and investigations of other researchers (Salonen, 1992) reported higher nutrient content in weeds compared to barley. The lower nitrogen need of many weed species can give them advantage in competition with cereals (Di Tomaso, 1995) and thus they have a greater ability to compete with barley for nutrients, water and light. Because weeds are more efficient in nutrient uptake, in particular nitrogen, the nitrogen content of a crop decreases with increasing competition with weeds. However, some researchers suggest that competition between weeds and crops is lower on nutrient rich than on nutrient-poor soils (Pyšek et al., 2005) and competition is most intense in plots with lowest resource levels (Wilson & Tilman, 1993). In our experiment, weeds were more able to compete with barley under moderate compaction conditions (3 pass treatment), where in many cases nutrient content in weeds increased, especially in common lambsquarters and common chickweed.

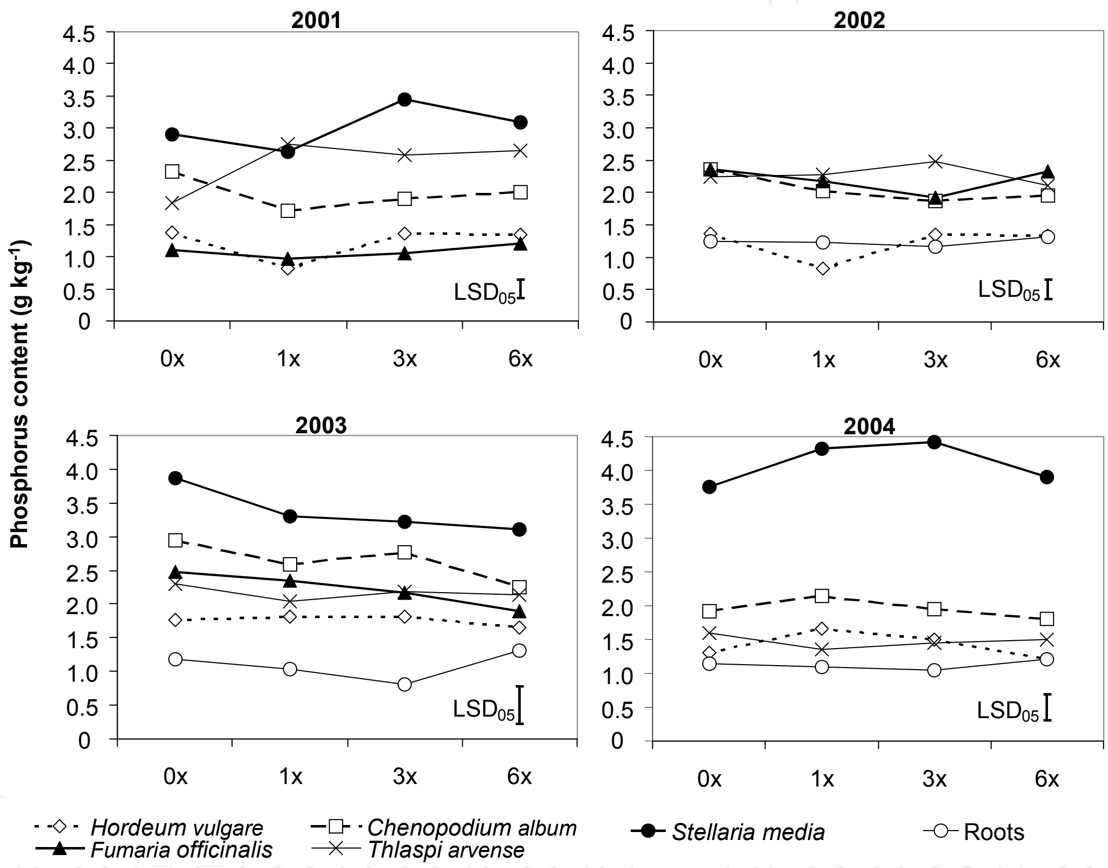

Fig. 7. Effect of soil compaction on plants and roots phosphorus content in earing phase of spring barley (*Hordeum vulgare* L.) in years 2001 – 2004; 0 – non-compacted control, 1, 3, 6 – number of passes; $LSD_{0.05}$ – least significant differences at significance at $p<0.05$

Also Bockholt and Schnittke (1996) observed the high nutrient, especially potassium assimilation of young chickweed plants. Common lambsquarters was especially rich in nitrogen, but also potassium. Common lambsquarters is reported as the highest competitor for the nutrients to cultivated plants because of its high mass and nutrient content (Parylak, 1996) and high ability to compete with cultivated plants. Common lambsquarters taproot makes it more competiveness on dense soil compared to the barley, which have fibrous roots. Thicker roots are better able to penetrate the compacted soil compared to thinner roots (Whitely & Dexter, 1984) and compaction influences less dicotyledonous than monocotyledonous plants (Materachera et al., 1991).

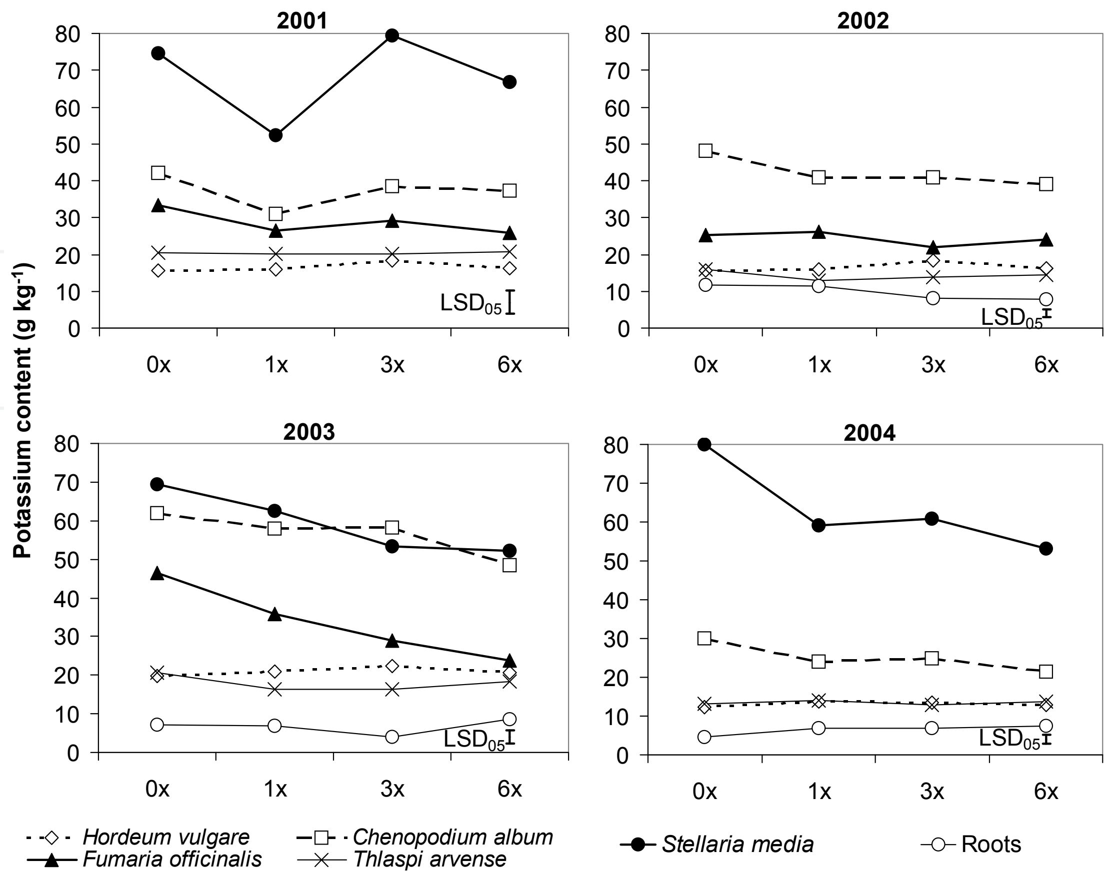

Fig. 8. Effect of soil compaction on plants and roots potassium content in earing phase of spring barley (*Hordeum vulgare* L.) in years 2001–2004; 0 – non-compacted control, 1, 3, 6 – number of passes; $LSD_{0.05}$ – least significant differences at significance at $p<0.05$; ns – differences are not significant

The increased nitrogen content in barley and weed species dry matter with increasing soil bulk density was likely due to better competitive conditions available to the survived plants on the most compacted soil. Plant density was there 1.3 to 3-times lower than on non-compacted soil and nutrient area per one plant was higher. In unsuitable conditions, barley tillering is higher and in dry year new sprouts may grow after adequate rainfall. In 2002, barley grew new sprouts in middle of the summer, and young plant tissues are always richer in nutrients than older. In the better competitive conditions plants are also producing more leaves than under lover radiation and less competitive conditions, and leaves usually containing more nitrogen than in stems. Planting density and ontogenetic processes significantly influence dry matter partitioning between leaves and stems (Röhrig & Stützel, 2001; Causin, 2004). With increasing competition (on non-compacted soil) common lambsquarters, field pennycress and common fumitory allocated relatively more biomass to stems than to leaves. In addition, higher soil moisture content over time is observed in compacted soil in dry seasons compared to less compacted soil. In moist soil, there are more plant available nitrates than in dry soil. In a dry year, due to compacted soil, uptake of elements such as nitrogen, calcium and magnesium, which are moving into the plant with water, might increase. Decrease of nitrogen content in plant dry matter in wet years, especially in 2001 and 2004, was probably connected next to poorer root development also with increased denitrification and decreased mineralization of organic matter in highly compacted soil due to decreased soil aeration. N_2O flux increases with decreasing distance from straw residues and air permeability, and with increasing cone resistance and wet bulk density (Ball et al., 2000).

No increase of phosphorus and potassium content in plants (barley and weeds) due to increasing soil bulk density and penetration resistance were detected during this experiment (Fig. 7 and 8). Due to compacted soil, the plants are in stress and in the stressed conditions (increased cellular pH) plants nutrient acquisition through proton pumping via the H^+-ATPase and transporters from roots to the stems and leaves is reduced (Bucher et al., 2001; Reintam & Kuht, 2003) and results in increased nutrients uptake by roots. These processes likely explain the increase of nutrients in the roots due to the compaction. Liepiec and Stepniewski (1995) found that root growth greatly affects uptake of nutrients transported by diffusion, such as phosphorus.

4. Conclusion

Soil over-compaction inhibits the nutrition of cultivated plants and decreases their ability to compete with weeds. Changing the field conditions also changes the weed composition with which cultivated plants will compete. In compacted soils without fertilizer use, relatively easily controlled weed species will likely be replaced with harder to control weed species due to selection for competitive species. Weeds are serious competitors in agricultural systems; they accumulated free nutrients from soil, especially in dense soil, at the detriment to less competitive cultivated crops. At the same time the nutrient assimilation by weeds may stop their leaching from soil and store the nutrients in organic matter also for the next growing period. However, in severely compacted soil even weeds are not able to flourish and free nutrients may start to pollute the environment. Both, changes in weed community composition and nutrient assimilation deserves further investigations to understand better plant–soil and plant–plant interactions of other cultivated plants and soils under stress conditions, such is soil compaction.

5. Acknowledgment

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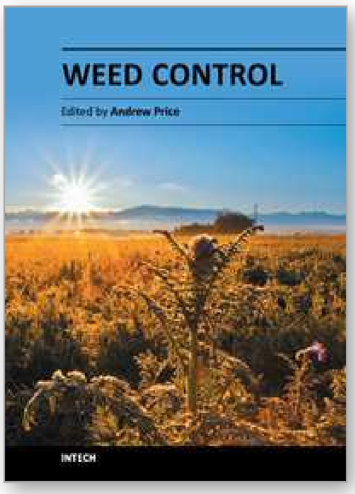

Weed Control
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Crop loss due to weeds has challenged agricultural managers since man began to develop the first farming systems. In the past century, however, much progress has been made to reduce weed interference in crop settings through effective yet mostly non-sustainable weed control strategies. With the commercial introduction of herbicides during the mid-1900's, advancements in chemical weed control tactics have provided efficient suppression of a broad range of weed species for most agricultural practices. Currently, with the necessity to design effective sustainable weed management systems, research has been pushing new frontiers on investigating integrated weed management options including chemical, mechanical as well as cultural practices. Author contributions to Weed Science present significant topics of research that examine a number of options that can be utilized to develop successful and sustainable weed management systems for many areas of crop production