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Effect of soil compaction on root system development and yields of tall fescue

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A b s t r a c t. Soil compaction caused by tractor traffic is one of the most important factors responsible for environmental degradation and leads to plant yields reduction. It is a serious problem for perennial crops, where the soil is wheeled and compacted without ever being loosened. The aim of this study was to evaluate the effect of tractor traffic on tall fescue (*Festuca arundinacea*) yields and roots development. The field experiment was located in Mydlniki near Cracow, Poland, on silty loam Mollic Fluvisol. Experimental plots were established in completely randomised 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 plots surface 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, and root length density (RLD), specific root length (SRL) and mean diameter (MD) were calculated. Bulk density of soil under perennial grass was increased with increase in the number of tractor passes. The tractor traffic resulted in significant decrease in tall fescue annual yields. However, this effect was not observed during the first cut, when the yields were equal for all the treatments. The soil compaction caused by multiple tractor passes changed the morphology and distribution of roots. More roots were found at compacted objects (RLD above 40 cm cm^{-3} at P4 treatment) with respect to untreated control, P0 (26 cm cm^{-3}). These roots were also significantly thicker. The MD value ranged from 0.44 mm at P4 treatment to 0.31 mm at P0.

K e y w o r d s: tall fescue, yields, roots, image analysis, soil compaction, tractor traffic

INTRODUCTION

Agricultural production systems tend to increase the number of passes and the loads carried on agricultural vehicles, resulting in soil compaction hazard. Nowadays, soil compaction is recognized as one of the main factors that can lower crop yields and thus is a serious agricultural problem. Many researchers agree that soil compaction leads to plant yield reduction (Domżał *et al*., 1987; Soane *et al*., 1982), including decreased production of perennial forage crops (Douglas, 1997; Frame, 1985; 1987; Frame and Merrilees, 1996; Kopeć and Głąb, 1998). 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-after-year and all machine traffic during field operation cause direct damage to plants. The damage is reported as more important in decreased plant yield than soil compaction (Meek *et al*., 1988). 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 than in non-compacted soil (Dwyer and Stadie, 1989; Frost, 1998). These trends could be attributed to better water and nutrient supply and recovery of soil pore system (Morrison *et al*., 1980).

Soil physical environment degraded due to compaction influences not only shoots but also roots growth and development. Soil compaction increases mechanical impendence, creates unfavourable growing conditions for roots, and restricts oxygen, water and nutrients supply (Bengough and Mullins, 1990; Cook *et al.*, 1996; Dexter, 1986; Lipiec and Stępniewski, 1995; Taylor and Brar, 1991). 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 (Lipiec *et al*., 1991; 1992). Strongly compacted soils are usually penetrated by roots in cracks, fissures and biopores (macropores formed by earthworms). This provides advantage to elongating roots but also results in heterogeneous root distribution (Asady and Smucker,

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1989; Logsdon and Linden, 1992). However, changes in root system appearance do not necessarily cause an alteration in above-ground growth or yield (Kopeć and Głąb, 2002; Taylor and Brar, 1991). Overall, it is very 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 tall fescue yields. For this purpose a field trial was established in 2004-2006 on silty loam Mollic Fluvisol in the south of Poland. The soil and climate condition were typical for grassland production in this region of Europe. Dry matter production of above ground shoots and of roots were measured with special focus on roots morphometric parameters. A soil physical property such as bulk density was also determined.

MATERIAL AND METHODS

Site, location and climate

This study was conducted as a field experiment located in Mydlniki near Cracow at the Department of Machinery Exploitation, Ergonomics and Agronomy Fundamentals, Agricultural University of Cracow, Poland, in 2004-2006. 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.

Field trial design and treatments

The field experiment was located on silty loam Mollic Fluvisol (FAO, 1998). The soil was developed from fluvio-glacial sediments covered by loess deposits. Table 2 reports some soil characteristics. Before trafficking the soil was ploughed and harrowed in 2003 due to seedbed preparation, then tall fescue (*Festuca arundinacea*) seeds were sown at the rate of 41 kg ha^{-1}. Fertilization was applied every year, at the rate of 100 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1} and 80 kg K_2O ha^{-1}. Experimental plots were established in completely randomised design with four replications, with a plot area of 9 m^2. Four compaction treatments were applied by a tractor, using the following range of number of passes: (P0) untreated control, (P2) two passes, (P4) four passes and (P6) six passes completely covering plots surface. The wheel tracking treatments were designed to simulate potential combinations of field operations from cutting, tedding, lifting and fertilizing. The URSUS C-360 tractor of 2056 kg weight was used for traffic simulation. The inflation pressure of the front tires (6-16) of the tractor was 150 kPa and that of the 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: 24th May, 19th July and 13th September in 2004; 23rd May, 21st July and 15th September in 2005; 5th June, 18th July and 12th September in 2006. The dry matter (DM) of the yield was determined by drying a subsample of 500 g at 70°C to a constant weight.

T a b l e 1. Monthly and annual temperatures and cumulated rainfall for the study period and long-term averages

Month/Year	2004	2005	2006	1961-99
		Monthly average temperature (°C)		
March	1.1	-0.2	0.2	2.4
April	7.3	6.8	5.6	7.9
May	10.6	11.4	10.9	13.1
June	14.6	14.4	15.0	16.2
July	16.0	17.6	18.6	17.5
August	17.0	15.4	15.6	16.9
September	12.3	12.5	13.4	13.1
October	7.1	7.1	9.1	8.3
November	3.6	3.9	6.3	3.2
Annual mean	6.8	6.9	7.5	7.7
		Sum of precipitation (mm)		
March	51	21	60	34
April	32	49	57	48
May	43	61	52	83
June	56	41	89	97
July	92	113	14	85
August	75	103	104	87
September	30	27	17	54
October	49	8	32	46
November	30	30	21	45
Annual sum	582	598	568	681

T a b l e 2. Mollic Fluvisol (silty loam) characteristics from trial location (0-25 cm layer)

Sand	$g\ kg^{-1}$	290
Silt		670
Clay		40
Total organic C		25.8
Total N		2.10
C/N		12.3
pH (KCl)		6.5

Sampling and analysis of roots

Roots were sampled using the soil-core method (Böhm, 1979) in autumn, 2005. 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 (Smucker *et al*., 1982) to remove mineral particles from the samples. Before scanning, all 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 analysed using APHELION software for image analysis (ADCIS S.A. and Amerinex Applied Imaging) and roots 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. 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 the total root length by the 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 70°C for dry matter determination (RDM).

Statistics

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

RESULTS AND DISCUSSION

Bulk density of soil

The results in bulk density are given in Fig. 1. The mean bulk density of the investigated soil was 1.5 g cm^{-3}, which was in the range of bulk density typical for agricultural soil that usually varies from 1.4 to 1.6 g cm^{-3} depending on texture, organic mater content, *etc*. (Słowinska-Jurkiewicz, 1994). The tractor traffic applied significantly affected bulk

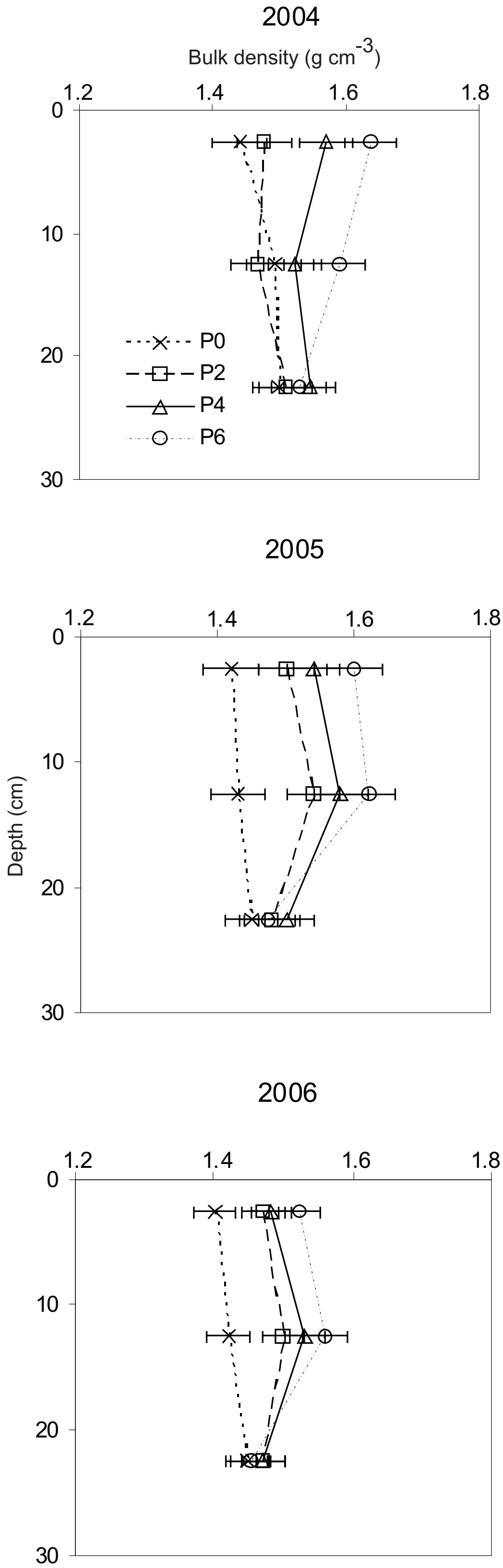

Fig. 1. Effect of tractor traffic on bulk density in the three years of the experiment (2004-2006). Horizontal bars represent standard errors.

density. The highest increase in bulk density was noticed in 2004. Significant differences were observed in the 0-5 and 10-15 cm soil layers. The more intensive wheeling applied the higher value of bulk density was recorded. This relation was widely confirmed by many authors (Soane *et al.*, 1981; Domżał and Hodara, 1991; Pagliai *et al.*, 2003). In 2005 and 2006 a slight decrease of bulk density in the upper soil layer was noticed with respect to 10-15 cm. However, these differences were not statistically significant.

Root growth

The highest root concentration was found in the upper soil layer. There was approximately 56% of dry root matter (RDM), whereas in the 5-10 and 10-15 cm soil layer there were only 26 and 18%, respectively (Fig. 2a). A similar relationship was obtained for RLD values, where the participations of roots were 56, 22 and 22% for the 0-5, 5-10 and 10-15 cm soil layers, respectively (Fig. 2b). According to Bengough and Mullins (1990) classification, the roots of tall fescue belong to root density class described as 'very dense' (RLD >20 cm cm^{-3}).

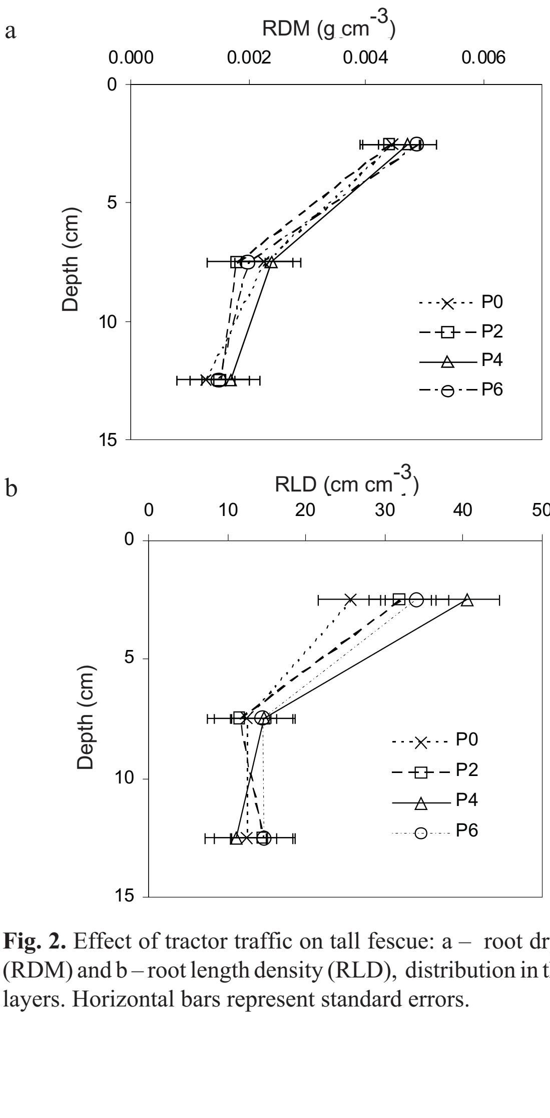

Fig. 2. Effect of tractor traffic on tall fescue: a – root dry matter (RDM) and b – root length density (RLD), distribution in three soil layers. Horizontal bars represent standard errors.

The tractor traffic significantly changed the root morphometric properties. However, the changes were noticed only in the upper, 0-5 cm, soil layer. The P6 and P4 treatments significantly increased length of roots in their diameter range of 0.2-1.0 mm. The root length distribution in particular root diameter classes is presented in Fig. 3. The highest RLD value, above 40 cm cm^{-3}, was noticed at P4 treatment, whereas in P0, untreated control, RLD was 26 cm cm^{-3}. Below the depth of 5 cm the RLD was only 13 cm cm^{-3} on average. Both the RDM and SRL parameters were not altered by multiple passes of tractor (Fig. 4). The MD value (Fig. 4) was significantly higher at P4 and P6 treatments (0.44 and 0.41 mm) with respect to P2 and P0 (0.33 and 0.31 mm). However, these changes were noticed only in the 0-5 cm soil layer. It can be stated that more roots were found in compacted soil due to tractor traffic. These roots were also significantly thicker.

The positive correlation between soil density and roots characteristics was confirmed by Ball-Coello *et al.* (1998). They stated that root length density was positively associated with capillary pore space and aggregation. Increased bulk density can trigger lateral root formation, and in this way contribute to greater root development in the top 10 cm of compacted soil. Schoonderbeek and Schoute (1994) also found a negative relationship between high macroporosity (pores with diameter >30 μm) and root length. In soil with greater macroporosity there were fewer roots than in compacted soil. In their case, horizontal cracking caused by wheel traffic compaction resulted in more horizontal root growth. The changes in roots morphology described above were attributed in some cases to increased moisture conditions (McCalla and Army, 1961) and in others to greater soil strength that reduced elongation of root main axes and stimulated branching (Cannell and Hawes, 1994). Many researchers reported that a common response of the root system to increasing bulk density is to decrease its length and to concentrate roots in upper layer (Gliński and Lipiec, 1990; Jurcova and Zrubec, 1989; Lipiec *et al.*, 1991; 1992). However, these works concerned mainly annual species. The results obtained in the current experiment with perennial species did not confirm this trend.

DM production

The mean annual yield of tall fescue was 8.56 t DM ha^{-1} (Fig. 5). 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 tractor traffic decreased the DM values. It was particularly noticeable during the second and third cuts. For the second cut the decrease of the P2 yield was 95% on average with respect to the P0, for the P4 and P6 it was 83 and 79%, respectively. The yield decrease at the third cut was very similar and it was 96, 83 and 82% for the P2, P4 and P6, respectively. These results are confirmed by those obtained

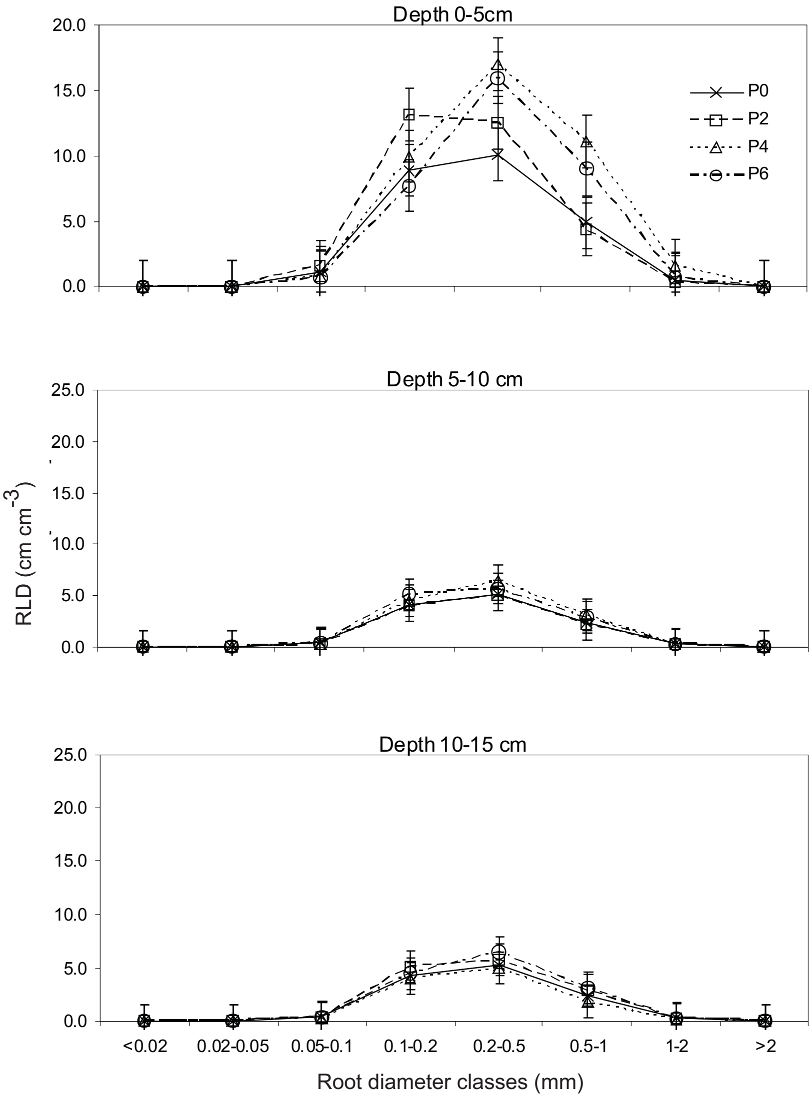

Fig. 3. Effect of tractor traffic on tall fescue root length density (RLD) distribution for different root diameter classes. Vertical bars represent standard errors.

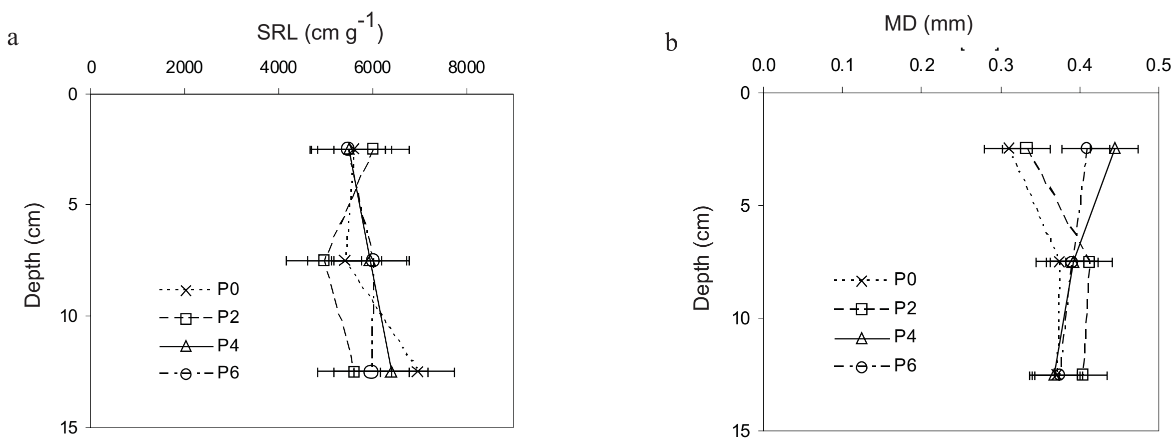

Fig. 4. Effect of tractor traffic on tall fescue: a – specific root length (SRL), and b – root mean diameter (MD), distribution in three soil layers. Horizontal bars represent standard errors.

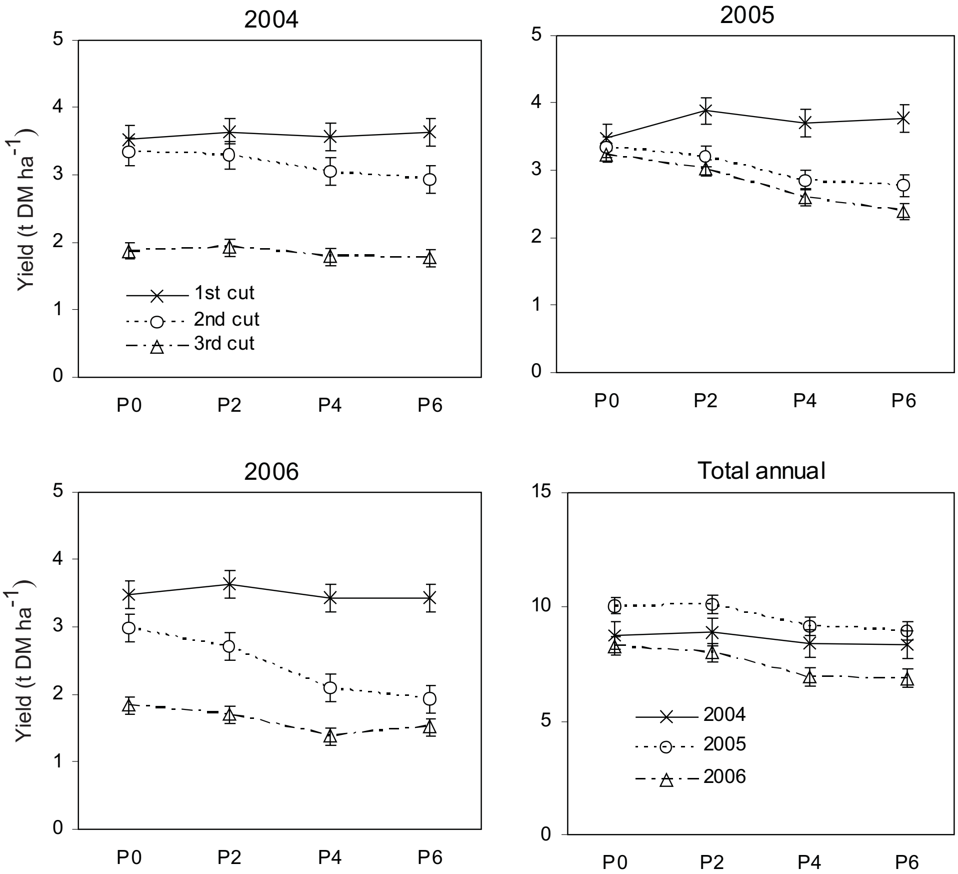

Fig. 5. Effect of tractor traffic on tall fescue dry matter (DM) production in three years of experiment and total annual DM. Vertical bars represent standard errors.

by many authors (Douglas, 1997; Frame, 1985; 1987; Frame and Merrilees, 1996). The exception was the first cut in 2005 when increase in the number of passes also increased the plants yields. Also during the first cut in 2006 the differences between treatments disappeared. This effect was probably a result of the long period of time between the first harvests in 2005 and the third harvests and traffic simulations in previous year. During this time plants recovered and regenerated damage to shoots caused by tractor wheels.

CONCLUSIONS

1. The tractor traffic treatments applied affect the soil physical parameters. Bulk density of soil under perennial grass was increased with increase in number of tractor passes. These results support the hypothesis that intensive tractor traffic plays an unfavorable role in physical properties of soil. However, this effect was clearly identified in the 5-10 cm soil layer. The upper, 0-5 cm layer, was characterized by lower bulk density (1.48 g cm^{-3}) with respect to 5-10 cm soil layer (1.5 g cm^{-3}). Bulk density slightly decreased during the experiment, especially in compacted soil.

2. The roots were significantly affected by tractor traffic only in the 0-5 cm soil layer. More roots were found in compacted soil (RLD above 40 cm cm^{-3}). These roots were also significantly thicker (MD of 0.44 mm). The permanent tractor passes increased the dry matter and length of roots only in their diameter of 0.2-1 mm, in the range from 26 cm cm^{-3} at untreated control to 41 cm cm^{-3} when very intensive (4 passes at each harvest term) tractor traffic was applied.

3. Tractor traffic results in changes in tall fescue annual yields. However, the interaction between terms of harvest and number of passes was observed. In the first cut it was noticed that increase in the number of passes increased the plants yields. These results correspond with those obtained in the length and dry matter of roots. During the second and the third cut it was found that multiple passes decreased plant yields, probably as an effect of damage caused to above ground parts of plants.

4. The results obtained in this experiment indicate that tall fescue found the optimal growing condition in rather compacted soil but could not be recommended when intensive traffic is present.

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