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Original Research

Effect of Soil Compaction on Root System Morphology and Productivity of Alfalfa (*Medicago sativa* L.)

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Abstract

Soil compaction connected with tractor traffic leads to changes in roots morphology and decreased plant yields of both annual and perennial forage plants. The aim of this study was to quantify the effect of soil compaction on alfalfa herbage production and root growth. A pot experiment with different levels of soil compaction was conducted in 2007-09. Plant yield and root morphology such as root length density (RLD), mean root diameter (MD), specific root length (SRL), and root dry matter (RDM) were determined.

Root dry matter distribution in uncompacted soil was uniform in the investigated soil layers. In compacted soil the main root matter was located in the upper soil layer. Generally, roots were also much longer in the upper soil layer (0-10 cm) than below 10 cm. The value of RLD decreased in treatments with a higher degree of compaction. It was observed that roots in more compacted soil were thinner than in uncompacted. Based on the results in herbage production, the reaction of plant yield to soil compaction can be described as positive. In the first year of the experiment (2007), soil compaction caused a significant decrease in plant yield. However, in 2008 and 2009 the opposite effect was noticed when yields were significantly higher in strongly compacted soil than in less compacted.

Keywords: *Medicago sativa*, soil compaction, roots, yields, image analysis

Introduction

Modern crop production systems tend to increase the number of passes and the loads carried on agricultural vehicles, resulting in a compaction hazard. Nowadays, soil compaction is recognized as one of the main factors that can lower crop yields, thus is a serious agricultural problem. Compaction leads to soil structure degradation, where the size and shape of pores is changed. Associated with these changes is increased bulk density and soil strength, measured as penetration resistance [1, 2]. Many researchers agree that soil compaction leads to plant yield reduction, including decreased production of perennial forage crops [3-7]. This yield decline is the consequence of both soil compaction and shoot injury caused by wheel traffic. It is a particularly serious problem for perennial crops, especially perennial forage legumes, where the soil is wheeled without ever being loosened. Soil strength is increased year-after-year by machine traffic during field operations. On the other hand, it has also been reported that yields of perennial plants were not always reduced by compaction and sometimes were larger in compacted soil than in non-compacted [8, 9]. These trends could be attributed to better water and nutrient supply and recovery of the soil pore system [10].

The degraded soil physical environment due to compaction influences not only shoots, but also root growth and

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development. Soil compaction increases mechanical impendence, creates unfavourable growing conditions for roots, and restricts oxygen, water, and nutrient supply [11-16]. A common response of the root system to increasing bulk density is to decrease in length, concentrating roots in the upper layer and decreasing rooting depth [17, 18]. Strongly compacted soils are usually penetrated by roots in cracks, fissures and biopores (macropores formed by earthworms). This provides an advantage to elongating roots, but also results in a heterogeneous root distribution [19, 20]. However, decrease in plant yield caused by soil compaction is not necessarily related to decrease in root length and matter [21, 22]. The author stated in his previous research [23] that tractor traffic increased the length of meadow fescue roots. Similar results have been also noticed by Ball-Coello et al. [24], who confirmed the positive correlation between soil compaction and morphometric parameters of roots as a result of an increase in capillary pore volumes. Another effect of root morphology in compactness soil observed by Cannel and Hawes [25] was a decrease in root length but an increase in a number of branches, which resulted in higher root matter. Overall, sometimes it is difficult to consistently quantify in field trials the relationship between root growth and plant yield.

Alfalfa (*Medicago sativa* L.) can be used not only for grazing, hay, and silage production, but also for soil improvement and conservation. However, alfalfa is one of the most susceptible forage species to mechanical damage caused by machinery. Traffic during harvesting can cause not only soil compaction but also damage to newly growing stems. Root exploration for soil water and nutrients and herbage growth, and subsequent yields, can all be affected [26]. In the previous study [23], the author reported the effect of tractor traffic on root morphology and yield of Lucerne during the field experiment. The objective of the research reported in this paper was to evaluate the effect of soil compaction on alfalfa (*Medicago sativa* L.) yields without the effect of shoot injuries caused by tractor wheels. This study was established as a pot experiment with strictly controlled soil physical parameters.

Material and Methods

Site, Location, and Climate

This study was conducted as a pot experiment located in Mydlniki near Krakow (50º04' N, 19º51' E) at the Institute of Machinery Exploitation, Ergonomics, and Production Processes, Agricultural University of Kraków, Poland, in 2007-09. The climate of the experimental site, south of Poland, is temperate. Data from the meteorological station located at the site are presented in Table 1.

Experimental Design and Treatments

The pot experiment was conducted in 2007-09. Soil compaction, as an experimental treatment, was applied in completely randomized design with four replications. The three levels of soil compaction were established according to the degree of compactness (D): 70% (D70), 80% (D80), and 90% (D90). The range of D (70-90%) was determined according to Hakansson and Lipiec [27], who stated that this range of values is characteristic of agricultural soils. The degree of compactness is defined as the dry bulk density as a percentage of reference bulk density obtained by a standardized uniaxial compression test (Proctor test) at 200 kPa [27, 28]. The reference bulk density of the soil used in the experiment was 1.65 g·cm^{-3}.

Table 1. Monthly and annual temperatures and cumulated precipitation for the study period and long-term averages.

	2007	2008	2009	1981-2002
	Monthly average temperature [ºC]			
January	3.2	1.2	-3.4	-4.4
February	1.2	2.2	-1.2	-3.2
March	6.0	3.8	2.7	1.2
April	8.5	9.1	11.4	6.2
May	15.2	13.6	13.6	11.5
June	18.4	18.4	16.0	14.2
July	19.4	18.7	19.9	16.0
August	19.0	18.2	18.6	14.8
September	12.4	12.6	12.9	11.2
October	7.7	9.6	9.8	7.0
November	0.8	3.3	5.7	0.9
December	-1.1	-1.2	-1.2	-2.7
Annual mean	9.2	9.1	8.7	6.1
	Sum of precipitation [mm]			
January	101	31	28	44
February	42	18	40	39
March	61	70	67	46
April	15	35	5	62
May	52	29	107	100
June	72	27	122	119
July	71	143	83	111
August	76	42	53	91
September	180	97	62	77
October	48	52	43	55
November	90	43	28	43
December	21	47	36	54
Annual sum	830	633	672	839

Table 2. Characteristics of soil used in studied pots and field experiment.

pH (KCl)		6.5
Total organic C	g·kg^{-1}	25.8
Total N	g·kg^{-1}	2.10
C/N		12.3
Solid particle density	g·cm^{-3}	2.53
Reference bulk density	g·cm^{-3}	1.65
Sand	g·kg^{-1}	290
Silt	g·kg^{-1}	670
Clay	g·kg^{-1}	40
Texture		Silty loam

Pots were 30 cm high, 40 cm diameter, and the volume of pots was 37,680 cm^3. Table 2 reports some characteristics of soil used to fill the pots. The D70 compaction level was established using a 1 kg compaction hammer dropped from a height of 50 cm. For the D80 and D90 levels, 5 and 10 kg hammers, respectively, were used. The soil compaction procedure in pots was repeated for every 5 cm soil layer. When the soil was compacted, the bottom of pots was removed to allow upward water movement and to avoid root deformation. After compaction, alfalfa (*Medicago sativa* L.) seeds were sown at a rate of 16 plants per pot. Fertilization for the first and second harvest was applied every year at a rate of 80 kg·ha^{-1} P_2O_5 and 120 kg·ha^{-1} K_2O. Pots were kept outside immersed in the soil up to ground level. The area surrounding the pots was covered with alfalfa plants to avoid a border effect (Fig. 1).

Soil Physical Parameters

Dry bulk density was measured by taking samples of soil using corer with a 100 cm^3 (5.2 cm diameter and 5.5 cm high) volume sample cores in six replications for every plot in 2007, at the beginning of the experiment, and in the next years, 2008 and 2009. The samples were weighted and dried until they reached a constant weight. Total porosity was calculated from soil particle density and dry bulk density of the samples. The soil particle density was determined using a pycnometer method. The mean values of particle density were 2.53 g·cm^{-3}.

A soil cone penetrograph STIBOKA (Eijkelkamp Agrisearch Equipments, Netherlands) with a base area of 100 mm^2 and 60º cone angle was used to take the penetration resistance measurement. The penetrograph was inserted at an approximately constant insertion rate of 20 mm·s^{-1} throughout the depth of the measurement.

Harvesting

Harvesting was done three times a year by cutting plants 5 cm above soil level. Harvest dates were: 20 June, 25 August, and 16 October in 2007; 3 June, 9 July, and 10 September in 2008; 6 June, 12 July, and 15 September in 2009. The dry matter (DM) of the yield was determined by drying a subsample of 500 g at 70ºC to a constant weight.

Sampling and Analysis of Roots

Roots were sampled using the soil-core method [29] in autumn 2009, the last year of the experiment. The only term of sampling was determined by the fact that pots were destroyed during root sample collecting. The core diameter was 80 mm. Samples were taken from a 30 cm depth and

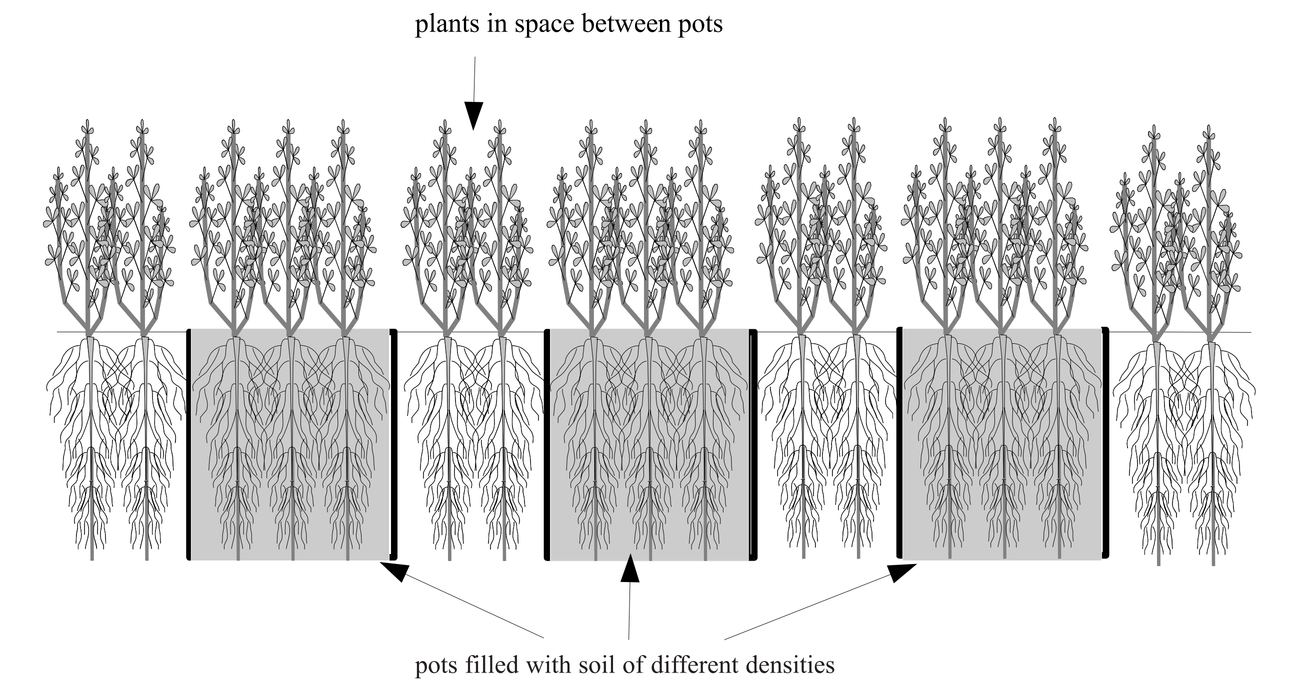

Fig. 1. Pot locations at the experimental site. Vertical soil section.

divided into 3 sections: 0-10, 10-20, and 20-30 cm. Roots were washed using a hydropneumatic elutriation [30] to remove mineral particles from the samples. Before scanning, any organic contaminations were manually removed. Digital images were obtained with an Epson Perfection 4870 Photo scanner. The collected images were saved in tiff format with a resolution of 600 dpi. Then the images were analyzed using APHELION software for image analysis (ADCIS S.A. and Amerinex Applied Imaging), and root characteristics were calculated. The measured root length was divided into eight diameter classes: 0-0.1, 0.1-0.2, 0.2-0.5, 0.5-1.0, 1.0-2.0, 2.0-5.0, 5.0-10.0, and >10.0 mm. The RLD (root length density) was calculated by dividing the total root length by the volume of the sample. The SRL (specific root length) was calculated by dividing total root length by root dry weight. The MD (mean diameter) was calculated as weighted mean of root length for particular diameter classes. After scanning, roots were dried at 70ºC for dry matter determination (RDM).

Statistics

An analysis of variance for a completely randomized design was performed to evaluate the significance of soil compaction on root characteristics and plant yields using the statistical package STATISTICA 6.0 (StatSoft Inc.). Means were compared using Duncan's test with a level of significance of P<0.05.

Results and Discussion

Roots Affect Physical Properties of Soil

At the beginning of the experiment the soil density was established at three compaction levels: 1.16, 1.32, and 1.49 $g \cdot cm^{-3}$, which corresponded with the degree of compactness of 70, 80, and 90%, respectively (Table 3). The roots of alfalfa changed the physical properties of soil during the three years of investigation. At the treatment with the lowest bulk density (D70), the self-compaction effect was observed. The bulk density increased from 1.16 $g \cdot cm^{-3}$ in 2007 to 1.27 $g \cdot cm^{-3}$ in 2009. The results in penetration resistance were 1.26 and 2.26 MPa, respectively. This effect of self-compaction is usually ascribed to meteorological factors like rains, snow cover, etc. At the strongly compacted treatment (D90), favourable changes in soil density were observed in 2008 and 2009 with respect to initial conditions in 2007 (Table 3). During three years of experiment a significant decrease in bulk density and penetration resistance was noticed. The opposite effect was observed in soil porosity, which increased from 0.44 $cm^3 \cdot cm^{-3}$ at the D90 in 2007 to 0.48 $cm^3 \cdot cm^{-3}$ in both 2008 and 2009. These changes can be ascribed to biological activity such as roots and earthworm activity, which opened pathways that permitted more efficient root penetration and soil water utilization in the compacted soil. A similar effect was reported by Coelho [2], who observed that in the second year of experiments the cotton crops demonstrated better shoot growth and higher yield on strongly compacted soil. Soil compaction affects significantly growth and yields, but successive cropping may alleviate the effects of the compaction. According to Radford et al. [31] sowing a suitable crop species may be a better option than tillage for repairing compaction damage by agricultural wheel traffic. This may be expected to be of special importance in direct drilling cropping systems [32].

Table 3. Physical properties of soil related to three compaction levels.

Treatments	Bulk density	Degree of compactness	Total porosity	Penetration resistance
	($g \cdot cm^{-3}$)	(%)	($cm^3 \cdot cm^{-3}$)	(MPa)
2007				
D70	1.16 [fa]	70	0.56 [a]	1.26 [g]
D80	1.32 [bcd]	80	0.50 [cde]	2.71 [cd]
D90	1.49 [a]	90	0.44 [f]	4.26 [a]
2008				
D70	1.24 [e]	75	0.53 [b]	1.99 [f]
D80	1.31 [cd]	79	0.51 [cd]	2.62 [d]
D90	1.37 [b]	83	0.48 [e]	3.18 [b]
2009				
D70	1.27 [de]	77	0.52 [bc]	2.26 [e]
D80	1.34 [bc]	81	0.49 [de]	2.90 [c]
D90	1.37 [b]	83	0.48 [e]	3.17 [b]

[a]Different letters within each column show significant differences among treatments (P<0.05, Duncan's multiple range test).

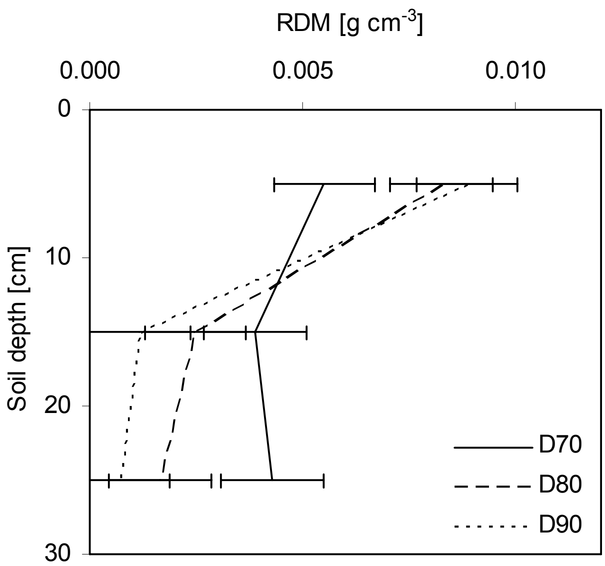

Fig. 2. Effect of soil compaction on alfalfa root dry matter (RDM). Data collected in September 2009. Error bars represent standard error.

DM Production

The soil compaction treatment in the experiment influenced shoot yields. However, the results in alfalfa yields in 2007 differ from these obtained in 2008 and 2009 (Table 4). In 2007, soil compaction significantly reduced DM yields. For the first harvest, the DM yield of the D90 treatment was approximately 50% in comparison with the D70 pot yield. This percentage for the second and third harvest was 65 and 76%, respectively. This tendency is confirmed by Logsdon and Karlen [33], who stated that soil compaction strongly determine the seed germination process and early root growth. Excessive compaction of seedbed increases soil strength and results in high soil resistance to coleoptile and root growth. It slows germination, lowers an emergence rate and suppresses root elongation [34]. In 2008 and 2009 the effect of soil compaction on plant yield totally changed. There were no significant differences between DM from the D70 and D80 pots for any harvest. Whereas the DM yield obtained at the D90 was larger with respect to the D70 and D80. These differences were significant for all terms of harvest, except the third cut in 2009, when any significant reaction to soil compaction was not recorded. In the second and third year of the experiment, alfalfa on strongly compacted soil (D90) had a greater total annual yield compared to less compacted soil (D70 and D80). In the previous research, during the field experiment, the author obtained the opposite effect. An increase in soil density caused by

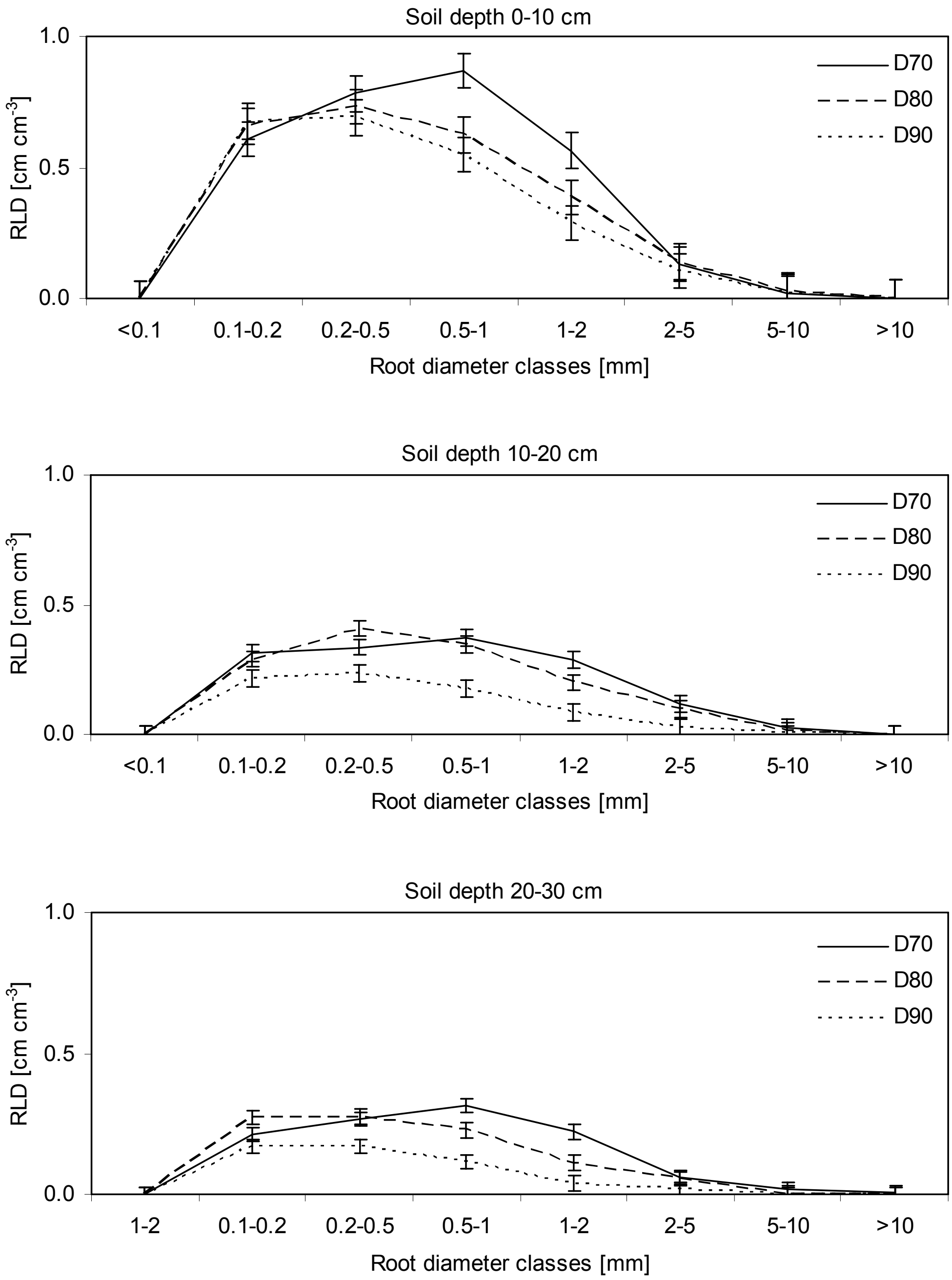

Fig. 3. Effect of soil compaction on alfalfa root length density (RLD) for different root diameter classes. Data collected in September 2009. Error bars represent standard error.

Table 4. Dry matter production of alfalfa for different soil compaction treatments.

Treatment	Yields [g DM·pot⁻¹]			
	1st cut	2nd cut	3rd cut	Total annual
2007				
D70	73.7 [da]	71.6 [cd]	35.2 [cd]	180.4
D80	72.5 [d]	64.3 [de]	29.5 [de]	166.3
D90	37.8 [e]	46.2 [f]	26.7 [e]	110.8
2008				
D70	84.1 [cd]	59.9 [e]	40.8 [bc]	184.7
D80	73.7 [d]	54.9 [ef]	42.0 [bc]	170.6
D90	101.5 [b]	75.2 [bcd]	59.1 [a]	235.8
2009				
D70	96.5 [bc]	86.1 [b]	40.1 [bc]	222.7
D80	97.7 [bc]	80.6 [bc]	36.4 [bcd]	214.8
D90	131.5 [a]	114.7 [a]	43.6 [b]	289.8

[a]Different letters within each column show significant differences among treatments ($P<0.05$, Duncan's multiple range test).

tractor passes resulted in a decrease in the DM yield of herbage. It was probably the effect of both soil compaction and shoot injuries by tractor wheels. The positive effect of soil compaction for other perennials were reported by Frost [9], and Dwyer and Stadie [8]. They ascribed this effect to better water and nutrient supply in compacted soil. Douglas [4] reported the favourable effect of soil compaction on grass yield, particularly during drier summer conditions when water supply was limited. Larger reserves of water on compacted soil directly impact plant yield.

Root Growth

Soil density significantly changed the root morphometric properties. Soil compaction decreased total root matter and their distribution. The total dry matter (RDM) of roots in the 0-30 cm soil layer was 0.0137 g·cm^{-3} for the D70 soil density and 0.0124 and 0.0107 g·cm^{-3} for the D80 and D90 treatments, respectively (Fig. 2). Root dry matter in the D70 treatment was uniformly distributed in the investigated soil layers (0.0046 g·cm^{-3} in average). Whereas the RDM of roots in both the D80 and D90 treatments got higher values in the 0-10 cm layer (0.0089 g·cm^{-3}) with respect to roots below 10 cm soil depth.

Soil density influenced not only root dry matter but also their length and diameter (Fig. 3). The highest root length density (RLD) was found in the upper soil layer in comparison with the 10-20 and 20-30 cm depths (Fig. 4). Roots with 0.5-2.0 mm in diameter were sensitive to soil compaction. Whereas the thick roots (>2.0 mm) and thin roots (<0.5 mm) were more resistant. At the D70 treatment the RLD values were significantly higher for thick roots 0.5-2.0 mm in diameter in comparison with the D80 and D90. The changes in RLD affected also the MD parameter (Fig. 5). Roots from compacted soil were significantly thinner with respect to these from looser soil, particularly in deeper soil layers. At the D70, the mean root diameter (MD) was 1.09 mm in the 20-30 cm layer. Whereas at both the D80 and D90 MD decreased to 0.70 and 0.60 mm, respectively. Specific root length (SRL) followed an opposite trend than root dry matter (Fig. 6). The lowest value of SRL was found in the 0-10 cm layer of the D80 and D90 treatments and it was significantly lower with respect to the D70. The depth of soil did not affect the SRL in the D70 treatment.

The reaction of root systems of perennial forage plans on soil compaction can vary and can be described as positive or negative. However, many researchers reported that a

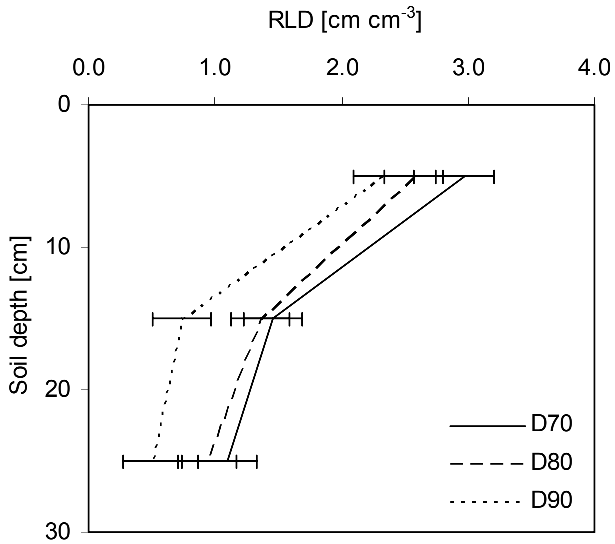

Fig. 4. Effect of soil compaction on alfalfa root length density (RLD). Data collected in September 2009. Error bars represent standard error.

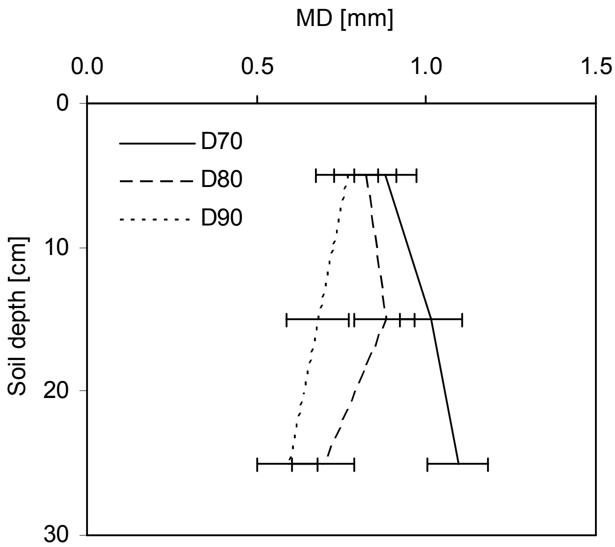

Fig. 5. Effect of soil compaction on alfalfa mean root diameter (MD). Data collected in September 2009. Error bars represent standard error.

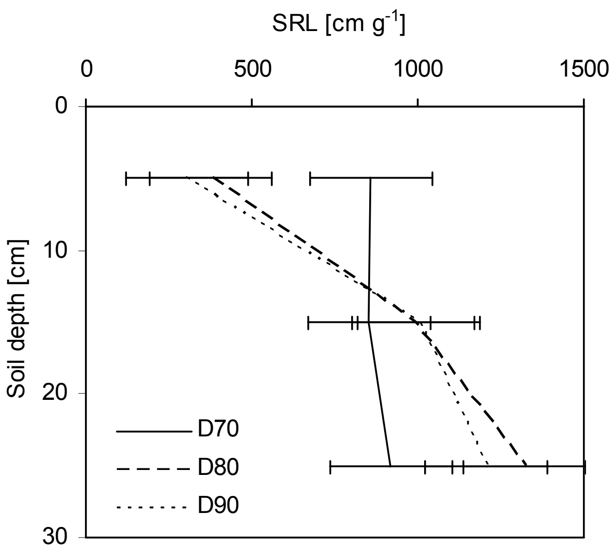

Fig. 6. Effect of soil compaction on alfalfa specific root length (SRL). Data collected in September 2009. Error bars represent standard error.

common response of the annual plant root system to increasing bulk density is to decrease its length and concentrating roots in the upper layer [17, 18, 35]. The results obtained in the current experiment confirm this trend also for alfalfa as a perennial plant.

Conclusions

The results presented in this paper indicate that soil compaction affect alfalfa shoot and root growth and vice versa, alfalfa roots influenced the compacted soil. After three years of the experiment the equalization of physical properties of soil was observed as a result of two effects:
(i) soil loosening caused by roots
(ii) self-compaction of soil with the lower density.

In the first year of the experiment, soil compaction significantly reduced yields. However, in the second and third year quite the opposite effect was noticed. The greatest yields were produced by plants under strong soil compaction regimes. This apparent benefit of compaction appeared to be due to larger reserves of water, and possibly nutrients.

In response to the soil compaction treatments imposed, alfalfa plants produced greater RDM in the upper layer of compacted soil. In lower layers of soil, root dry matter is strongly reduced by compaction. However, they are much thinner and probably more useful for water and nutrient uptake.

The alfalfa root system characterized good ability to penetrate severely compacted soil, even when penetration resistance was above 4 MPa, The roots adapted to soil condition by changes in their morphology and sufficiently supply plant with water and mineral nutrients. These properties make the alfalfa suitable for cultivation in physically degraded soils due to their reclamation.

We can also conclude that the main reason for yield reduction as the result of tractor traffic is rather connected with injuries in above-ground parts of plant. Changes in soil physical parameters, like higher bulk density and penetration resistance, are not responsible for yield reduction.

References

1. HAMZA M.A., ANDERSON W.K. Soil compaction in cropping systems. A review of the nature, causes and possible solutions. Soil and Tillage Research, **82**, 121, **2005**.
2. 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 and Tillage Research, **57**, 129, **2000**.
3. WHALLEY W.R., WATTS C.W., GREGORY A.S., MOONEY S.J., CLARK L.J., WHITEMORE A.P. The effect of soil strength on the yield of wheat. Plant and Soil, **306**, 237, **2008**.
4. DOUGLAS J.T. Soil compaction effects on second-harvest yields of perennial ryegrass for silage. Grass and Forage Science, **52**, 129, **1997**.
5. FRAME J., MERRILEES D.W. The effect of tractor wheel passes on herbage production from diploid and tetraploid ryegrass swards. Grass and Forage Science, **51**, 13, **1996**.
6. KOPEĆ S., GŁĄB T. The effect of tractor wheel passes on the productivity grass and red clover swards. Proceedings of the 17th General Meeting EGF, Debrecen, Hungary, vol. **3**, 769, **1998**.
7. GŁĄB T., KOPEĆ S. Effect of soil compaction on root system morphology and yields of meadow fescue (*Festuca pratensis*). Pol. J. Environ. Stud., **18**, 2, 219, **2009**.
8. DWYER M.J., STUDIE A.L. Damage to grassland by tractors. Proceedings of the 4th European Conference of the International Society for Terrain Vehicle Systems, Wageningen, 123, **1989**.
9. FROST J.P. Effects on crop yields of machinery traffic and soil loosening. Part 1. Effects on grass yield of traffic frequency and date of loosening. Journal of Agricultural Engineering Research, **39**, 302, **1998**.
10. SCOTT D.I., TAMS A.R., BERRY P.M., MOONEY S.J. The effects of wheel-induced soil compaction on anchorage strength and resistance to root lodging of winter barley (*Hordeum vulgare* L.). Soil and Tillage Research, **82**, 147, **2005**.
11. BENGOUGH A.G., MULLINS E.C. Mechanical impedance to root growth: a review of experimental techniques and root growth responses. Journal of Soil Science, **40**, 341, **1990**.
12. COOK A., MARRIO C.A., SEEL W., MULLINS E.C. Effects of soil mechanical impedance on root and shoot growth of *Lolium perenne* L., *Agrostis capilaris* and *Trifolium repens* L. Journal of Experimental Botany, **47**, 1075, **1996**.
13. WILPERT K., SCHAFFER J. Ecological effects of soil compaction and initial recovery dynamics: a preliminary study. European Journal of Forest Research, **125**, 129, **2006**.
14. LIPIEC J., WÓJCIGA A., HORN R. Hydraulic properties of soil aggregates as influenced by compaction. Soil and Tillage Research, **103**, 170, **2009**.
15. CHEN G., WEIL R.R Penetration of cover crop roots through compacted soils. Plant and Soil, **331**, 31, **2010**.
16. RAPER R.L. Agricultural traffic impacts on soil. Journal of Terramechanics, **42**, 259, **2005**.

17. LIPIEC J., HAKANSSON I., TARKIEWICZ S., KOSSOWSKI J. Soil physical properties and growth of spring barley related to the degree of compactness of two soils. Soil and Tillage Research, **19**, 307, **1991**.
18. LIPIEC J., MEDVEDEV V.V., BIRKAS M., DUMITRU E., LYNDINA T.E., ROUSSEVA S., FULAJTAR E. Effect of soil compaction on root growth and crop yield in Central and Eastern Europe. International Agrophysics, **17**, 61, **2003**.
19. MILLERET R., LE BAYON R.C., LAMY F., GOBAT J.M., BOIVIN P. Impact of roots, mycorrhizas and earthworms on soil physical properties as assessed by shrinkage analysis. Journal of Hydrology, **373**, 499, **2009**.
20. LOGSDON S.D., LINDEN D.R. Interactions of earthworms with soil physical conditions influencing plant growth. Soil Science, **154**, 330, **1992**.
21. KRISTOFFERSEN A.R., RILEY 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. Nutrient Cycling in Agroecosystems, **72**, 135, **2005**.
22. KOPEĆ S., GŁĄB T. Influence of soil compaction on yield and root development of *Lolium perenne*, *Phleum pratense* and *Trifolium pratense*. FAO Regional Office for Europe, REU Technical Serie **66**, 129, **2002**.
23. GŁĄB T. Effects of tractor wheeling on root morphology and yield of Lucerne (*Medicago sativa* L.). Grass and Forage Science, **63**, 398, **2008**.
24. BALL-COELHO B.R., ROY R.C., SWANTON C.J. Tillage alters corn root distribution in coarse-textured soil. Soil and Tillage Research, **45**, 237, **1998**.
25. CANNELL R.Q., HAWES J.D. Trends in tillage practices in relation to sustainable crop production with special reference to temperate climates. Soil and Tillage Research, **30**, 245, **1994**.
26. RECHEL E.A., DETAR W.R., MEEK B.D. AND CARTER L.M. Alfalfa (*Medicago sativa* L.) water use efficiency as affected by harvest traffic and soil compaction in a sandy loam soil. Irrigation Science, **12**, 61, **2004**.
27. HAKANSSON I., LIPIEC J. A review of the usefulness of relative bulk density values in studies of soil structure and compaction. Soil and Tillage Research, **53**, 71, **2000**.
28. HAKANSSON I. A method for characterizing the state of compactness of the plough layer. Soil and Tillage Research, **16**, 105, **1990**.
29. BOHM W. Methods of studying root systems. Berlin, Springer-Verlag, pp. 188, **1979**.
30. SMUCKER A.J.M., MC BURNEY S.L., SRIVASTOVA A.K. Quantitative separation of roots from compacted soil profiles by the hydropneumatic elutriation system. Agronomy Journal, **74**, 500, **1982**.
31. RADFORD B.J., BRIDGE B.J., DAVIS R.J., MCGARRY D., PILLAI U.P., RICKMAN J., WALSH P.A., YULE D.F. Changes in the properties of a Vertisol and responses of wheat after compaction with harvester traffic. Soil and Tillage Research, **54**, 155, **2000**.
32. CZYŻ E.A. Effects of traffic on soil aeration, bulk density and growth of spring barley. Soil and Tillage Research, **79**, 153, **2004**.
33. LOGSDON S.D., KARLEN D.L. Bulk density as a soil quality indicator during conversion to no-tillage. Soil and Tillage Research, **78**, 143, **2004**.
34. RADFORD B.J. Effect of a press wheel and depth of sowing on the establishment of semidwarf and tall wheat. Australian Journal of Experimental Agriculture, **26**, 697, **1986**.
35. GLIŃSKI J., LIPIEC J. Soil physical conditions and plant roots. CRC Press, Boca Raton USA, pp. 250, **1990**.