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Root and shoot development in winter crops in soils of different textures and degrees of compaction[1]

Desenvolvimento radicular e da parte aérea de cultivos de inverno em solos com diferentes texturas e graus de compactação

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ABSTRACT - Compaction is one of the main physical factors of the soil to affect plant development. The aim of this study was to evaluate root and shoot development in winter plants grown in soils of different textures under varying degrees of soil compaction (DSC). The experiment was conducted in a greenhouse of the State University of Ponta Grossa, in the south of Brazil. Wheat (*Triticum aestivum*) and an intercropping system of black oats (*Avena strigosa*) and forage turnip (*Raphanus sativus*) were tested in a sandy loam Cambisol and a clayey loam Latosol under a DSC of 85%, 90%, 95% and 100% of the maximum bulk density in a completely randomised design with four replications. Each plot consisted of one PVC column, 0.1 m in diameter and 0.2 m in height, comprising three cylinders placed one on top of the other, with a respective height of 0.08, 0.04 and 0.08 m. The sub-surface layer (0.08-0.12 m) was compacted, and corresponded to the middle cylinder. In the compacted sub-surface layer, the intercropped black oats and forage turnip presented 28.5% more root dry matter (RDM) than did the wheat. The total RDM decreased by 32% for an increase of 85% to 100% in the DSC, where both the compacted sub-surface layer (0.08-0.12 m) and the layer below that (0.12-0.2 m) were most affected, with a reduction of 45.2% and 53%, respectively. Considering the conditions of this study, which evaluated soils that offer no water or chemical restrictions on the plants, shoot dry matter (SDM) was less affected than the roots, decreasing by 12% for an increase of 85% to 100% in the DSC. There was no difference between the types of soil on crop response due to the variation in the DSC.

Key words: Soil physics. Relative density. Cover crops. Sub-surface compaction.

RESUMO - A compactação é um dos principais fatores físicos do solo que afetam o desenvolvimento vegetal. A pesquisa objetivou avaliar o desenvolvimento aéreo e radicular de plantas de inverno cultivadas em solos de diferentes granulometrias e submetidos a diferentes graus de compactação do solo (GCS). O experimento foi conduzido em casa de vegetação na Universidade Estadual de Ponta Grossa. Foram testados o trigo (*Triticum aestivum*) e o consórcio de aveia preta (*Avena strigosa*) + nabo forrageiro (*Raphanus sativus*) em Cambissolo franco arenoso e Latossolo franco argiloso nos GCS de 85, 90, 95 e 100% da densidade máxima, no delineamento experimental inteiramente casualizado com quatro repetições. Cada parcela era formada por uma coluna de PVC com diâmetro de 0,1 m e altura de 0,2 m, composta por três anéis sobrepostos com altura de 0,08, 0,04 e 0,08 m respectivamente na porção superior, intermediária e inferior. A camada compactada foi a subsuperficial (0,08-0,12 m), correspondente ao anel intermediário. O consórcio de espécies apresentou massa seca de raízes (MSR) 28,5% superior ao trigo na camada subsuperficial compactada. A MSR total diminuiu 32% com o aumento de 85 para 100% no GCS, sendo a camada compactada (0,08-0,12 m) e a camada abaixo dela (0,12-0,2 m) as mais afetadas, com redução de 45,2 e 53%, respectivamente. Considerando as condições deste estudo, o qual avaliou solos sem restrições hídricas e químicas para as plantas, a massa seca de parte aérea (MSA) foi menos afetada que as raízes, pois diminuiu 12% com o aumento de 85 para 100% no GCS. Não houve diferença entre o tipo de solo sobre a resposta das culturas devido a variação no GCS.

Palavras-chave: Física do solo. Densidade relativa. Plantas de cobertura. Compactação subsuperficial.

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INTRODUCTION

The no-tillage system is a type of management practice whose purpose is to reduce soil degradation by eliminating soil preparation prior to sowing, maintaining ground cover by using crop residue and living plants, and using crop rotation (BOLLIGER *et al*., 2006; INAGAKI *et al*., 2021). On the other hand, the formation of a compacted layer of soil is common under this management system (COLLARES *et al*., 2008; PRAZERES *et al*., 2020), and can hamper root growth. This is the result of not adopting the principles of a no-tillage system. Among the causes that generate soil compaction is the pressure imposed on the soil by machine traffic under inadequate soil moisture, together with a lack of diversification of plant species and, often, poor ground cover afforded by the crop residue (BARETA JUNIOR *et al*., 2022; LIMA; PETTER; LEANDRO, 2015).

The greatest degree of compaction under a no-tillage system usually occurs in the sub-surface layer of soil, restricting root development (BENGOUGH *et al*., 2011; NOSALEWICZ; LIPIEC, 2014) and, as a result, impairing the absorption of water and nutrients by the plants (PARLAK; PARLAK, 2011) and reducing agricultural productivity (CHEN; WEIL, 2011).

To reduce soil compaction under a no-tillage system, and increase ground cover, farmers in the south of Brazil use cover crops during the winter, generally alternating with wheat (*Triticum aestivum*), which is the species with the greatest commercial value during this season. Black oats (*Avena strigosa*) and the forage turnip (*Raphanus sativus*), whether as single crops or in an intercropping system, are among the principal crops used as cover (GIMENEZ *et al*., 2021). Black oats stand out for their high biomass yield, ease of seed acquisition, robustness, rapid cover formation, and slow decomposition of the plant residue (SILVA *et al*., 2006; WOLSCHICK *et al*., 2018). The forage turnip is characterised by rapid initial growth, a greater rate of residue decomposition, the rapid release of nutrients to successor crops, and aggressive roots (INAGAKI *et al*., 2021; NAGAOKA; SILVEIRA, 2012).

Bulk density is an important parameter for evaluating soil compaction and comparing the effects of different plants on the physical attributes of the soil (REICHERT; REINERT; BRAIDA, 2003). However, there is no consensus on the critical levels for bulk density that might limit plant development, since bulk density results in crop-response curves and optimal values for crop yield that are different in different types of soil. Efforts have therefore been made to find a parameter that would eliminate, as far as possible, the differences between soils relative to crop-response curves and optimal yield values (HAKANSOON; LIPIEC, 2000).

The degree of soil compaction (DSC) is a physical parameter of the soil, determined as the ratio of the current bulk density evaluated in the field to the maximum bulk density estimated in the laboratory by the Proctor test (ANDOGNINI *et al*., 2020; KLEIN, 2006). Bulk density can therefore be expressed in relative terms and, if different values for density are found in different soils, these can be converted into a degree of compaction, which can eliminate most of the differences in crop responses between soils (HAKANSOON; LIPIEC, 2000; SILVA; KAY; PERFECT, 1997). Recent studies indicate the applicability of the DSC to evaluating the physical quality of the soil, which is highly correlated with plant development (BARETA JUNIOR *et al*., 2022; OLIVEIRA *et al*., 2016; SUZUKI; REICHERT; REINERT, 2013). It is therefore necessary to broaden studies that relate the DSC to plant growth, by including different crops and types of soil (ANDOGNINI *et al*., 2020).

The aim of this study was to evaluate the capacity for shoot and root development of winter plants grown in soils of different textures under varying degrees of compaction of the sub-surface layer. The research considered the following questions: i) What increase in root biomass in compacted soil is afforded under an intercropping system of black oats and forage turnip compared to single wheat? ii) When relativising bulk density using the DSC parameter, is the rate of reduction in shoot and root biomass that is due to increased soil compaction influenced by the type of soil? iii) Are shoots less affected than roots by an increase in the DSC for soil that offers no water or chemical restrictions on the plants?

MATERIAL AND METHODS

Location of the experiment

The experiment was conducted in a greenhouse of the State University of Ponta Grossa, in the state of Paraná, Brazil (25°05’22” S, 50°06’08” W, altitude 906 m), during 2017. The mean temperature of the experimental environment was controlled, and kept at around 24 ºC.

Treatments and experimental design

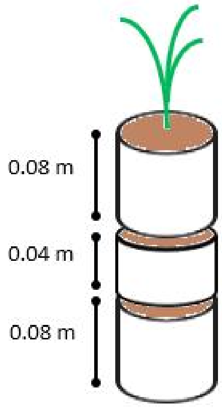
The treatments comprised a combination of two cropping systems and two types of soil subjected to four degrees of compaction in 2 x 2 x 4 factorial scheme. The experimental design was completely randomised, with four replications, giving a total of 64 plots. Single wheat (*Triticum aestivum*) (cultivar TBIO Toruk®) and an intercropping system of cover crops comprising black oats (*Avena strigosa*) (cultivar IPR-61®) and the forage turnip (*Raphanus sativus*) (public variety) were evaluated. The soils were a sandy loam Cambisol (Inceptisol) and a clayey

Table 1 - Chemical and granulometric characterisation of the soils used in the experiment

Soil	Clay	Silt	Sand	P	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al
	------------------ $g\ kg^{-1}$ ------------------			$mg\ dm^{-3}$	---------------------------- $cmol_c\ dm^{-3}$ ----------------------------				
Cambisol	171	54	775	30.5	0.15	2.5	0.6	0.0	3.7
Latosol	390	160	450	13.5	0.35	5.5	1.3	0.0	5.4
	Maximum bulk density		pH	Organic carbon	CEC (pH 7)		Sum of bases	Base saturation	
	---------- $g\ cm^{-3}$ ----------		($CaCl_2$)	----- $g\ dm^{-3}$ -----	--------------- $cmol_c\ dm^{-3}$ ---------------			--------- % ---------	
Cambisol	1.85		5.2	13.0	7.0		3.3	47.1	
Latosol	1.40		5.2	32.0	12.6		7.2	57.1	

Clay, silt, and sand: pipette method (DONAGEMA *et al*., 2011); Maximum bulk density: Proctor test (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2016); P, and K: Mehlich-1; Ca, Mg, and Al: extracted by KCl 1 mol L^{-1}; H+Al: SMP buffer; pH: 0.01 mol L^{-1} $CaCl_2$ solution 1:2.5 v/v; Organic carbon: Walkley-Black

Figure 1 - Schematic representation of one plot comprising a PVC column divided into three segments, with the compacted layer of soil located in the middle segment



loam Latosol (Oxisol) (SANTOS *et al*., 2018), submitted to different degrees of compaction of the sub-surface layer, corresponding to 85%, 90%, 95% and 100% of the maximum bulk density. A chemical and granulometric characterisation of the soils is shown in Table 1.

Each plot consisted of one PVC (polyvinyl chloride) column with an internal diameter of 0.10 m and height of 0.20 m. The column comprised three cylinders fitted one on top of the other, with a respective height of 0.08, 0.04 and 0.08 m for the upper, middle and lower cylinders (Figure 1). The upper and lower cylinders were filled with sieved soil, while the soil in the middle cylinder was compacted as per each treatment.

Soil sampling and experimental procedure

The selected soils came from an agricultural area managed under a no-tillage system, at the Farming School of the State University of Ponta Grossa (25°05’39” S, 50°02’56” W, altitude 1,012 m). The Cambisol was collected from the lower region of the toposequence, in undulating relief, while the Latosol was collected from the upper region, in softly undulating relief. The soils were collected at a depth of 0-0.2 m, and once air-dried, were passed through a 4.75 mm mesh sieve and submitted to the Proctor test to determine the compaction curve and maximum bulk density, as per the Brazilian Association of Technical Standards (ABNT, 2016). Samples were taken for particle size and chemical analysis (Table 1).

The soils were then standardised chemically by applying limestone and fertiliser. To this end, 1.19 and 1.74 g kg^{-1} dolomitic limestone, 0.08 and 0.07 g kg^{-1} N, 0.04 and 0.04 g kg^{-1} P_2O_5 and 0.049 and 0.010 g kg^{-1} K_2O were applied to the Cambisol and Latosol, respectively. The doses were calculated as per the Brazilian Society of Soil Science (SBCS, 2016), and considered fertilisation for winter cereals (wheat and black oats) and correcting for soil acidity by increasing the base saturation to 70%. After homogenisation, the soils were moistened to field capacity (Soil Matric Potential of -10 kPa), covered with black plastic sheeting, and left for 30 days for the chemicals to react, thereby improving the base saturation and fertility of both soils, so that these were no limiting factors on plant development. Following this period, the soils were again passed through a 4.75 mm sieve and placed in the PVC columns.

Based on the soil compaction curve and maximum bulk density determined by the Proctor test, the soils in the middle cylinders were compacted. The required amount of soil was weighed, ignoring the initial moisture of the sample. Enough water was then added to the sample to reach the desired bulk density. The soil was then compacted using the metal rammer of the Proctor test equipment, and the three cylinders that formed the PVC column (upper, middle and lower) were joined together. To prevent roots from growing at the interface between the PVC cylinder and the soil, plastic adhesive tape, 0.01 m in width and folded inside-out, was placed on the upper surface of the middle cylinder, as per the method described by Müller, Ceccon and Rosolem (2001).

Sowing was carried out during the winter, in early September 2017, at a depth of 0.03 m. Based on the treatment, four plants of wheat or four plants of black oats + one of forage turnip were grown per column. After sowing, the soil moisture in the plots was maintained at 90% of field capacity (thereby offering no water restriction on the plants), replacing the water lost to evapotranspiration by means of daily weighing and manual irrigation.

Collection and determining the variables

Plant height was determined 30 days after emergence and again at the end of the experiment. The plants were cut, and the PVC columns dismantled 72 days after emergence. The plants were collected, and the shoots separated from the roots. The shoots were placed in paper bags and dried in an oven at 60 °C to constant weight to determine the dry matter.

To evaluate root dry matter, the columns were separated into three parts (upper, middle and lower cylinders). The mass of soil and roots was left for 30 minutes in a solution containing water and NaOH 1 mol L^{-1} (ratio of 10:1) for the soil to disperse. The material was then passed through a 0.5 mm mesh sieve with the aid of water jets to separate the soil from the roots, as per the procedure described in Wolschick *et al*. (2018). The roots were placed in aluminium trays and dried in an oven at 60°C to constant weight.

Statistical analysis

The data were subjected to analysis of variance using the Sisvar 5.6 software (FERREIRA, 2011). When a statistical significance was found at a level of 5% ($p < 0.05$), the mean values were compared by the SNK (Student-Newman-Keuls) test for a qualitative effect, and by regression analysis for a quantitative effect, adjusting the shoot and root dry matter equations as a function of the degree of soil compaction (DSC).

RESULTS AND DISCUSSION

Table 2 shows a summary of the analysis of variance, including the sources of variation (crop, soil, DSC and their interactions), degrees of freedom, mean squares of the variables, coefficients of variation, and overall mean values.

The root dry matter in the upper layer of soil (RDM-upper), i.e. above the compacted layer, was significantly influenced by the crop x soil and soil x DSC interactions (Table 2). The result of breaking down the interaction between the crop and the soil is shown in Figure 2A. RDM-upper was greater under the intercropped black oats + forage turnip compared to the single wheat in the Cambisol, with respective values of 2.87 and 2.11 g $plot^{-1}$, representing a difference of 36%. The greater root development under the intercropping system is due to the greater robustness of both species compared to the wheat.

A breakdown of the interaction between the soil and the DSC for RDM-upper is shown in Figure 3A. There was a significant effect of the degree of soil compaction in the Latosol. The regression was linear and negative, with a coefficient of determination (R^2) of 0.796; there was a 32.5% reduction in RDM-upper with the 85% to 100% increase in the DSC. This result corroborates that of Silva and Rosolem (2001) who evaluated different plant species and found a reduction in root dry matter

Table 2 - Analysis of variance showing the degree of freedom and mean square for root dry matter in the upper, middle (compacted) and lower layers of soil, total root dry matter, plant height at 30 and 72 days after emergence (DAE), shoot dry matter, and total dry matter (shoot + roots). C: crop; S: soil; DSC: degree of soil compaction. *significant by F-test ($p < 0.05$). **significant by F-test ($p < 0.01$)

Source of variation	Degree of freedom	Mean square							
		Root dry matter (upper)	Root dry matter (middle)	Root dry matter (lower)	Root dry matter (total)	Plant height 30 DAE	Plant height 72 DAE	Shoot dry matter	Total dry matter
C	1	1.2	1.9*	0.24	8.79	17.2	5,700.3**	0.51	5.1
S	1	0.01	0.38	0.26	0.03	260.1**	2.3	0.01	0.02
DSC	3	0.18	2.6*	2.54*	12.5*	24.7	15.7	0.93*	19.1*
C x S	1	3.8*	1.34	0.01	10.2	188.4**	272.3*	0.05	8.9
C x DSC	3	0.4	0.18	0.15	1.4	9.5	72.6	0.10	1.5
S x DSC	3	1.7*	0.85	0.66	9.0	27.1	40.9	0.56	6.7
C x S x DSC	3	0.69	0.29	0.53	3.2	26.6	82.9	0.27	2.7
Error	48	0.64	0.45	0.85	4.5	17.7	36.4	0.35	5.4
CV (%)		32.1	47.9	56.5	37.8	14.9	11.2	18.8	26.1
Mean		2.5	1.4	1.6	5.6	28.1	54.0	3.2	8.7

above the compacted layer proportional to the increase in bulk density. On the other hand, various studies have shown an inverse behaviour, where root penetration in the compacted layer is more difficult, and results in an increase in the number of roots in the surface layer of the soil (BEULTER; CENTURION, 2004).

Figure 2 - Root dry matter in the single wheat and the intercropped black oats + forage turnip. (A) Upper layer of soil (significant effect of crop x soil). (B) Middle compacted layer of soil (significant simple effect of the crop). Mean values followed by the same lowercase letter (comparing the crops) or uppercase letter (comparing the soil) do not differ by the SNK test ($p < 0.05$)

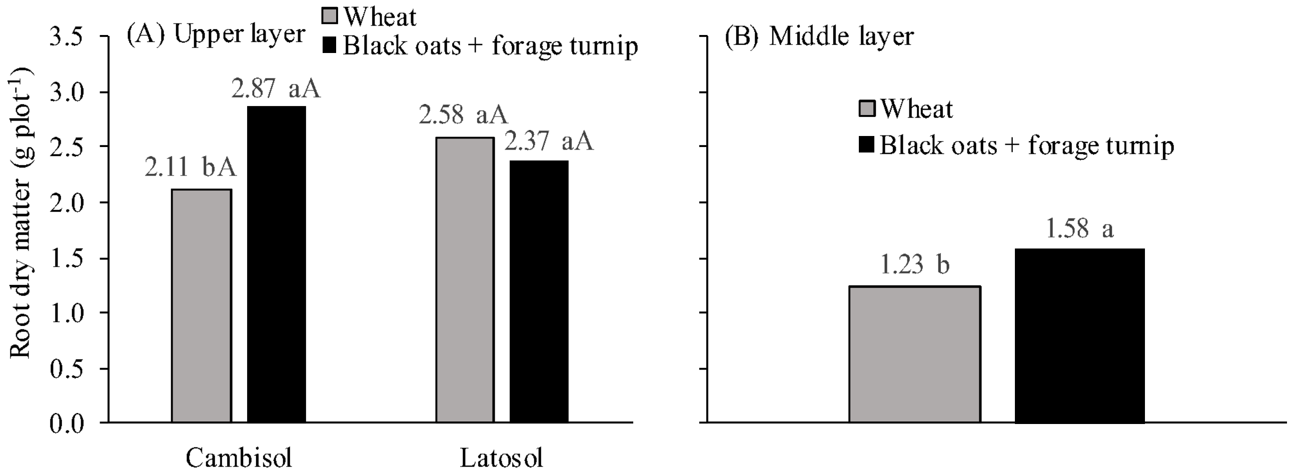
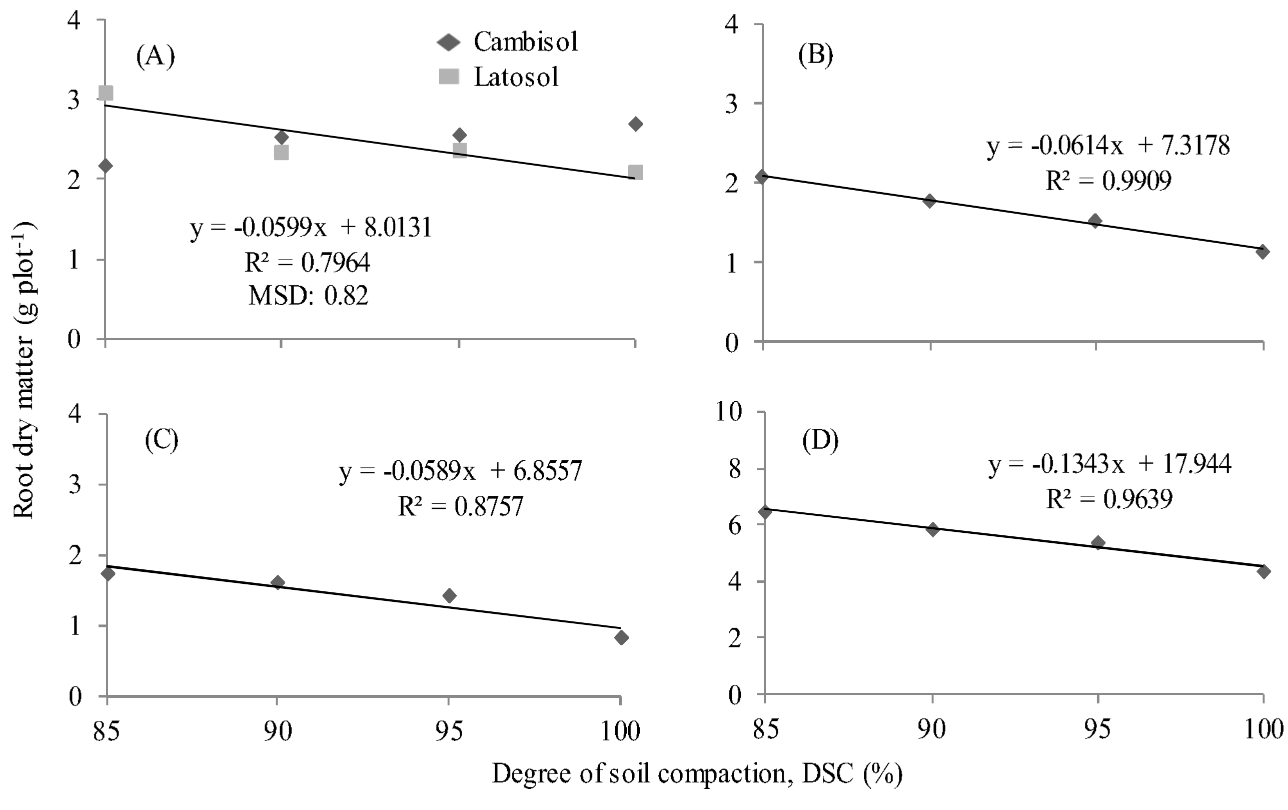


Figure 3 - Relationship between the degree of soil compaction (DSC) and root dry matter. (A) Upper layer of soil (significant effect of soil x DSC). (B) Compacted middle layer of soil. (C) Lower layer of soil. (D) Total root dry matter (sum of all the layers). MSD: minimum significant difference by the SNK test ($p < 0.05$) for soil type



When verifying the effect of the soil on the DSC, there was significant difference (MSD > 0.82) in RDM-upper for the first degree of soil compaction (DSC 85%) (Figure 3A). The value in the Latosol, with a higher clay content, was 42% greater than in the Cambisol. This effect may be associated with the excess drainage caused by the high sand content and low number of pores responsible for water retention in the Cambisol, resulting in less water available for plant production (BEUTLER *et al*., 2002).

Root dry matter in the middle layer of soil (RDM-middle), i.e. the sub-surface layer that was subjected to compaction, was significantly influenced by the crop and DSC, with no effect of the type of soil or interaction between the variables (Table 2). RDM-middle was 28.5% higher under the intercropped black oats + forage turnip compared to the single wheat (Figure 2B). Due to their robustness, cover plants are more adapted to adverse environments, such as lower aeration and porosity, and higher bulk density and soil resistance to penetration (CALONEGO *et al*., 2011; SILVA; ROSOLEM, 2001). This result shows that wheat is more sensitive to root development in compacted layers of soil.

The degree of soil compaction had an effect on RDM-middle, resulting in a negative linear regression, with an R^2 of 0.991 (Figure 3B). Based on the data, RDM-middle had a 45.2% reduction due to the increase from 85% to 100% in the DSC. The same behaviour was seen for root dry matter in the lower layer of soil (RDM-lower), for which there was a significant effect of the DSC only (Table 2). RDM-lower was reduced by 53% with the increase from 85% to 100% in the DSC (Figure 3C). A greater reduction in root matter were therefore found in the compacted layer of soil and the layer below that in relation to the surface layer.

The observed effect is due to the increase in bulk density and soil resistance to penetration, with a consequent reduction in total- and macroporosity (ANDOGNINI *et al*., 2020; COLLARES *et al*., 2008). This damages the roots, which generally use the existing larger pores and lines of weakness in the soil for their development; as such, the conditions for root growth in compacted soils are less favourable (REINERT *et al*., 2008). Furthermore, when roots do succeed in developing, they are thin and sparse (FOLONI; LIMA; BÜLL, 2006).

Foloni, Calonego and Lima (2003) found a reduction in the root matter of maize for an increase in the degree of compaction of the sub-surface layer, with no root growth at the highest bulk density. Beulter and Centurion (2004) observed a linear reduction in root dry matter in soya with increasing bulk density. In the present study, each of the crops developed roots in the compacted layer and the layer below that for all degrees of compaction (Figure 3).

The total root dry matter of all the layers under evaluation was affected by the DSC (Table 2), with a linear reduction of 32.5% for an increase from 85% to 100% in the degree of compaction (Figure 3D). When evaluating the cover crops *Urochloa brizantha*, *Pennisetum glaucum*, *Crotalaria ochroleuca* and *Eleusine coracana* spp. in a Latosol, an effect was seen from the degree of compaction on root matter above and below the compacted layer (LIMA; PETTER; LEANDRO, 2015), corroborating the results obtained in the present study. The same authors concluded that approximately twice the amount of root matter occurred in the upper layer of soil compared to the lower layer. In the present study, root dry matter was 1.26 and 2.11 times greater in the upper layer compared to the lower layer, considering the lowest and highest DSC, respectively.

Plant height 30 days after emergence (DAE) was significantly influenced by the soil and the crop x soil interaction, whereas by the end of the experiment, at 72 DAE, it was influenced by the crop and the crop x soil interaction (Table 2). The results of the breakdown of the interaction for both periods are shown in Figure 4.

At 30 DAE, plant height in the intercropped black oats + forage turnip was greater in the Cambisol compared to the Latosol, with a difference of 0.075 m. Compared to the single wheat, plant height under the intercropping system was 16% greater in the Cambisol, with no statistical difference in the Latosol (Figure 4A). At 72 DAE, plant height in the single wheat was less in both soils compared to the intercropping system, with a difference of 0.23 and 0.148 m for the Cambisol and Latosol, respectively (Figure 4B). The type of soil had no influence on plant height in the wheat, whereas under the intercropping system, plant height was 0.045 m greater in the Cambisol.

In the first evaluation (30 DAE), the greater plant height under the intercropping system in the Cambisol may be related to the black oats being better adapted to develop in soils with a higher sand content (SILVA; ROSOLEM, 2001). Under the intercropping system, it was found that the forage turnip showed less initial development in this environment. Furthermore, the lower plant height in the Latosol compared to the Cambisol is due to the increase in compaction affecting macroporosity to a greater degree in soils with a higher clay content; this is caused by the laminar shape of the clays resulting in a more-compact arrangement due to compression (BRADY; WEIL, 2013). The lower height of the wheat can also be explained by the genetic improvement of this species for grain production, which is characterised by lower height to reduce the risk of lodging (FEDERIZZI; FANTINI; CARVALHO, 1994).

Figure 4 - Plant height in single wheat and intercropped black oats + forage turnip. (A) 30 days after plant emergence. (B) 72 days after plant emergence (at the end of the experiment). Mean values followed by the same lowercase letter (comparing the crops) or upper case (comparing the soil) do not differ by the SNK test ($p < 0.05$)

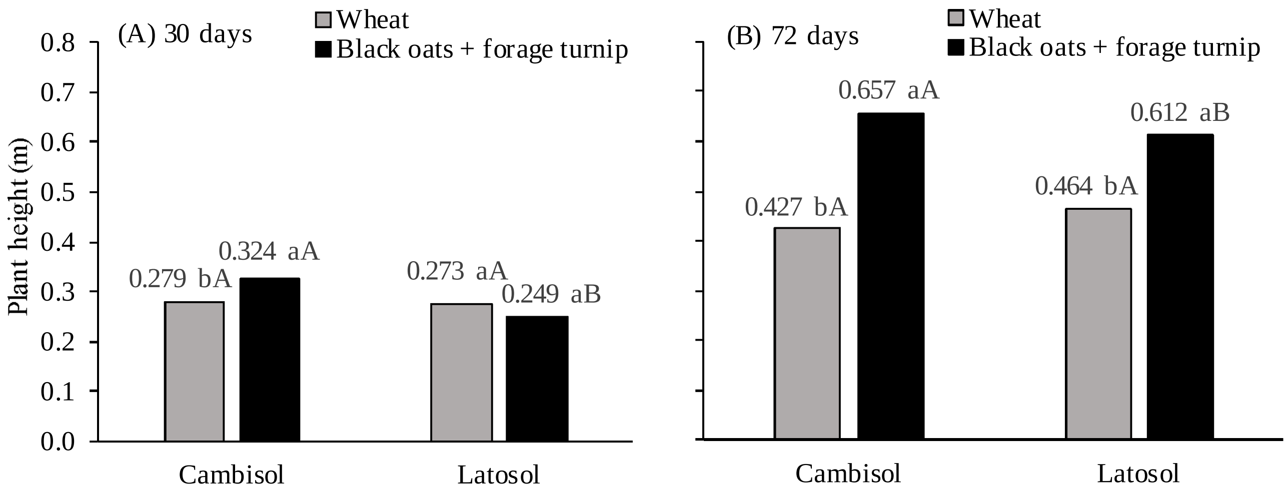
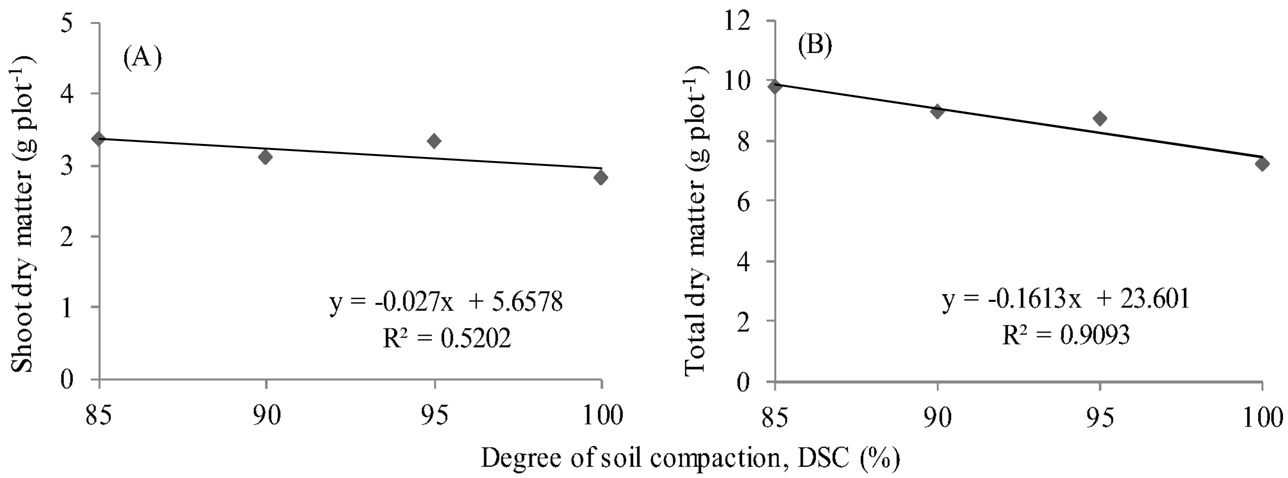


Figure 5 - Relationship between the degree of soil compaction (DSC) and dry matter. (A) Shoot dry matter. (B) Total dry matter (shoots + roots)



Shoot dry matter (SDM) was significantly influenced by the DSC, with no effect of the crops, soil or the interaction between the variables (Table 2). SDM showed a linear and inverse correlation with the DSC, with a coefficient of determination of 0.520 (Figure 5A). Based on the fitted equation, dry matter was reduced by 12% with the increase from 85% to 100% in the DSC. When evaluating the performance of cover crops at different bulk densities in a Latosol of medium texture, it was found that the highest degrees of soil compaction caused a significant reduction in shoot matter in forage turnip and white oats (MÜLLER; CECCON; ROSOLEM, 2001). The authors attributed this effect to the shoots being dependent on the number of roots produced, which was affected by the increase in soil compaction.

There was a reduction in both root and shoot dry matter for an increase in the sub-surface DSC; on the other hand, the rate of reduction was lower for the shoots, due to the smaller slope of the relationship shown in Figure 5A (-0.027x) compared to that of Figure 3D (-0.1343x). The smaller reduction in SDM is possibly due to the negative effect on the roots from the compacted sub-surface layer being partially offset by the increased water and nutrient uptake by the roots in the looser upper layer of soil (NOSALEWICZ; LIPIEC, 2014). It should be noted that in the present study the soils were maintained under conditions offering no water or chemical restrictions on the plants. Total plant dry matter, considering the sum of the shoots and roots, showed a linear and negative effect of the degree of soil compaction. It was found that the total dry matter was reduced by 32.5% for the increase from 85% to 100% in the DSC (Figure 5B).

Foloni, Calonego and Lima (2003), evaluating maize, observed that shoot matter was reduced by up to 20% with increasing soil compaction, and found that the reduction in root matter had a negative effect on the shoots. Bareta Junior *et al*. (2022) found a negative linear effect between the degree of soil compaction in the 0-0.05 and 0.07-0.12 m layers and the yield of maize and black oats, respectively. Silva, Albuquerque and Costa (2014), evaluating soya, observed that DSC values greater than 75% impaired root development, and that values greater than 87% caused a reduction in shoot dry matter. Beulter and Centurion (2004) found a reduction in root and shoot matter with increasing soil compaction. Research has thus demonstrated the negative effect of compaction on plant development, as also seen in this study for root and shoot biomass.

CONCLUSIONS

The intercropping system of black oats + forage turnip showed greater capacity for root biomass production than did the single wheat in the compacted sub-surface layer (0.08-0.12 m), regardless of the degree of soil compaction (DSC). Root dry matter in this layer was 28.5% greater under the intercropping system. The rate of reduction in shoot and root biomass from increases in the DSC does not appear to be associated with soil type. There was therefore no difference between the sandy loam Cambisol and the clayey loam Latosol in crop response due to variations in the DSC. The total root dry matter decreased by 32% at a DSC of 100% compared to the initial level of 85%, with the compacted sub-surface layer (0.08-0.12 m) and the layer below the compacted layer (0.12-0.2 m) being the most affected, presenting a reduction in root dry matter of 45.2% and 53%, respectively. The study further detected that in soil with no water or chemical restrictions, shoot dry matter was less affected than root dry matter by an increase in the DSC, decreasing by 12% for an increase from 85% to 100% in the degree of compaction.

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