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Original Research

Effect of Soil Compaction on Root System Morphology and Yields of Meadow Fescue (*Festuca Pratensis*)

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Abstract

Tractor traffic as a cause of soil compaction is widely recognized as one of the most important factors responsible for environmental degradation and plant yield losses. It is a serious problem for perennial crops, where the soil surface is wheeled without any opening operation. The aim of our study was to evaluate the effect of tractor traffic on meadow fescue (*Festuca pratensis*) yields and root development. The field experiment was located in Mydlniki near Kraków, Poland, on silty loam Mollic Fluvisol. Experimental plots were established in randomized block design with four replications. Four compaction treatments were applied using the following range of number of passes: (P0) untreated control, (P2) two passes, (P4) four passes and (P6) six passes completely covering plot surfaces after each harvest. The dry matter (DM) of the yield and roots (RMD) were determined. Morphometric parameters of roots were estimated using image analysis software. Root length density (RLD), specific root length (SRL), and mean diameter (MD) were calculated.

Tractor traffic resulted in significant influence on meadow fescue annual yields. The highest annual yields were obtained at the P2 and P4 treatments. However, in the first cut it was noticed that an increase in the number of passes increased plant yields. During the second and the third cut it was found that intensive tractor traffic decreased plant yields, probably as an effect of damage caused to above-ground parts of plants. The meadow fescue roots were significantly affected by tractor traffic only in the 5-15 cm soil layer. Tractor traffic increased the RLD value in a root diameter range of 0.1-0.5 mm. However, any other morphometric parameters, like mean root diameter (MD), specific root length (SRL) or dry root diameter (RDM) were not affected by soil compaction.

Keywords: meadow fescue, yields, roots, image analysis, soil compaction, tractor traffic

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. Nowadays, soil compaction is recognized as one of the main factors that can lower crop yields, thus is a serious agricultural problem. Many researchers agree that soil compaction leads to plant yield reduction [1, 2], including decreased production of perennial forage crops [3-5]. This yield decline is the consequence of both soil compaction and shoot injury caused by wheel traffic. It is a serious problem for perennial crops, where the soil is wheeled without ever being loosened. Soil strength is increased year

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after year, and all machine traffic during field operation cause direct damage to plants. These damages are reported as more important in decreased plant yield than soil compaction [6]. 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 [7]. These trends could be attributed to better water and nutrient supply and recovery of soil pore system [8].

The degraded soil physical environment due to compaction influences not only shoots but also root growth and development. Soil compaction increases mechanical impendence, creates unfavourable growing conditions for roots and restricts oxygen, water and nutrient supplies [9-12]. 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 [13, 14]. 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 heterogeneous root distribution [15]. However, changes in root system appearance do not necessarily cause alteration in above-ground growth or yield [16]. Overall, it is sometimes difficult to consistently quantify in field trials the relation between root growth and plant yield.

The main objective of the research reported in this paper was to evaluate the effect of multiple tractor passes on meadow fescue yields. For this purpose a field trial was established in 2004-06 on silty loam Mollic Fluvisol in southern Poland. The soil and climate conditions were typical for grassland production in this region of Europe. Dry matter production of above-ground shoots and roots were measured with a special focus on root morphometric parameters.

Material and Methods

Site, Location and Climate

This study was conducted as a field experiment located in Mydlniki near Kraków (50º04'N, 19º51'E) at the Department of Machinery Exploitation, Ergonomics and Agronomy Fundamentals, Agricultural University of Kraków, Poland, in 2004-06. The climate of the experimental site, in southern Poland, is temperate. Data from the meteorological station located at the site are presented in Table 1.

Field Trial Design and Treatments

The field experiment was located on silty loam Mollic Fluvisol [17]. The soil was developed from fluvioglacial sediments covered by loess deposits. Table 2 reports some soil characteristics. The soil before trafficking was ploughed and harrowed in 2003 due to seedbed preparation, then meadow fescue (*Festuca pratensis*) seeds were sown at a rate of 48 kg ha^{-1}. Fertilization was applied every year at a rate of 100 kg N ha^{-1}, 26 kg P ha^{-1} and 66 kg K ha^{-1}.

Table 1. Monthly and annual temperatures and accumulated rainfall for the study period and long-term averages.

	1961-99	2004	2005	2006
	Monthly average temperature [ºC]			
January	-3.3	-7.8	1.2	-2.4
February	-1.6	-0.3	4.3	-3.0
March	2.4	1.1	-0.2	0.2
April	7.9	7.3	6.8	5.6
May	13.1	10.6	11.4	10.9
June	16.2	14.6	14.4	15.0
July	17.5	16.0	17.6	18.6
August	16.9	17.0	15.4	15.6
September	13.1	12.3	12.5	13.4
October	8.3	7.1	7.1	9.1
November	3.2	3.6	3.9	6.3
December	-1.0	-1.3	-0.7	0.9
Annual mean	*7.7*	*6.7*	*7.8*	*7.5*
	Precipitation [mm]			
January	34	36	66	58
February	32	57	33	49
March	34	51	21	60
April	48	32	49	57
May	83	43	61	52
June	97	56	41	89
July	85	92	113	14
August	87	75	103	104
September	54	30	27	17
October	46	49	8	32
November	45	30	30	21
December	51	31	47	16
Annual sum	*696*	*582*	*598*	*568*

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

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	Mg m^{-3}	2.53
Bulk density	Mg m^{-3}	1.49
Sand	%	29
Silt	%	67
Clay	%	4
Texture		Silty loam

Experimental plots were established in randomized block design with four replications, with a plot area of 9 m^2. Four compaction treatments were applied by tractor using a following range of number of passes: (P0) untreated control, (P2) two passes, (P4) four passes and (P6) six passes completely covering plot surface. The wheel tracking treatments were designed to simulate potential combinations of field operations from cutting, tedding, lifting and fertilizing. An URSUS C-360 tractor of 2056 kg weight was used for traffic simulation. The inflation pressure of the front tires (6.00-16) of tractor was 150 kPa and that of rear tires (14.9-28) 100 kPa. The multiple passes were applied after every harvest in wheel-beside-wheel design, three times a year. Harvest dates were: 24 May, 19 July and 13 September in 2004; 23 May, 21 July and 15 September in 2005; 5 June, 18 July and 12 September in 2006. The dry matter (DM) of the yield was determined by drying a subsample of 500 g at 70ºC to a constant weight.

Measurements of Soil Physical Properties

The soil samples were collected in September 2006, after the third harvest. Three soil layers: 0-10, 10-20 and 20-30 cm, were chosen for the investigation. Dry bulk density was measured by taking samples of soil using a corer with a 100 cm^3 volume sample ring in four replications for every plot [18]. The samples were weight and dried (105ºC) until they reached a constant weighed. Total porosity was calculated from solid phase density (2.56 Mg m^{-3}) and dry bulk density of the samples. The penetration resistance was measured using STIBOKA penetrometer (Ejkelkamp Agrisearch Equipment, The Netherlands) with a cone base area of 100 mm^2 and 60º cone angle [19].

Sampling and Analysis of Roots

Roots were sampled using the soil-core method [20] in autumn 2006. The core diameter was 80 mm. Samples were taken from a 15 cm depth and were divided into 3 sections: 0-5, 5-10 and 10-15 cm. Roots were washed using a hydropneumatic elutriation system [21] 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 the 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: 0-0.02, 0.02-0.05, 0.05-0.1, 0.1-0.2, 0.2-0.5, 0.5-1.0, 1.0-2.0 and >2.0 mm. Root length density RLD was calculated by dividing total root length by sample volume. Specific root length SRL was calculated by dividing total root length by root dry weight. Mean diameter MD was calculated as weighted mean of root length for particular diameter classes. After scanning, roots were dried at 70ºC for dry matter determination (RDM).

Table 3. Physical properties of soil related to four compaction levels applied in the field experiment.

Treatments	Bulk density	Total porosity	Penetration resistance
	(Mg m^{-3})	(cm^3 cm^{-3})	(MPa)
0-10 cm soil depth			
P0	1.43 c	0.441 a	2.14 a
P2	1.47 b	0.426 b	2.28 ab
P4	1.48 b	0.421 b	2.30 ab
P6	1.52 a	0.405 c	2.47 b
10-20 cm soil depth			
P0	1.42 c	0.445 a	2.45 a
P2	1.50 b	0.415 b	2.55 a
P4	1.53 ab	0.402 bc	2.57 a
P6	1.56 a	0.391 c	2.50 a
20-30 cm soil depth			
P0	1.45 b	0.435 b	2.20 a
P2	1.47 ab	0.426 bc	2.33 a
P4	1.51 a	0.410 c	2.38 a
P6	1.49 ab	0.418 bc	2.32 a

Means in the same column followed by the same letters are not significantly different ($P<0.05$).

Statistics

An analysis of variance for a randomized block 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 $P<0.05$.

Result and Discussion

Bulk Density, Penetration Resistance

The results in bulk density, total porosity and penetration resistance are given in Table 3. The mean bulk density of the investigated soil was 1.50 Mg m^{-3}, which was in the range of bulk density typical for agricultural soil, which usually varies from 1.4-1.6 Mg m^{-3} depending on texture, organic mater content etc. [22]. The tractor traffic applied significantly affected measured physical parameters of soil. The more intensive wheeling was applied the higher bulk density was recorded. The bulk density at the P0, untreated control, was 1.43 Mg m^{-3} on average at the 0-30 cm soil layer. The highest value of bulk density was recorded in the 10-20 cm soil layer at P6 treatment. The opposite effect was recorded in total porosity.

The intense tractor traffic resulted in a decrease in total porosity. The lowest value was observed at the P6 treatment (0.391 cm^3 cm^{-3} in the 10-20 cm soil layer). The increase in number of tractor passes resulted in increase in penetration resistance. However, the impact of tractor traffic in penetration resistance was noticed only in the 0-10 cm soil layer. The tractor wheeling resulted in higher penetration resistance at the P6 treatment (2.47 MPa) with respect to control untreated (2.14 MPa). The highest value of penetration resistance was noticed in the 10-20 cm soil layer (2.52 MPa in average). These relations in physical properties of soil were widely confirmed by many authors [11, 23].

Root Growth

The mean RDM value of total investigated soil layer (0-15 cm) was 0.00828 g cm^{-3}. The highest root concentration was found in the upper (0-5 cm) soil layer. There was approximately 79% of dry root matter (RDM), whereas in the 5-10 and 10-15 cm soil layer, there were only 14% and 7%, respectively (Fig. 1). A similar relationship was obtained for RLD values, where the participations of roots were 71, 15 and 14% for the 0-5, 5-10 and 10-15 cm soil layers, respectively (Fig. 2). According to Bengough and Mullins [24] classification, the roots of meadow fescue belong to root density class described as 'very dense' (RLD >20 cm cm^{-3}).

Applied tractor traffic significantly changed the RLD parameter in the 5-15 cm soil layer. Although the main root concentration was located at 0-5 cm soil depth, there was not any significant influence of tractor traffic. The tractor traffic decreased the RLD in a root diameter range of 0.1-0.5 mm (Fig. 3). The differences were significant only between control (P0) and treated plots (P2, P4 and P6). Both the MD and SRL parameters were not altered by multiple passes of tractors (Figs. 4 and 5). The mean root diameter was 0.36 mm in the upper soil layer and slightly decreased in the 5-10 cm (0.32 mm) and 10-15 cm soil layer (0.30 mm). The opposite effect was observed due to SRL parameter. The lowest value (6519 cm g^{-1}) was noticed in the 0-5 cm and it increased to 7887 and 8809 cm g^{-1} in the 5-10 and 10-15 cm soil layers, respectively.

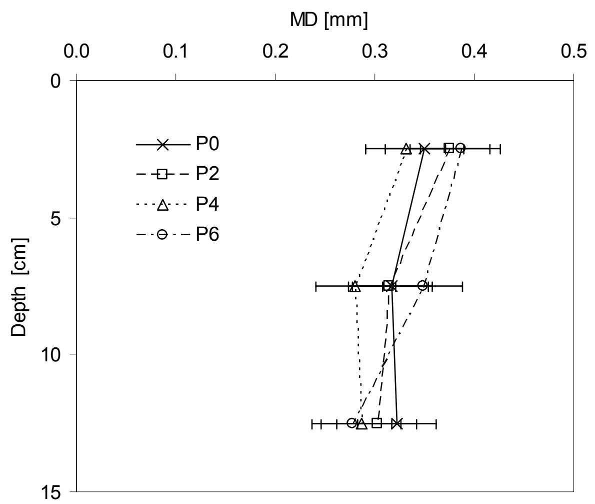

Fig. 1. Effect of tractor traffic on meadow fescue root dry matter (RDM) distribution in three soil layers. Horizontal bars represent standard errors.

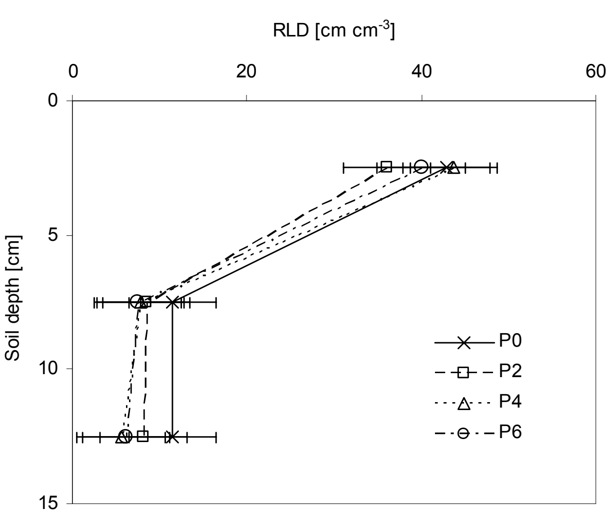

Fig. 2. Effect of tractor traffic on meadow fescue root length density (RLD) distribution in three soil layers. Horizontal bars represent standard errors.

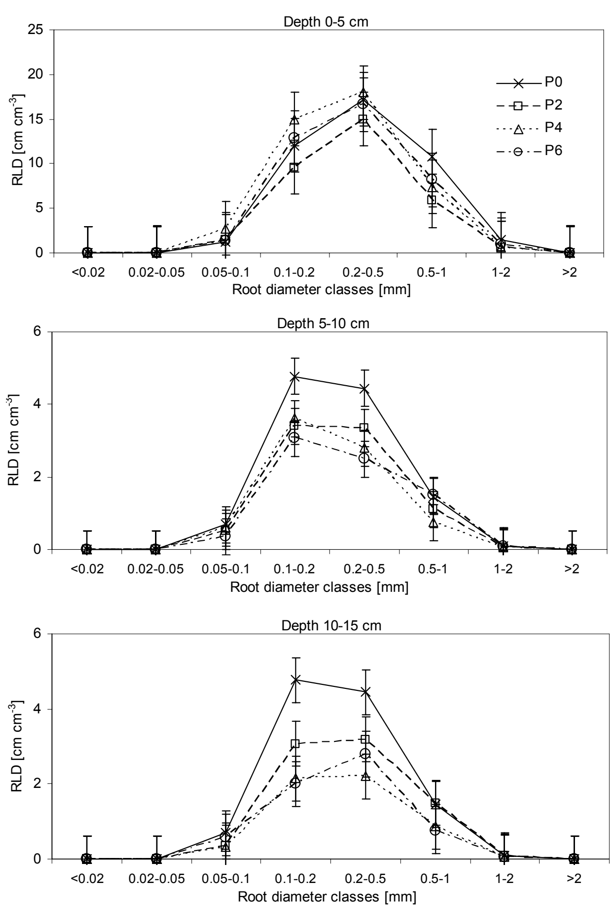

Fig. 3. Effect of tractor traffic on meadow fescue root length density (RLD) distribution for different root diameter classes. Vertical bars represent standard errors.

Many researchers reported that a common response of the root system to increasing bulk density is to decrease its length and concentrating roots in the upper soil layer [13, 14]. The results obtained in the current experiment with meadow fescue confirmed this trend. Sometimes the positive correlation between soil density and root characteristics was observed, particularly for perennial crops [25, 26]. In the investigation with tall fescue (*Festuca arundinacea*) soil compaction increased the dry matter, length of roots and their diameter [27]. Ryegrass (*Lolium perenne*) was also found as a species with better growing conditions in rather compacted soil [16]. The results presented in this study indicated that meadow fescue can be described as a species more sensitive to soil compaction than ryegrass and tall fescue.

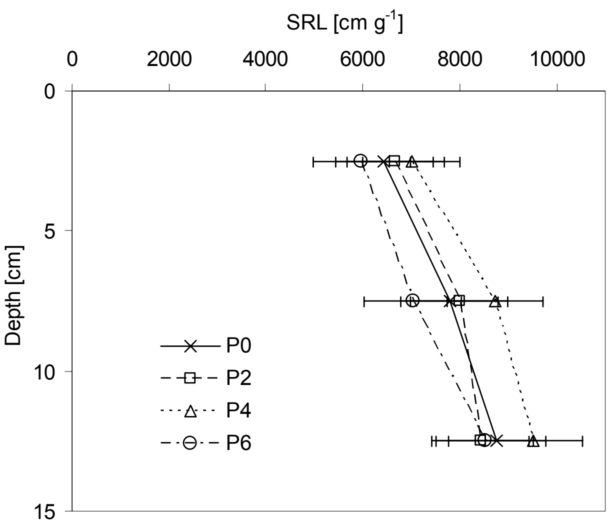

Fig. 4. Effect of tractor traffic on meadow fescue specific root length (SRL) distribution in three soil layers. Horizontal bars represent standard errors.

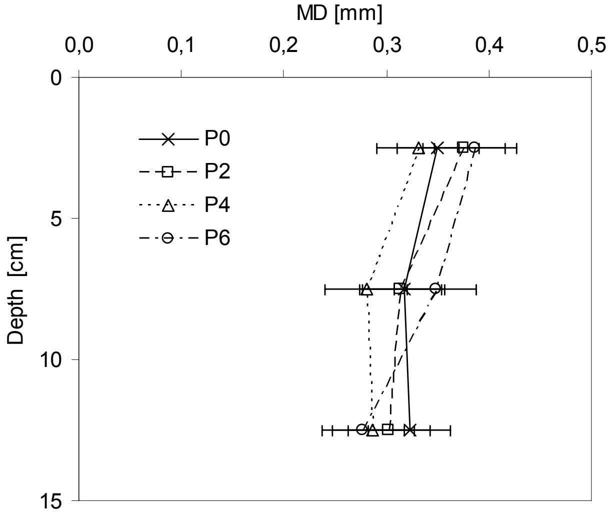

Fig. 5. Effect of tractor traffic on meadow fescue root mean diameter (MD) distribution in three soil layers. Horizontal bars represent standard errors.

DM Production

The mean annual yield of meadow fescue was 6.92 t DM ha^{-1} (Table 4). Three cuts were obtained every year and they were 42, 34 and 24% of total annual yield. There was significant influence of treatment applied on DM production. The P2 and P4 treatments resulted in the highest herbage production, 7.01 and 7.11 t DM ha^{-1} on average, respectively. Significantly lower values were noticed for the P0 and P6 treatments (6.76 and 6.78 t DM ha^{-1}) (Fig. 6). However, the different effect of tractor traffic on herbage production for particular terms of harvests was observed. During the spring harvest dry matter production was higher at strongly compacted plots with respect to untreated control. This effect was probably a result of a long period of time between the spring harvests and the third harvests and trafficking simulations in the previous year. During this time plants recovered and regenerated damage to shoots caused by tractor wheels. The pressure of tractor tires during the passes caused mechanical injuries to above-ground parts of plants. This resulted in delay in plant growth after harvests, as found by the author in research with *Dactylis glomerata* [28]. However, this effect was noticed only in the thirst phase (two or three weeks) of regrowth. Plants strongly compacted by tractor wheels needed more than three weeks to cure injuries and the beginning of the intensive regrowth phase was delayed. These changes in growth dynamics resulted in the final height of plants and their DM production. The investigation into the influence of tractor traffic on DM production of *Phleum pratense* and *Lolium perenne* indicated that the yields obtained at the first harvest were not affected by tractor passes [29]. The differences between treatments become significant during the second and the third harvest. The similar interaction between the term of harvest and tractor traffic was also reported by the author for tall fescue [27].

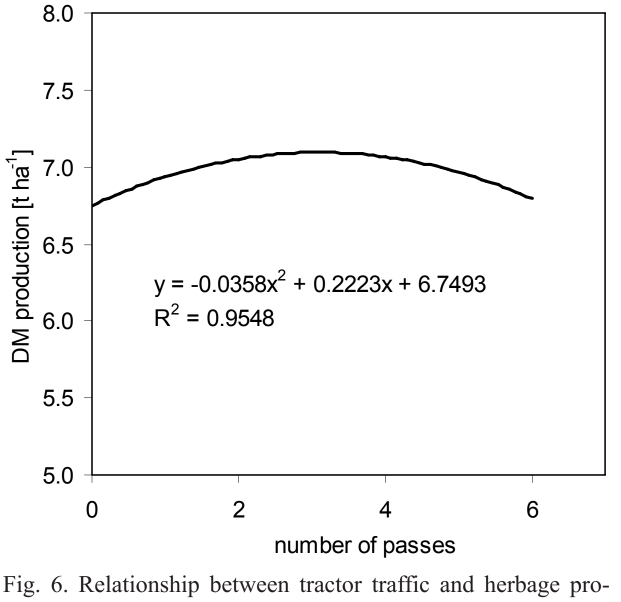

Fig. 6. Relationship between tractor traffic and herbage production (t DM ha^{-1}) of meadow fescue.

Table 4. Effect of tractor traffic on herbage production (t DM ha^{-1}) of meadow fescue at field trial in 2004-06.

Treatments	DM production t ha^{-1}			
	1st cut	2nd cut	3rd cut	Total annual
2004				
P0	2.94 a	3.00 ab	1.70 a	7.64 a
P2	2.87 a	2.93 ab	1.68 a	7.48 ab
P4	2.84 a	3.04 a	1.71 a	7.58 ab
P6	2.85 a	2.84 b	1.64 a	7.33 b
2005				
P0	2.41 b	2.11 b	1.89 ab	6.42 b
P2	2.70 a	2.41 a	1.93 a	7.04 a
P4	2.74 a	2.24 a	2.05 a	7.03 a
P6	2.89 a	2.18 ab	1.72 b	6.79 ab
2006				
P0	3.11 b	1.83 ab	1.29 a	6.23 b
P2	3.10 b	1.93 a	1.48 a	6.51 a
P4	3.32 a	2.01 a	1.38 a	6.71 a
P6	3.29 a	1.65 b	1.29 a	6.22 b

Means in the same column followed by the same letters are not significantly different ($P<0.05$).

During the second and third cuts the plant yielding was significantly decreased at the P6 treatment. This effect has been confirmed by results obtained by many authors [3, 4].

Conclusions

The tractor traffic treatments applied affect soil physical parameters. Bulk density of soil under perennial grass was increased with increases in the number of tractor passes. These results support the hypothesis that intensive tractor traffic played an unfavorable role in physical properties of soil. However, this effect was clearly identified in the 10-20 cm soil layer (bulk density of 1.50 g cm^{-3}), whereas the upper, 0-10 cm layer, was characterized by lower bulk density (1.48 g cm^{-3}). The meadow fescue root system was significantly affected by tractor traffic only in the 5-15 cm soil layer. Tractor traffic increased the RLD value in a root diameter range of 0.1-0.5 mm. However, any other morphometric parameters, like mean root diameter (MD), specific root length (SRL) or dry root diameter (RDM), were not affected by soil compaction. The tractor traffic resulted in changes in meadow fescue annual yields. However, the interaction between terms of harvest and number of passes were observed. In the first cut the increase in number of passes increased plant yields. During the second and the third cut the intensive tractor traffic decreased plant yields, probably as an effect of damage caused to above-ground parts of plants.

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