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Original Research

The Influence of Soil Compaction on Chemical Properties of Mollic Fluvisol Soil under Lucerne (*Medicago sativa* L.)

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Abstract

The purpose of this study was to determine the effects of soil compaction on the chemical properties of soil and herbage yield of lucerne (*Medicago sativa* L.). A field experiment was conducted on a silty loam Mollic Fluvisols soil in 2003-07. Four compaction treatments were applied three times annually by tractor using the following number of passes: control without experimental traffic, two passes, four passes, and six passes. This study confirmed the unfavorable effect of multiple tractor passes on lucerne dry matter production. The results showed that tractor traffic reduced the yields of lucerne, particularly during the second and third harvests in each year. Soil compaction caused by tractors changed some chemical properties of soil. Tractor passes resulted in increasing pH and EC. It also increased P and Zn content. Most of these changes were statistically significant only in the deeper 20-30 cm soil layer. This effect could be ascribed to higher soil density and lower air permeability. The upper (0-20 cm) soil layer was resistant to changes in chemical properties, probably due to the dense root system that recovers the soil after compaction and improves physical properties. The decrease in lucerne production probably was the result of mechanical damages to roots and above-ground parts of plants rather than problems in nutrient uptake. We can conclude that chemical properties, particularly N content, are not significantly important factors in reduction of lucerne production exposed to tractor traffic.

Keywords: lucerne, Mollic Fluvisols, tractor wheeling, soil compaction, chemical properties

Introduction

Modern production systems in agriculture tend to increase the number of passes and the loads carried on agricultural vehicles, resulting in a compaction hazard. Soil compaction problems have recently increased in forage crops as a result of frequent and usually heavy vehicle traffic. Many researchers agree that the yields of most forage plants are affected adversely by tractor traffic. It is a serious problem for perennial crops, particularly perennial forage grasses, where the soil is wheeled without ever being loosened [1, 2]. The tractor passes result in unfavorable changes of soil properties. Soil compaction leads to soil structure degradation, which is strongly associated with changes in physical properties of soil like porosity, bulk density, and penetration resistance [3]. The degraded soil physical environment due to compaction influences not only shoots, but also root growth and development. Soil compaction increases mechanical impendence, creates unfavorable growing conditions for roots, and restricts oxygen, water, and nutrient supply [4, 5]. Changes in physical properties also resulted in biological activity of compacted soil [6-10].

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Table 1. Monthly rainfall and average daily temperature at the experimental site during 2003-07 and long-term mean (1961-99).

Month	Sum of monthly precipitation (mm)						Monthly average temperature (ºC)					
	2003	2004	2005	2006	2007	1961-99	2003	2004	2005	2006	2007	1691-99
January	30	36	66	58	101	34	-3.7	-7.8	-1.2	-2.4	3.2	-3.3
February	12	57	33	49	42	32	-6.3	-0.3	-4.3	-3.0	1.2	-1.6
March	22	51	21	60	61	34	1.3	1.1	-0.2	0.2	6.0	2.4
April	44	32	49	57	15	48	5.0	7.3	6.8	5.6	8.5	7.9
May	127	43	61	52	52	83	14.4	10.6	11.4	10.9	15.2	13.1
June	38	56	41	89	72	97	16.5	14.6	14.4	15.0	18.4	16.2
July	137	92	113	14	71	85	18.3	16.0	17.6	18.6	19.4	17.5
August	32	75	103	104	76	87	17.3	17.0	15.4	15.6	19.0	16.9
September	31	30	27	17	180	54	12.0	12.3	12.5	13.4	12.4	13.1
October	46	49	8	32	48	46	4.7	7.1	7.1	9.1	7.7	8.3
November	28	30	30	21	90	45	3.4	3.6	3.9	6.3	0.8	3.2
December	41	31	47	16	21	41	0.4	-1.3	-0.7	0.9	-1.1	-1.0

According to Marschener et al. [11], physical properties of soil affect the number and activity of microorganisms and their physiological diversity. Changes in biological activity resulted in processes catalyzed by microorganisms that can be reflected in chemical properties of soil and availability of nutrients [12-15]. It could be expected that reduced root system and decreased nutrient availability in compacted soils causes lower nutrient uptake by the growing crop and hence decreases shoot growth and crop yield [16]. Kristoffersen and Rile [17] confirmed this relationship for phosphorus uptake by barley.

Lucerne (*Medicago sativa* L.) is one of the forage species that can be used not only for grazing, hay, and silage production, but also for soil improvement and soil conservation. Inclusion of lucerne in a crop sequence has long been used to increase the yield and crude protein concentration of crops of subsequent crops [18]. There have also been found reduced incidence of diseases, weeds, and invertebrate pests, and increased organic matter content of the soil, better soil aggregation, and water infiltration in the soil [19]. On the other hand, lucerne is one of the most susceptible forage species to mechanical damage caused by machinery. The yield reduction is a result of mechanical damage to above-ground parts and changes in root morphology caused by soil compaction [1].

In this research our hypothesis was that soil compaction caused by tractor traffic results in changes to biological and chemical properties of the soil. The objectives of this study were:

(i) to evaluate the effect of multiple tractor passes on chemical properties of soil with special focus on basic nutrients

(ii) to evaluate the effect of compaction caused by tractor traffic on biological activity of soil. The investigation was carried out through a field experiment over a 5-year period.

Materials and Methods

This study was conducted as a field experiment located in Mydlniki near Kraków (latitude 50º04' N, longitude 19º51' E) at the Institute of Machinery Exploitation, Ergonomics and Production Processes, University of Agriculture in Kraków, Poland. The climate of the experimental site is temperate-continental. Data from the meteorological station at the site are presented in Table 1. The field experiment was located on silty loam Mollic Fluvisol [20]. Table 2 reports some soil characteristics.

The soil was ploughed and the seed bed was prepared by harrowing in 2002, after which lucerne seeds were sown at a rate of 15 kg·ha^{-1}. Fertilizer was applied every year (2003-07) for the first and second harvest at rates of 80 kg P_2O_5 ha^{-1} and 120 kg K_2O ha^{-1}. Experimental plots, each with an area of 9 m^2, were established in a randomized complete block design with four replicates. Four compaction treatments were applied by tractor using the following numbers of passes: control without experimental traffic (P0), two passes (P2), four passes (P4), and six passes (P6) completely covering the surface area of the plots. An URSUS C-360 tractor (Ursus Ltd., Warsaw, Poland) with a weight of 2,056 kg was used for traffic simulation. The inflation pressure of the front tyres (6.00-16) of the tractor was 150 kPa and that of the rear tyres (14.9-28) was 100 kPa. The multiple passes were applied after every harvest in a wheel-beside-wheel design, three times a year. The soil moisture content at the time of applying the compaction passes was approximately equal to the field water capacity (0.30 cm^3·cm^{-3} with a standard error of mean 0.03). The wheel-tracking treatments were designed to simulate potential combinations of field operations from cutting, tedding, lifting, and fertilizing.

Table 2. Soil characteristics of Mollic Fluvisol from the trial location (0-30 cm layer).

pH_{KCl}		6.5
Organic C	g·kg^{-1}	25.8
Total N	g·kg^{-1}	2.10
C:N ratio		12.3
P	mg·kg^{-1}	268
K	mg·kg^{-1}	298
Mg	mg·kg^{-1}	63
Solid particie density	g·cm^{-3}	2.56
Sand	g·kg^{-1}	290
Silt	g·kg^{-1}	670
Clay	g·kg^{-1}	40
Texture		Silty loam

Harvests were made three times a year and all harvests were made at the early-flowering stage. Harvest dates were: 20 June, 25 August, and 16 October in 2003; 3 June, 9 July, and 10 September in 2004; 6 June, 12 July, and 15 September in 2005; 5 June, 18 July and 12 September in 2006; and 24 May, 19 July, and 13 September in 2007. The lucerne was harvested with an Agria 3200 mower (Agria-Werke GmbH, Germany) with the blade set to a cutting height of 5 cm. The dry matter (DM) content of the yield was determined by drying a subsample of 500 g at 70ºC to a constant weight.

Soil samples for analyses were collected from three layers (0-10, 10-20, and 20-30 cm). In air-dried samples of soil material sifted through a sieve with 1 mm mesh assessed were: soil pH – by potentiometer in a soil and water suspension at soil to water ratio 1:2.5, soil electrolytic conductivity (EC) – by conductometer, organic carbon content – after sample wet mineralization in potassium dichromate (VI) using Tiurin's method, total nitrogen – after nitrate nitrogen reduction to ammonia using a mixture of metallic zinc and iron (9:1), and sample mineralization in concentrated sulphuric acid (VI) by means of Kjeldahl's method, the content of selected macro and microelements (P, K, Mg, Zn, Cu, Mn, and Fe) after extraction with a 0.01 mol·dm^{-3} $CaCl_2$ solution for 2 hours on a rotating mixer at the soil:solution ratio 1:10 [21]. The content of the analyzed elements in the obtained extracts were assessed using the ICP-AES method on a JY 238 Ultrace apparatus (Jobin Yvon, France). Soil reference material AgroMAT AG-2 (SCP Science) was attached to each analyzed series. Activity of soil dehydrogenases (DHA) was measured using Thalmann's methods [22]. Soil for enzymatic analyses was sampled from individual objects (P0, P2, P4, and P6) from the 0-5 cm layer, after 3rd cut harvesting. Activity of dehydrogenases was analyzed in the soil with natural moisture. The soil samples were incubated at 37ºC for 24 hours with 1% triphenyltetrazolium chloride (TTC) solution as a hydrogen-ion acceptor. The applied method bases on spectrophotometric measurement (at wavelength 546 nm) of the amount of triphenylformazan (TPF) formed as a result of triphenyltetrazolium chloride (TTC) reduction. The result of the measurement was converted according to prepared standard curve and expressed in mgTPF kg^{-1}·24h^{-1}.

Table 3. Dry-matter (DM) yields of lucerne for the four different wheel traffic treatments for three annual cuts. Different superscript letters within columns show significant differences among treatments (P<0.05, Duncan's Multiple Range Test).

Treatment	Yields (t DM·ha^{-1})				
	1st cut	2nd cut	3rd cut	Mean	Total
2003					
P0	3.31	2.99	3.12	3.14 a	9.42 a
P2	3.29	2.97	3.00	3.09 ab	9.25 ab
P4	3.33	3.15	3.09	3.19 a	9.57 a
P6	3.26	2.78	2.75	2.93 b	8.78 b
Mean	3.30 a	2.97 b	2.99 b		
2004					
P0	4.20	3.79	3.94	3.74 a	11.93 a
P2	4.24	3.28	4.05	3.62 a	11.57 a
P4	4.55	3.30	3.76	3.61 a	11.60 a
P6	4.23	3.06	3.18	3.25 b	10.46 b
Mean	4.30 a	3.36 a	3.73 a		
2005					
P0	4.45	4.27	3.58	4.10 a	12.30 a
P2	4.36	3.62	3.21	3.73 b	11.19 b
P4	4.59	3.53	3.33	3.82 b	11.45 b
P6	3.93	3.11	3.10	3.38 c	10.14 c
Mean	4.33 a	3.63 b	3.31 b		
2006					
P0	4.69	4.31	3.50	4.17 a	12.50 a
P2	4.50	3.87	3.87	3.31 b	11.73 b
P4	4.55	4.02	3.05	3.87 b	11.62 b
P6	4.06	3.44	3.03	3.51 c	10.53 c
Mean	4.45 a	3.91 b	3.24 b		
2007					
P0	4.20	3.98	2.43	3.54 a	10.61 a
P2	4.24	3.69	2.23	3.39 ab	10.16 ab
P4	4.32	3.78	2.19	3.43 ab	10.29 ab
P6	4.13	3.43	2.14	3.23 b	9.70 b
Mean	4.22 a	3.72 b	2.25 c		

An analysis of variance for a randomized complete block design was performed to evaluate the significance of soil compaction on chemical properties of soil and herbage DM yields using the STATISTICA 7.0 package (StatSoft Inc., Tulsa, OK, USA). Means were compared using Duncan's test with a level of significance of $P<0.05$.

Results and Discussion

The mean annual harvested DM production of lucerne was approximately 9.26 $t \cdot ha^{-1}$ in 2003. In the second, third, fourth, and fifth years of the experiment they were 11.39, 11.27, 11.59, and 10.19 $t \cdot ha^{-1}$, respectively. The highest DM yield was obtained in the first cut and it was lower in the second and third cuts. Only in 2004 were there no significant differences between times of harvesting. Trafficking had a significant effect on annual DM yields. Increasing the number of passes resulted in a decrease in DM yield (Table 3). The highest DM yields were obtained on the treatment P0. The DM yields obtained from the P2 and P4 treatments were usually not significantly different. Over the 5-year duration of the experiment the P6 treatment was the one that had the lowest levels of herbage production.

A reduction in productivity of lucerne following soil compaction caused by tractor passes also was reported by Głąb [1]. However, in the current experiment the unfavorable influence of wheel trafficking was clearly identified only during the second and third harvests. The DM yields obtained from the first harvest were not significantly different between traffic treatments in any of the 4 years. This was probably the result of a long period between the first and the third harvests and between the applications of the trafficking treatments between years. During this time plants recovered from damage and regenerated their shoots [1, 2].

Soil reaction is one of the most important and changeable chemical parameters. Crops and soil tillage can easily modify soil reaction in the upper soil layer. At the trial site pH_{KCl} was approximately 6.5 in the upper soil layer, a typical value for mineral soil under grassland. It was observed that soil reaction significantly increased in the lower soil layers (Fig. 1). The effect of soil compaction by tractor traffic was noticed only in the 0-10 cm soil layer. The more intensive soil compaction, the higher the observed pH. The lowest value of pH_{KCl} (6.47) was noticed at P0, whereas at P6 pH_{KCl} increased to 6.59. A similar relationship was recorded for pH_{H_2O}. Below 10 cm the differences between treatments were not significant. Similar results were obtained by Bhandral et al. [15], who noticed significantly higher pH throughout the measurement period over the uncompacted soil. They attributed this effect to a low level of nitrification in the compacted soil, resulting in the release of only a small amount of protons to the soil.

The EC measurement is influenced by several soil physical and chemical properties: soil salinity, saturation percentage, water content, and bulk density [13, 15]. As expected, the multiple passes of tractor changed bulk density of soil [1], but this not clearly reflected in electrocoductivity (Table 4). In the upper soil layers (0-10 and 10-20 cm) there were no significant differences between treatments. However, at the 20-30 cm soil layer the P6 treatment characterized the highest EC value (0.159 $mS \cdot cm^{-1}$), whereas at P0, P2, and P4 EC values were 0.110, 0.136, and 0.134 $mS \cdot cm^{-1}$, respectively. Significantly higher soil EC also was measured for compacted versus non-compacted soils by Motavalli et al. [23]. A significant positive relationship between soil bulk density and soil EC also has been observed in farmland in Nebraska [15]. Authors noticed this relationship between EC and bulk density in whole plough

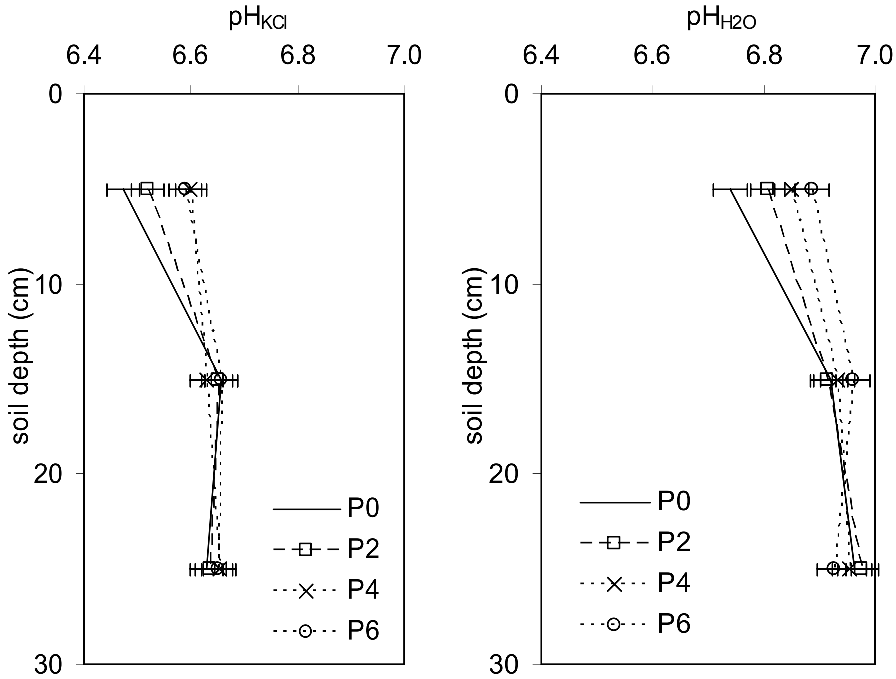

Fig. 1. Effect of tractor traffic on soil pH. Error bars represent standard error of mean.

Table 4. Effect of tractor traffic on soil electrolytical conductivity (EC), soil organic carbon (C_{org}), total soil N (N_{tot}), and C/N ratio. Different superscript letters within columns show significant differences among treatments (P<0.05, Duncan's Multiple Range Test).

Treatment	EC (mS·cm^{-1})	C_{org} (g·kg^{-1})	N_{tot} (g·kg^{-1})	C/N ratio
0-10 cm				
P0	0.123 bc	15.86 a	1.672 abc	9.49 a
P2	0.116 bc	16.13 a	1.842 a	8.76 a
P4	0.119 bc	15.27 a	1.825 ab	8.37 a
P6	0.102 c	13.21 a	1.746 abc	7.57 a
10-20 cm				
P0	0.125 bc	15.61 a	1.487 bc	10.50 a
P2	0.109 bc	14.90 a	1.556 abc	9.58 a
P4	0.109 bc	15.64 a	1.593 abc	9.82 a
P6	0.106 bc	15.17 a	1.545 abc	9.82 a
20-30 cm				
P0	0.110 bc	14.86 a	1.434 c	10.36 a
P2	0.136 ab	16.65 a	1.613 abc	10.32 a
P4	0.134 abc	13.78 a	1.699 abc	8.11 a
P6	0.159 a	13.84 a	1.513 abc	9.15 a

layer 0-30 cm. In the present experiment the differences were observed only in the lower 20-30 cm soil layer.

It was expected that soil compaction could increase organic carbon content. According to De Neve and Hofman [24], the C mineralization rate can be depressed at compacted soil and this depression of C mineralization can lead to higher organic matter accumulation. However, in this experiment no significant differences in carbon content were obtained for all treatments (Table 4).

Nitrogen is one of the most mobile elements in soil and its content in soil is influenced by many factors such as soil physical properties, microorganisms, crops, etc. It is widely confirmed that soil compaction leads to increasing denitrification processes that result in nitrogen losses [4, 14]. However, different management systems result in different microbial communities, so the effect of compaction on microbial activity will vary with different soil histories [25]. In this experiment, similar to C content, nitrogen content also was not affected by soil compaction. Probably it was connected with the higher N content in soil as an enrichment of soil in addition to N, which is characteristic in legume cultivation. As a result of the lack differences in C and N contents, the C/N ratio also was not significantly different for particular treatment (Table 4) and varied in the range 7.57-10.36.

Other macroelements also were not affected by changes in compacted soil except phosphorus (Table 5). P content varied in the range 7.65-10.95 mg·kg^{-1}. Generally higher values were noticed in the deeper 20-30 cm soil layer.

Table 5. Effect of tractor traffic on macroelement (P, K, Mg) and microelement (Cu, Fe, Mn, Zn) content in soil after extraction using $CaCl_2$ solution (0.01 mol·dm^{-3}). Different superscript letters within columns show significant differences among treatments (P<0.05, Duncan's Multiple Range Test).

Treatment	mg·kg^{-1} d.m. of soil						
	P	K	Mg	Cu	Fe	Mn	Zn
0-10 cm							
P0	7.890 bc	477 a	95.70 a	0.310 a	0.327 a	4.893 a	0.660 b
P2	7.657 c	447 ab	101.03 a	0.633 a	0.317 a	4.030 abc	0.727 b
P4	8.243 bc	467 a	99.03 a	0.530 a	0.317 a	4.170 abc	0.780 b
P6	8.767 abc	451 ab	99.83 a	0.587 a	0.497 a	4.463 ab	0.970 bc
10-20 cm							
P0	8.313 bc	373 c	92.90 a	0.603 a	0.370 a	2.980 c	0.850 ab
P2	8.550 bc	384 c	96.93 a	0.773 a	0.370 a	3.400 bc	0.860 ab
P4	9.430 abc	400 bc	96.97 a	0.853 a	0.467 a	2.967 c	0.893 ab
P6	8.777 abc	385 c	90.60 a	0.740 a	0.390 a	3.540 abc	0.943 ab
20-30 cm							
P0	7.653 c	360 c	84.70 a	1.007 a	0.393 a	2.877 c	0.767 b
P2	9.340 bc	374 c	93.93 a	1.070 a	0.487 a	3.047 bc	0.860 ab
P4	10.950 a	389 c	103.70 a	0.570 a	0.897 a	3.210 bc	0.993 ab
P6	10.113 ab	382 c	94.47 a	0.560 a	1.317 a	3.300 bc	1.293 a

Table 6. Dehydrogenase activity. Different superscript letters within the column show significant differences among treatments (P<0.05, Duncan's Multiple Range Test).

Treatment	$mgTPF \cdot kg^{-1} \cdot 24h^{-1}$
P0	9.22 c
P2	9.82 bc
P4	10.86 b
P6	14.41 a

At this depth soil compaction increased P content from 7.65 $mg \cdot kg^{-1}$ at the P0 to 10.11 $mg \cdot kg^{-1}$ at the P6 treatment. This could be explained as a result of lower plant uptake, which reduced phosphorus losses in soil. Some authors confirm that in compacted soil plant uptake of macroelements is limited. This effect is usually ascribed to restricted root growth and differences in the configuration of the root system [4, 17].

Neither potassium nor magnesium changed their content in all investigated soil layers under any treatment. Microelements like Cu, Fe, and Mn also did not show any reaction to soil compaction (Table 5). Only Zn in the 20-30 cm soil layer increased in compacted soil. The higher values were noticed at the P6 treatment (1.293 $mg \cdot kg^{-1}$), compared with 0.767 $mg \cdot kg^{-1}$ at the untreated control P0.

Dehydrogenase activity is widely used as an index of biological activity of soil and it is strictly connected with metabolism of soil microorganisms [9]. Dehydrogenase activity appeared most sensitive to the treatments where soil physical parameters are variable [10]. At the experiment the multiple tractor passes by the soil surface resulted in increasing DHA. At the control P0 plot the dehydrogenase activity was 9.22 $mgTPF \cdot kg^{-1} \cdot 24h^{-1}$, whereas at the most compacted P6 treatment it was 14.41 $mgTPF \cdot kg^{-1} \cdot 24h^{-1}$. This indicates that soil compaction favors microorganism activity. This statement is confirmed by results obtained by Nosalewicz and Nosalewicz [14]. A similar relationship was also shown by Angers et al. [19] in an investigation with a no-tillage system. However, Pengthamkeerati et al. [26] reached the opposite conclusion in their investigation with compacted soil amended with poultry litter. They stated that this effect could be ascribed to soil aeration. In wet years, compaction may lead to wet or saturated soil due to poor water infiltration, causing denitrification and potentially limiting aerobic microbial activity.

Conclusions

The results show that tractor traffic reduced the DM yields of lucerne, particularly during the second and third harvests in each year. Soil compaction caused by tractor wheeling changed some chemical properties of soil. Tractor passes resulted in increasing pH and EC. It also increased P and Zn content. Most of these changes were statistically significant only in the deeper 20-30 cm soil layer. This effect could be ascribed to higher soil density and lower air permeability. The upper (0-20 cm) soil layer was resistant to changes in chemical properties, probably due to the dene root system which recover the soil after compaction and improves physical properties of the soil. Probably the decrease in lucerne production was the result of mechanical damage to roots and above-ground parts of plants rather than problems in nutrient uptake. We can conclude that chemical properties, particularly N content, are not significantly important factors in the reduction of lucerne production exposed to tractor traffic.

References

1. GŁĄB T. Effect of tractor wheeling on root morphology and yield of lucerne (*Medicago sativa* L.). Grass Forage Sci., **63**, 398, **2008**.
2. VOLDEN B., SVEISTRUP T.E., JORGENSEN M., HARALDSEN T.K. Effects of traffic and fertilization levels on grass yields in northern Norway. Agr. Food Sci. Finland, **11**, 219, **2002**.
3. COELHO M.B., MATEOS L., VILLALOBOS F.J. Influence of a compacted loam subsoil layer on growth and yield of irrigated cotton in Southern Spain. Soil Till. Res., **57**, 129, **2000**.
4. LIPIEC J., STĘPNIEWSKI W. Effect of soil compaction and tillage system on uptake and losses of nutrients. Soil Till. Res., **35**, 37, **1995**.
5. BHANDRAL R., SAGGAR S., BOLAN N.S., HEDLEY M.J. Transformation of nitrogen and nitrous oxide emission from grassland soils as affected by compaction. Soil Till. Res., **94**, 482, **2007**.
6. HORN R., WAY T., ROSTEK J. Effect of repeated tractor wheeling on stress/strain properties and consequences on physical properties in structured arable soils. Soil Till. Res., **73**, 101, **2003**.
7. BRZEZIŃSKA M., STĘPNIEWSKA Z., STĘPNIEWSKI W., WŁODARCZYK T., PRZYWARA G., BENNICELLI R. Effect of oxygen deficiency on soil dehydrogenase activity (pot experiment with barley). International Agrophysics, **15**, 3, **2001**.
8. PIEKARZ J., LIPIEC J. Selected physical properties and microbial activity earthworm casts and non-ingested soil aggregates. International Agrophysics, **15**, 181, **2001**.
9. KACZMAREK Z., WOLNA-MURAWKA A., JAKUBAS M. Changes of the number of selected microorganism groups and enzymatic activity in the soil inoculated with effective microorganisms (EM). Journal of Research and Applications in Agricultural Engineering, **53**, (3), 122, **2008**.
10. MIJANGOS I., PEREZ R., ALBITU I., GARBISU C. Effects of fertilization and tillage on soil biological parameters. Enzyme Microb. Tech., **40**, 100, **2006**.
11. MARSCHNER P., KANDELER E., MARSCHNER, B. Structure and function of the soil microbial community in a long-term fertilizer experiment. Soil Biol. Biochem., **35**, 453, **2003**.
12. DORAN W.J., PERKIN T.B. Quantitative indicators of soil quality: A minimum data set. [in:] Methods for assessing soil quality. J. W. Doran and A. J. Jones (Ed.), SSSA Special Publication, 49, SSSA, Madison, WI, USA, 25, **1996**.
13. CORWIN D.L., LESCH S.M. Apparent soil electrical conductivity measurements in agriculture. Comput. Electron. Agr., **46**, 11, **2005**.

14. NOSALEWICZ A., NOSALEWICZ M. Effect of soil compaction on dehydrogenase activity in bulk soil and rhizosphere. International Agrophyics, **25**, 47, **2011**.
15. JOHNSON C.K., DORAN J.W., DUKE H.R., WIENHOLD B.J., ESKRIDGE K.M., SHANAHAN J.F. Field-scale electrical conductivity mapping for delineating soil condition. Soil Sci. Soc. Am. J., **65**, 1829, **2001**.
16. NEVENS F., REHEUL D. The consequences of wheel-induced soil compaction and subsoiling for silage maize on a sandy loam soil in Belgium. Soil Till. Res., **70**, 175, **2003**.
17. KRISTOFFERSEN A.R., RILE H. Effects of soil compaction and moisture regime on the root and shoot growth and phosphorus uptake of barley plants growing on soils with varying phosphorus status. Nutr. Cycl. Agroecosys., **72**, 135, **2005**.
18. CAPORALI F., ONNIS O. Validity of rotation as an effective agroecological principle for a sustainable agriculture. Agr. Ecosyst. Environ., **41**, 101, **1992**.
19. ANGERS D.A., BISSONNETTE N., LEGERE A., SAMSON N. Microbial and biochemical changes induced by rotation and tillage in a soil under barley production. Can. J. Soil. Sci., **73**, 39, **1993**.
20. IUSS Working Group WRB. 2007. World Reference Base for Soil Resources 2006, first update 2007. World Soil Resources Reports No. 103. FAO. Rome. **2007**.
21. RUTKOWSKA B., SZULC W., BOMZE K., FELCZYŃSKI K. Usefulness of Different Extraction Solutions for Determination of Plant Availability of Heavy Metals. Ecological Chemistry and Engineering, **17**, (4-5), 483, **2010**.
22. BRZEZIŃSKA M., WŁODARCZYK T. Enzymes of intracellular redox transformations (oxidoreductases). Acta Agrophysica, Rozprawy i Monografie, **3**, 11, **2005**.
23. MOTAVALLI P.P., ANDERSON S.H., PENGTHAMKEERATI P., GANTZER C.J. Use of soil cone penetrometers to detect the effects of compaction and organic amendments in claypan soils. Soil Till. Res., **74**, 103, **2003**.
24. DE NEVE S., HOFMAN G. Influence of soil compaction on C and N mineralization from soil organic matter and crop residues. Biol. Fert. Soils, **30**, 544, **2000**.
25. WHALLEY W.R., DUMITRU E., DEUTER A.R. Biological effects of soil compaction. Soil Till. Res., **35**, 53, **1995**.
26. PENGTHAMKEERATI P., MOTAVALLI P.P., KREMER R.J., ANDERSON S.H. Soil carbon dioxide efflux from a claypan soil affected by surface compaction and applications of poultry litter. Agr. Ecosyst. Environ., **109**, 75, **2005**.