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Effect of soil compaction on the aerial and root development of *Stylosanthes* cv. Campo Grande

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ABSTRACT

This study aimed to evaluate the effects of soil compaction on the morphological and root characteristics of the species *Stylosanthes* cv. Campo Grande, cultivated in Yellow-Red Latosol. The experiment was conducted from July 5th to September 19th, 2023, at the Federal University of Alagoas (*Universidade Federal de Alagoas*) - Arapiraca *Campus*, using five levels of soil density (1.3 to 1.7 Mg.m³), with three plants per plot and four repetitions. The analyzed variables were: Number of leaves, plant height, stem diameter, leaf area, chlorophyll index, and fresh and dry masses of leaves, stems, and roots (0-20 cm and 20-35 cm). The results showed that the increase in soil compaction caused a significant reduction in the number of leaves, plant height, and stem diameter. Soil density above 1.4 Mg.m³ was limiting for the development of *Stylosanthes* cv. Campo Grande, with an emphasis on the density of 1.7 Mg/m³, which resulted in a significant decrease in the production of fresh and dry mass of the aerial and root parts.

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RESUMO

Este estudo teve como objetivo avaliar os efeitos da compactação do solo nas características morfológicas e radiculares da espécie *Stylosanthes* cv. Campo Grande, cultivada em Latossolo Vermelho-Amarelo. O experimento foi conduzido de 05 de julho a 19 de setembro de 2023, na Universidade Federal de Alagoas – *Campus* Arapiraca, utilizando cinco níveis de densidade do solo (1,3 a 1,7 Mg.m³), com três plantas por parcela e quatro repetições. As variáveis analisadas foram: número de folhas, altura das plantas, diâmetro do caule, área foliar, índice de clorofila, e massas fresca e seca de folhas, hastes e raízes (0-20 cm e 20-35 cm). Os resultados mostraram que o aumento da compactação do solo causou redução significativa no número de folhas, altura das plantas e diâmetro do caule. A densidade do solo superior a 1,4 Mg.m³ foi limitante para o desenvolvimento da *Stylosanthes* cv. Campo Grande, com destaque para a densidade de 1,7 Mg.m³, que resultou em uma diminuição significativa na produção de massa fresca e seca das partes aéreas e radiculares.

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Introduction

The soil not only plays a crucial role in human livelihood but also serves as the main support for agricultural production, in addition to housing and sustaining terrestrial ecosystems (Lopes, 2017; Sternberg; Thomas, 2018).

The growing demand for food, fiber, and bioenergy, driven by the rapid global population growth that reached the milestone of 8 billion inhabitants in 2022 (G1 Mundo, 2022), has increased the use of natural resources, including soil. According to the Food and Agriculture Organization of the United Nations (*Organização das Nações Unidas para Alimentação e Agricultura*) (FAO, 2015), soil compaction is one of the main limitations of soil physics, responsible for the degradation of 33% of the world's agricultural areas. Its occurrence in arable land compromises root growth and water movement, directly affecting plant development (Bonfim-Silva *et al.*, 2014).

Soil quality plays a crucial role in the growth and productivity of crops, being evaluated by indicators such as density, porosity, penetration resistance, and water infiltration capacity. These factors determine the soil structure and the availability of essential resources for plants. Inadequate management practices can negatively alter these indicators, intensifying compaction and reducing the productive capacity of agricultural systems (Santos, 2016).

Soil compaction occurs when there is an increase in soil density due to the reduction of pore volume, resulting from the compression of unsaturated soil (Gupta; Allmaras, 1987; Gupta; Hadas; Schafer, 1989). This process is due to the expulsion of air from the pores under pressure, reducing aeration and water availability (Dias Júnior; Tassinari; Martins, 2019). Generally, compaction is caused by dynamic loads applied over short periods, such as the traffic of agricultural machinery and animal trampling (Drescher *et al.*, 2023).

Improper soil management can intensify the negative effects of compaction, compromising root development and leading to root malformation. In addition, there is an increase in mechanical resistance to root growth and a reduction in water infiltration, macroporosity, aeration, and nutrient availability (Tavares Filho *et al.*, 2001; Piffer; Benez, 2009; Silva, 2012).

The *Stylosanthes* cv. Campo Grande, launched by *Embrapa Gado de Corte* in 2000, is a cultivar composed of the species *Stylosanthes macrocephala* and *Stylosanthes capitata*. This forage legume stands out for its high protein concentration, biological nitrogen fixation capability, adaptation to poor and sandy soils, its ability to decompact soil, and its effective remineralization of the soil, contributing to replenishing deficient nutrients and restoring soil fertility. Furthermore, it shows resistance to anthracnose, a disease that compromises the persistence of *Stylosanthes* spp. in tropical pastures (Garcia *et al.*, 2008; Andrade; Assis; Sales, 2010). However, there are still gaps regarding its response to different levels of soil compaction, especially concerning root development and aerial biomass.

In light of this scenario, it is evident that there is a need to investigate the genus *Stylosanthes* spp. regarding development in soils with different levels of compaction, in order to understand its mechanisms of adaptation and potential benefits for the recovery of soil physical quality. The cultivation of plants with a deep and extensive root system is an effective strategy to mitigate the effects of compaction, as it promotes the formation of channels in the soil, improving its structure (Cardoso *et al.*, 2006).

This study aimed to evaluate the effects of soil compaction on the morphological and root characteristics of the species *Stylosanthes* cv. Campo Grande, grown in Red-Yellow Latosol.

Material and methods

The experiment was conducted from July 5th to September 19th, 2023, held in the experimental area of the research group of the Postgraduate Program in Agriculture and Environment (*Programa de Pós-Graduação em Agricultura e Ambiente* - PPGAA) at the Federal University of Alagoas (*Universidade Federal de Alagoas*), Arapiraca Campus, in a protected environment (Greenhouse), under the geographical coordinates 9°41'55" S, 36°41'08" W and an altitude of 321 meters above sea level.

The experimental region is located in the *Agreste* of Alagoas, an area of transition between the Zona da Mata and the Alagoas *Sertão*, with annual precipitation varying between 750 and 1000 mm. The climate is classified according to Köppen's criteria (1948) as type 'As', with winter rains (April - September) and summer drought (October - March) (Santos, 2023).

The soil material used for filling the pots was sourced from a Red-Yellow Latosol, medium texture (Santos *et al.*, 2018), collected at a depth of 0.00-0.20 m, originating from the experimental area of UFAL - Arapiraca Campus. After collection, this soil was air-dried, crushed, sieved through a 2 mm mesh to separate stones (rocks), roots, and straw, and then a sample of 0.7 kg was taken for chemical and physical analysis (Tables 1 and 2).

Table 1

- Chemical characteristics of the soil used for filling the pots, at a depth of 0.0-0.20 m.

Analytical Results of Soil									
pH	**P**	**K**	**Ca**	**Mg**	**Al**	**H+Al**	**S.B.**	**T**	**CTC**
	------ mg/dm³ ----		---------------------------- cmolc/dm³ -------------------------						
5.0	10	61	1.5	0.5	0.22	3.1	2.26	2.48	5.36
Na	**Fe**	**Cu**	**Zn**	**Mn**	**V**	**m**	**Na/CTC**	**PST**	**M.O.**
--------------- mg/dm³ -----------------					------------------------- % -------------------				
23	325.2	2.2	0.05	0.85	42.1	8.9	2.9	1.87	0.9

Source: Central Analítica (2023).

Table 2 .

Physical characteristics of the soil used for filling the pots, at a depth of 0.0-0.20 m.

Parameters	**Sample Result g/Kg**
Coarse Sand	366
Fine Sand	202
Total Sand	568
Silte	145
Clay	287
Textural Class	**Sandy Clay Loam**

Source: Central Analítica (2023).

The treatments consisted of five levels of soil density with compaction of 1.3; 1.4; 1.5; 1.6 and 1.7 $Mg.m^{-3}$, the crop used was *Stylosanthes* cv. Campo Grande with a completely randomized design (CRD) with 4 replications, totaling 20 plots, with each experimental unit consisting of 3 plants.

The compaction levels were defined considering the relationship between the container volume and the mass of added soil. Thus, the pots of the treatments received 3.9 kg, 4.2 kg, 4.5 kg, 4.8 kg, and 5.1 kg of soil, compacted to reach a height of 15 cm. The experimental plots were composed of two rigid PVC rings of 20 cm and one of 15 cm in height, all with a diameter of 15 cm, joined with “Silver Tape”. The soil used was from the 0-20 cm depth layer. The lower rings were filled with uncompacted soil, while the upper rings were filled and compacted according to the treatments. To ensure the initial establishment of the plants, the top 5 cm remained uncompacted.

15 cm of the upper rings were considered to submit the density levels, leaving the 5 cm of the surface with uncompacted soil to provide adequate initial development for the plants. At the bottom of the plots, a plastic container was placed with an anti-mite screen with a 1mm mesh, which was secured with a nylon clamp. The soil compaction was performed with a Charlott PH5T hydraulic press. Soil correction was not carried out, as the decision was made to maintain the same characteristics present when in fallow conditions.

The sowing was carried out directly into the pots on July 5th, 2023, distributing ten seeds per experimental plot. Emergence occurred on July 9th, 2023, and after 30 days, thinning was performed, keeping three vigorous and homogeneous seedlings per experimental unit. Irrigation was done superficially until the plants were established (60 days after sowing). From that period on, moisture was maintained through capillarity by adding water to the containers under the pots, encouraging root growth through the compacted layer in search of water and nutrients.

The experiment lasted 75 days after sowing (DAS). Assessments were conducted before and after the end, with the analyzed variables being: Plant height (AP), stem diameter (DC), number of leaves (NF), leaf area (AF), fresh leaf mass (MFF), fresh stem mass (MSF), fresh root mass (MFR), dry leaf mass (MSF), dry stem mass (MSC), dry root mass (MSR).

The results were subjected to analysis of variance and when F was significant ($p<0.05$), regression was applied to the densities, using the statistical program Sisvar, version 5.6.

Results and Discussion

According to the results obtained, it was evident that the increase in soil compaction had a significant influence on most of the variables evaluated throughout the study. However, two notable exceptions were observed: The stem diameter at 45 and 75 days after sowing (DAS) and the Chlorophyll Index (SPAD) at 75 DAS did not show a significant response to the variation in soil density (Table 3).

Table 3.

Analysis of variance of growth variables of *Stylosanthes* cv. Campo Grande based on different soil densities and times in a protected environment in the Alagoas *agreste*.

SOURCE OF VARIATION	G.L.	MEAN SQUARES			
		45 DAYS			
		NF	***AP***	***DC***	***SPAD***
Soil Density	4	37.977*	5.471*	0.135 ^{NS}	159.116*
Waste	15	6.737	0.714	0.064	42.199
C.V. (%)		21.33	27.65	28.42	22.55
SOURCE OF VARIATION	**G.L.**	**60 DAYS**			
		NF	***AP***	***DC***	***SPAD***
Soil Density	4	763.286*	72.163*	0.792*	155.126*
Waste	15	184.534	8.026	0.049	65.781
C.V. (%)		37.95	29.73	14.09	18.95
SOURCE OF VARIATION	**G.L.**	**75 DAYS**			
		NF	***AP***	***DC***	***SPAD***
Soil Density	4	3585.450*	133.136*	0.819 ^{NS}	69.118 ^{NS}
Waste	15	714.762	21.560	0.312	51.510
C.V. (%)		36.30	32.49	24.18	19.64

G.L. - Degrees of freedom; C.V. - Coefficient of variation; NS - Not significant; * - Significant by the F test ($p < 0,05$); NF - Number of leaves; AP - Height of the plant; DC - Stem diameter; SPAD - Chlorophyll Index.

Source: Authors (2024).

In table 4, it was observed that the variables of fresh stem mass (MSF), dry stem mass (MSC), fresh leaf mass (MFF), dry leaf mass (MSF), fresh root mass 0-20 cm (MFR 0-20), fresh root mass 20-35 cm (MFR 20-35), dry root mass 0-20 cm (MSR 0-20), and dry root mass 20-35 cm (MSR 20-35) were significant. In contrast, the variable leaf area (AF) did not show statistical significance.

This can be explained by the physiological compensation of plants in response to stress caused by soil compaction. According to Ferraz *et al.* (2017), when studying the development of the root system of beans (*Phaseolus vulgaris* L.) under different soil densities, they observed that in more compacted soils, plants increased the number of leaves, although with smaller areas. In contrast, the initial treatments had larger leaves, but in smaller quantities.

According to Gubiani, Reichert, and Reinert (2014), studying the interaction between water availability and soil compaction on the growth and production of common bean revealed that soil compaction is a critical factor. It significantly restricts plants' access to water, exacerbating water stress. This phenomenon leads to a significant loss of water through evapotranspiration, without adequate compensation through absorption by the roots. As a direct consequence, soil compaction negatively impacts the leaf area of the plants, limiting their aerial growth and, consequently, compromising plant production.

Table 4.

Analysis of variance of growth variables of *Stylosanthes* cv. Campo Grande based on different soil densities and times in a protected environment in the Alagoas *agreste*.

SOURCE OF VARIATION	G.L.	MEAN SQUARES				
		Area	***MFH***	***MSH***	***MFF***	***MSF***
Soil Density	4	0.332^{NS}	2.073*	0.488*	2.301*	0.580
Waste	15	0.940	0.572	0.109	0.637	0.170
C.V. (%)		27.42	29.98	24.91	26.54	25.68
		MFR 0-20	***MFR 20-35***	***MSR 0-20***	***MSR 20-35***	
Soil Density	4	2.586*	5.853*	0.192*	0.477*	
Waste	15	0.821	1.078	0.062	0.152	
C.V. (%)		32.43	43.95	21.25	33.41	

G.L. - Degrees of freedom; C.V. - Coefficient of variation; NS - Not significant; * - Significant by the F test (p <0,05). *AF* - Leaf Area; *MFH* - Fresh Stem Weight, *MFH* - Dry Stem Weight; *MFF* - Fresh Leaf Weight; *MSF* - Dry Leaf Weight; *MFR (0-20)* - Fresh Root Weight from 0 to 20 cm depth; *MFR (20-35)* - Fresh Root Weight from 20 to 35 cm depth; *MSR (0-20)* - Dry Root Weight from 0 to 20 cm depth; *MSR (20-35)* - Dry Root Weight from 20 to 35 cm depth.

Source: Authors (2024).

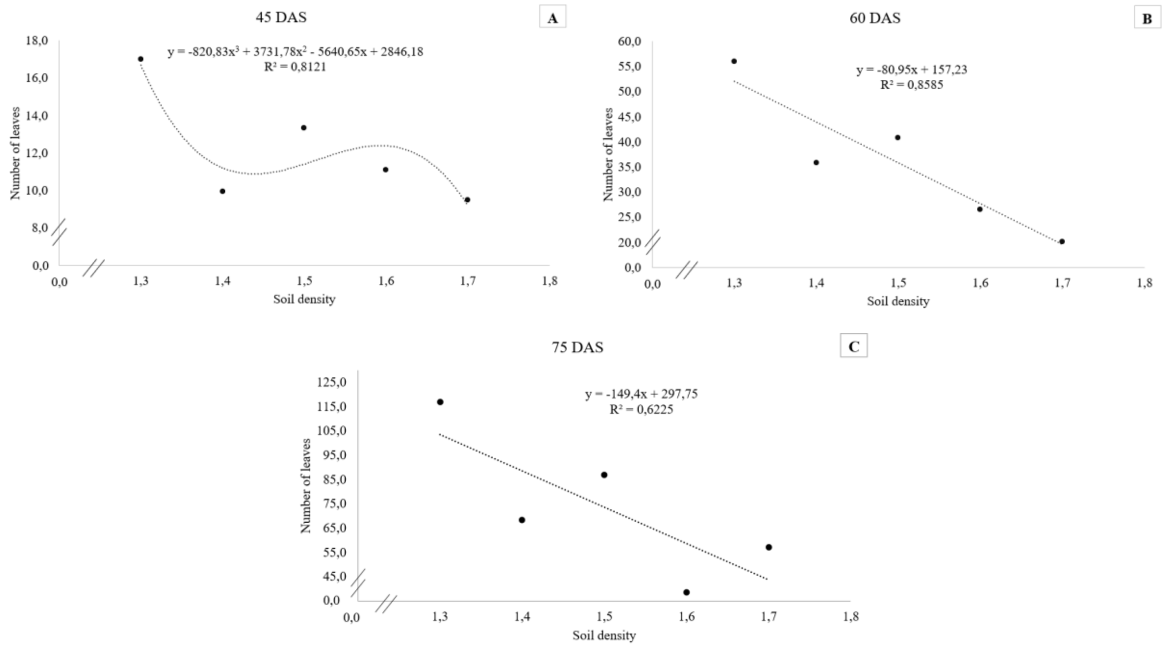
The results analyzed for the number of leaves indicate that soil density had a significant influence on the variable. At 45 days after sowing (DAS), as shown in figure 1A, it demonstrated an impact at the lower densities promoting the development of a greater number of leaves, while higher densities resulted in fewer leaves. Soil density directly influenced the availability of nutrients and water, which are essential for leaf development.

At 60 DAS (Figure 1B), soil density continued to have a significant effect on the number of leaves. Treatments with lower densities maintained the pattern of stimulating greater leaf development, while higher densities showed less pronounced results. The persistence of this pattern over time suggests that the number of leaves is a growth variable that consistently responds to variations in soil density. A greater number of leaves may indicate a higher photosynthetic capacity, contributing to more robust plant growth.

At the end of the experiment, at 75 DAS (figure 1C), soil density continued to significantly impact the number of leaves, similarly to the observations made in previous periods. Treatments with lower compaction resulted in more expressive leaf development, while treatments with higher compaction showed lower results. This significant variation in the number of leaves is attributed to the negative influence of soil compaction on plant development, resulting in difficulties in the absorption and efficient distribution of nutrients by the roots to the aerial part of the plants.

Figure 1.

Number of leaves at 45 DAS (A), number of leaves at 60 DAS (B), and number of leaves at 75 DAS (C), in the culture of *Stylosanthes* cv. Campo Grande.



Source: Authors (2024).

As discussed by Bonfim-Silva *et al.* 2011 and Bonelli *et al.* (2011), the decrease in leaf production is interpreted as a strategy of the plant to direct the photoassimilates to the roots, in response to the restrictive conditions imposed by the compacted layer.

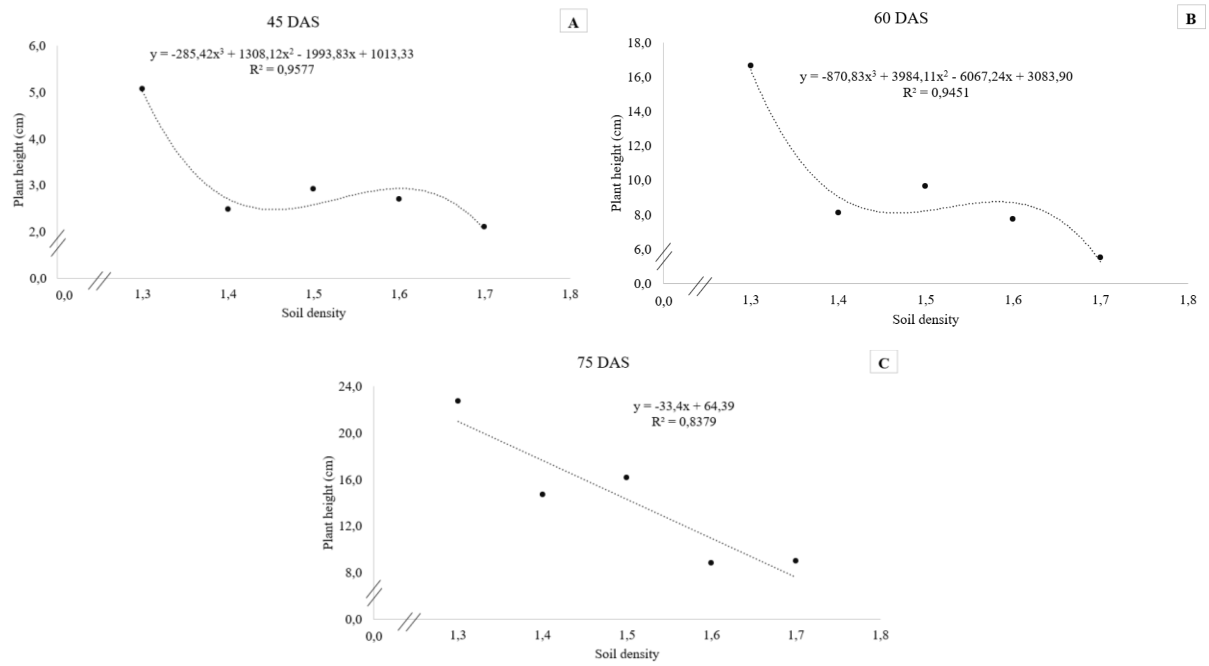
Previous studies corroborate the presented findings, such as the work of Rosa *et al.* (2019) which investigated the effects of soil compaction on soybean (*Glycine max*) cultivation and Sabóia *et al.* (2022) who analyzed the effect of soil density on forage radish (*Raphanus sativus* L) cultivation. The results reinforce the hypothesis that soil compaction has a direct influence on the morphology and physiology of cultivated plants, negatively impacting leaf development.

The height of the plants was significantly influenced by soil density at 45 DAS, as shown in figure 2A. From the beginning of growth, the plants showed a clear response to compaction conditions, with variations in their aerial growth. Soil density affects the availability of nutrients and water, influencing plant growth.

At 60 DAS and 75 DAS, as represented in figures 2B and 2C, the height of the plants continued to be significantly affected by soil density. Plants grown in soils with lower compaction showed greater height, while those in more compacted soils exhibited reduced above-ground development. The persistent response of height to variations in density over time indicates that this environmental factor has a continuous impact on plant growth. Plant height is often associated with efficiency in light capture and competition for resources, suggesting that plants in soils with adequate density exhibit more vigorous growth.

Figure 2.

Averages of plant height measurements under soil density levels at 45 DAS (A), at 60 DAS (B), and at 75 DAS (C) in the culture *Stylosanthes* cv. Campo Grande.



Source: Authors (2024).

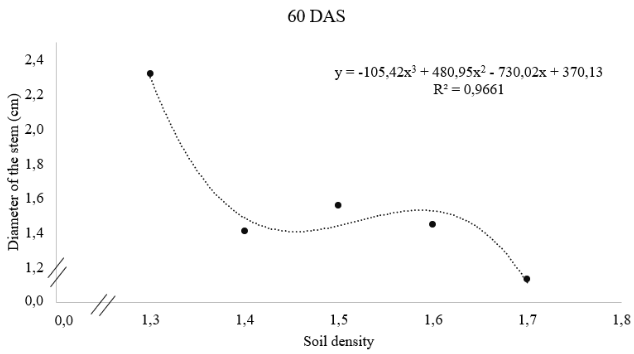
The work developed by Labegalini *et al.* (2016) and Scapinelli *et al.* (2016) expands our understanding of the effects of soil compaction on the vegetative development of crops. Labegalini investigated the growth of the corn crop in response to different levels of soil compaction, while Scapinelli analyzed the root system and productive components of sunflower in compacted soil. Both studies demonstrated that the increase in soil density resulted in significant impacts on plant height, indicating a direct relationship between soil compaction and the vegetative development of crops.

Furthermore, Rosa, Junior, and Santos (2020) highlight the importance of soil porosity in the context of compaction. They pointed out that compacted soils have lower porosity, which reduces their ability to retain water essential for vital plant processes, such as nutrient transport, osmotic regulation, and cell growth. The scarcity of available water resulting from this scenario has a direct impact on plant size, negatively influencing their development.

As shown in figure 3, at 60 days after sowing (DAS), a statistically significant difference was observed in the stem diameter of *Stylosanthes* cv. Campo Grande, evidenced by the statistical analysis. The treatment with the lowest soil density resulted in the largest stem diameter. In contrast, higher soil densities resulted in smaller diameters. These results suggest that, during this initial growth period, stem diameter is sensitive to variations in soil density. The pressure exerted by the soil affects the plants' ability to expand their stems, reflecting an adaptation to the more restrictive and less favorable soil conditions.

Figure 3.

Stem diameter as a function of soil density levels at 60 DAS in the crop *Stylosanthes* cv. Campo Grande.



Source: Authors (2024).

The study conducted by Sabóia *et al.* (2022) revealed that the increase in soil density resulted in a significant reduction in the stem diameter of the plants, with a decrease of 34.66% observed at 45 days after emergence and 27.38% at 60 days when comparing the densities of 1.0 $Mg.m^{-3}$ to 1.8 $Mg.m^{-3}$.

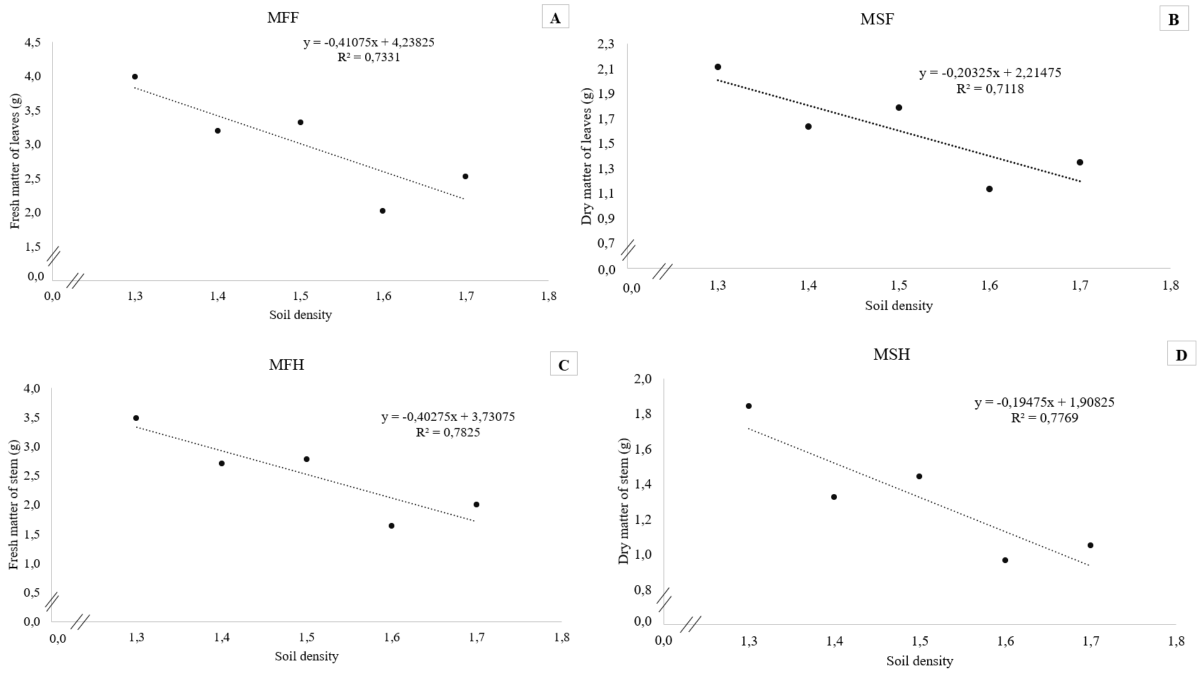
Similarly, Paludo (2018) found that the increase in soil density resulted in a decrease in the stem diameter of the plants, highlighting this relationship by comparing the different levels of density applied.

The results of the fresh leaf mass (MFF), dry leaf mass (MSF), fresh stem mass (MSF), and dry stem mass (MSC) variables of the crop *Stylosanthes* cv. Campo Grande indicate a decreasing relationship with increasing soil density, as shown in Figure 4. With the increase in soil density of 1.3 $Mg{\cdot}m^{-3}$ for 1.7 $Mg{\cdot}m^{-3}$, a reduction in the production of these crops has been observed. This is explained by the difficulty of the plants to absorb water and nutrients in more compacted soils, which have less porosity and lower availability of oxygen, crucial factors for the healthy development of plants and biomass production.

The study by Sabóia *et al.* (2022) evidenced an inversely proportional relationship between soil density and plant dry mass, through a decreasing linear regression model. They found that the increase in soil density resulted in a significant reduction of 37.36% in the maximum weight obtained when comparing the extreme levels of density. These results reinforce the negative influence of soil compaction on plant development, highlighting the importance of considering this factor in agricultural management.

Figure 4.

Fresh leaf mass (MFF) (A), dry leaf mass (MSF) (B), fresh stem mass (MSF) (C), and dry stem mass (MSC) (D), in the culture *Stylosanthes* cv. Campo Grande.



Source: Authors (2024).

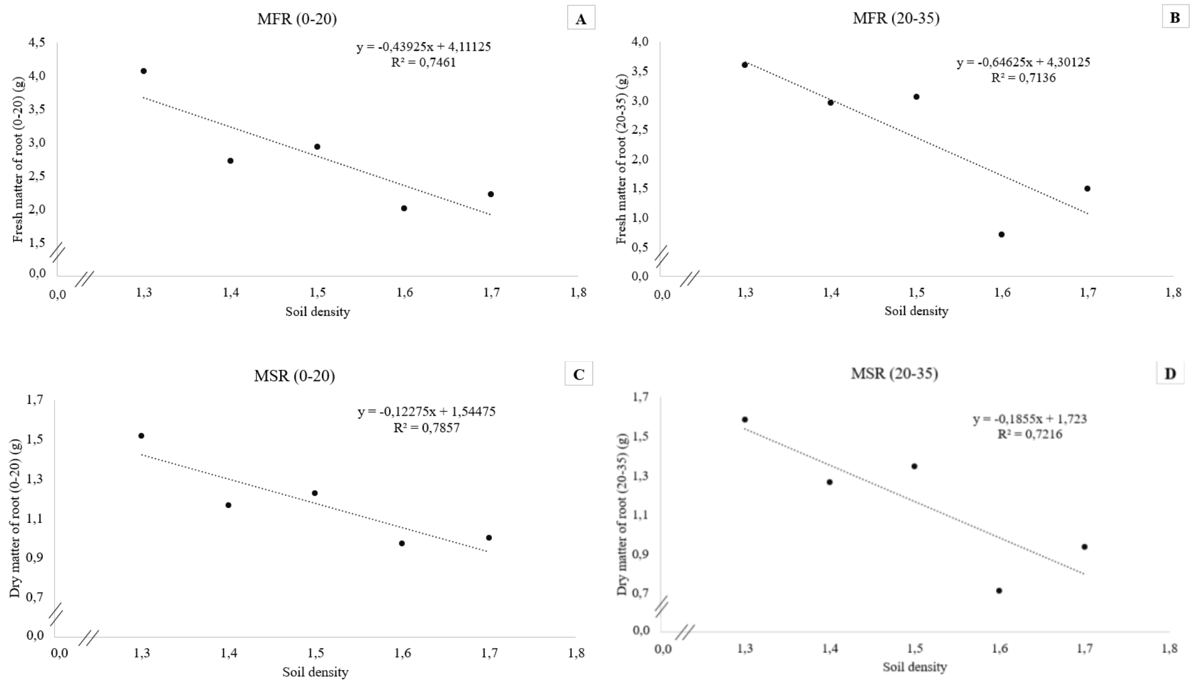
The research conducted by Montiel *et al.* (2024) on the components of canola production in a clayey Latossolo under different levels of compaction also revealed a marked decrease in the dry mass of the above-ground part of the plants as soil compaction increased. These results indicate the detrimental effects of soil compaction on crop productivity, emphasizing the need for proper assessment and control of this phenomenon in the agricultural context.

As observed in the variables of fresh and dry mass of leaves and stems, the results for the variables of fresh root mass (MFR) and dry root mass (MSR) also showed a decreasing linear model with the increase in soil density, as we can see in figure 5. The analysis showed that, with the increase in soil density, root mass production decreased, indicating that more compacted soils hinder root penetration, adversely affecting both root and aerial development of plants.

According to Nunes *et al.* (2016), when studying soil water densities and tensions in corn root production, they observed that an increase in soil density results in a direct reduction in porosity. This decrease in porosity compromises root development and negatively affects the aerial part of the plants. Soil compaction hinders the absorption of nutrients and water, which are essential for the healthy growth of plants (Ferraz *et al.*, 2017).

Figure 5.

Fresh matter of root (0-20) (MFR 0-20) (A), fresh matter of root (20-35) (MFR 20 --35) (B), fresh matter of root (0-20) (MSR 0-20) (C) and dry matter of root (20-35) (MSR 20-35) (D), in the culture of *Stylosanthes* cv. Campo grande.



Source: Authors (2024).

The study conducted by Andognini (2019) investigated the impact of soil compaction on the physical attributes of the soil in Santa Catarina, as well as on the productive and nutritional characteristics of black oats. One of the observed results was the reduction of root dry mass, which showed an inverse relationship with the increase in soil compaction.

Similarly, Castagnara *et al.* (2013), while studying the growth of *Stylosanthes* cv. Campo Grande at different density levels of a Red Latosol, found a decrease in root dry matter as soil density increased in the compacted layers. They observed that the increase in soil density hinders the penetration and growth of roots towards deeper layers. This limits the exploration of the soil by the roots, resulting in lower absorption of nutrients and water.

The increase in soil density hinders the ability of roots to expand and penetrate deeper into the soil. As a result, plants have limited access to nutrients and water available in the deeper layers, which negatively affects the development of the aerial part. With less developed roots, the plant is unable to sustain vigorous growth of the aerial part, leading to a reduction in biomass production and productive potential.

Conclusion

Soil density values higher than 1.4 $Mg.m^{-3}$ were identified as limiting for the aerial and root development of the *Stylosanthes* cv. Campo Grande under greenhouse conditions. The treatment with a soil density of 1.7 $Mg.m^{-3}$ resulted in a statistically significant reduction in all variables analyzed in the crop.

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