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Effect of soil compaction on aerial and root development of *Crotalaria juncea* L.

Efeito da compactação do solo no desenvolvimento aéreo e radicular da *Crotalaria juncea* L.

SANTOS, Ilâine Benício dos[1]; CAVALCANTE, Julio Cesar Silva[2]; SILVA, Jorge Oliveira da[3]; SILVA, Simão Gaspareto da[4]; CALIXTO COSTA, Julio César[5]; SANTOS, Cícero Gomes dos[6]

[1] 0009-0004-4797-3296; Federal University of Alagoas (*Universidade Federal de Alagoas*) - Campus Arapiraca. Arapiraca, AL, Brazil. ilainebenicio@gmail.com

[2] 0009-0001-7825-4882; Federal University of Alagoas (*Universidade Federal de Alagoas*) - Campus Arapiraca. Arapiraca, AL, Brazil. juliocesar.cavalcante2011@hotmail.com

[3] 0009-0002-1933-6885; Federal University of Alagoas (*Universidade Federal de Alagoas*) - Campus Arapiraca. Arapiraca, AL, Brazil. jorge.zootc@gmail.com

[4] 0009-0002-6695-9209; Federal University of Alagoas (*Universidade Federal de Alagoas*) - Campus Arapiraca. Arapiraca, AL, Brazil. biologiamcz@gmail.com

[5] 0009-0001-7220-1798; Federal Rural University of Pernambuco (*Universidade Federal Rural de Pernambuco*). Recife, PE, Brazil. julio.calixto@ufrpe.br

[6] 0000-0002-2264-6772; Federal University of Alagoas (*Universidade Federal de Alagoas*) - Campus Arapiraca. Arapiraca, AL, Brazil. cgomes@arapiraca.ufal.br

ABSTRACT

Soil quality is important for the sustainability of terrestrial ecosystems. Soil compaction poses a threat to agricultural systems by reducing permeability, hindering water infiltration and root development, as well as impairing gas movement in the soil profile. To restore and preserve the physical properties of the soil, it is essential to promote vigorous biological activity, ensuring a continuous supply of organic compounds. Thus, this study aimed to evaluate the development of the aerial and root parts of *Crotalaria juncea* L. in response to increased levels of soil compaction in a protected environment at the Federal University of Alagoas (*Universidade Federal de Alagoas*), Arapiraca Campus. The treatments consisted of five levels of soil density, corresponding to compaction densities of 1.3, 1.4, 1.5, 1.6, and 1.7 Mg m^{-3}. The evaluated variables included plant height, stem diameter, number of leaves, fresh and dry mass of the root, stem, number of leaves, and leaf area. The growth of the root system and the aerial part of *Crotalaria juncea* L. was hindered by the increase in soil compaction, particularly evident from a soil density of 1.6 Mg m^{-3}. Both the fresh and dry mass of the aerial and root parts were reduced with the increase in compaction levels, especially above a density of 1.5 Mg m^{-3}.

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RESUMO

A qualidade do solo é importante para a sustentabilidade dos ecossistemas terrestres. A compactação do solo representa uma ameaça aos sistemas agrícolas, reduzindo a permeabilidade, dificultando a infiltração de água e o desenvolvimento radicular, além de prejudicar a movimentação de gases no perfil do solo. Para restaurar e preservar as propriedades físicas do solo, é essencial promover uma atividade biológica vigorosa, garantindo um suprimento contínuo de compostos orgânicos. Com isso, este estudo teve como objetivo avaliar o desenvolvimento da parte aérea e radicular da *Crotalaria juncea* L., em resposta ao aumento dos níveis de compactação do solo em ambiente protegido na Universidade Federal de Alagoas, *Campus* Arapiraca. Os tratamentos consistiram em cinco níveis de densidade do solo, correspondendo a densidades de compactação de 1.3, 1.4, 1.5, 1.6 e 1.7 Mg m^{-3}. As variáveis avaliadas incluíram altura da planta, diâmetro caulinar, número de folhas, massa fresca e seca da raiz, do caule e do número de folhas e área foliar. O crescimento do sistema radicular e da parte aérea da *Crotalaria juncea* L., foi prejudicado pelo aumento da compactação do solo, especialmente evidente a partir de uma densidade do solo de 1,6

***Palavras-chave*:**
Níveis de compactação, crescimento radicular, plantas de cobertura.

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Mg m^{-3}. Tanto a massa fresca quanto a massa seca de parte aérea e radicular foram reduzidas com o aumento dos níveis de compactação, principalmente acima da densidade de 1,5 Mg m^{-3}.

Introduction

As a vital natural resource, soil provides physical support, water, and essential nutrients for plant growth. Thus, various techniques are employed in soil management and conservation, with soil preparation being a practice that greatly influences the attributes that indicate good soil physical quality, as it directly impacts its structure (Hamza; Anderson, 2015).

The porous space of the soil can be divided into two classes, both macropores and micropores. Sandy soils are known for having high macroporosity and low microporosity, resulting in a reduction of water retention (Barros, 2020). Thus, soil density becomes one of the most important measures for assessing the physical quality of the soil, as it provides an indication of the total volume of soil, composed of the sum of the volume of solids and the volume of pores (Rabot *et al.*, 2018).

The excessive use of heavy agricultural machines and implements increases soil density, favors microporosity, and alters water availability for plants, affecting the field capacity and the permanent wilting point (Ortiz, 2019). Soil compaction reduces the number of macropores, hindering root growth in dry soils due to increased physical resistance and, in wet soils, limiting oxygenation, which damages root respiration. Furthermore, the reduction of micropores impairs water storage and gas circulation, intensifying surface runoff and increasing soil and water loss. This process depletes the fertility of the topsoil, directly impacts plant development, and reduces the productive potential of crops (Santos *et al.*, 2018; Silva, 2021).

This concern is amplified during soil preparation in conventional systems, where excessive tillage can lead to subsurface compaction, also known as “plow pan” or “tillage pan.” This compaction hinders root development at depth, making plants more fragile during prolonged droughts and can also cause oxygen deficiency in conditions of excessive rainfall (Embrapa, 2006). These effects of compaction can compromise nutrient absorption, plant support capacity, and consequently reduce crop productivity (Araújo, 2015).

The recovery of the physical properties of the soil can be favored by biological activity, and the use of cover crops protects the soil against erosion and nutrient leaching, in addition to being used for grazing, grain production, seeds, and straw for direct planting (Oliveira, 2014; Silva *et al.*, 2021). Legumes are essential in green manuring, enriching the soil with their biomass, as they improve its properties and help control apparent plants through allelopathic effects, releasing substances that inhibit their germination and growth (Bertoncelli, 2015; Bianchini, 2017).

The use of species such as the leguminous *Crotalaria juncea* L. stands out for being plants capable of breaking through compacted layers, mainly through their vigorous roots and extensive root system, which allow deep penetration into the soil to reach these layers (Santos *et al.*, 2018). Furthermore, it adapts well to different types of soils, even those with low fertility, contributing to nitrogen conservation in the soil and promoting good fertility. Its roots also increase soil organic matter as they decompose, providing essential nutrients for subsequent crops (Cieslik, 2014).

In light of this, the objective of this study was to evaluate the development of the aerial and root parts of *Crotalaria juncea* L., in response to the increase in soil compaction levels in a protected environment at the Federal University of Alagoas (*Universidade Federal de Alagoas*), Arapiraca Campus.

Methodology

Location of the experiment

The experiment was conducted in a protected environment, starting from July 5th to September 2nd, 2023, located at the Federal University of Alagoas (*Universidade Federal de Alagoas*) - Arapiraca Campus, in the Agreste region of Alagoas. The area is situated between the geographic coordinates 09° 41' 55'' S and 36° 41' 08'' W, at an altitude of 321 m above sea level. The municipality is part of the Agreste region, which represents a transition between the Forest Zone and the Alagoas *Sertão*.

Regarding the climate, the region is classified as tropical type 'As', characterized by winter rains (April - September) and dry seasons in summer (October - March), according to the Köppen classification criteria (1948).

Soil material

The soil material used to fill the pots was obtained from an experimental area located at the Arapiraca Campus, sourced from a Sandy Clay Loam soil collected at a depth of 0 - 20 cm. After collection, the soil was subjected to air drying and crushing. It was then passed through a 2 mm mesh sieve to separate clods, roots, and straw, and subsequently, a 0.7 kg sample was taken for physical analysis, the results of which are presented in Table 1.

Table 1.
Result of the physical soil analysis of the layer from 0 to 20 cm used in the experiment.

Results of Physical Analysis					
Coarse Sand	Fine Sand	Total Sand	Silt	Clay	Textural Class
g/kg					
366	202	568	145	287	F. Arg. Ar

Embrapa Extraction Method: Water (pH); Mehlich (P, K, Na, Fe, Cu, Zn, Mn); KCl 1N (Ca, Mg and Al); Calcium Acetate pH 7.0 (H + Al); Hot water (Boron); F.Arg.Ar. = Sandy Clay Loam.

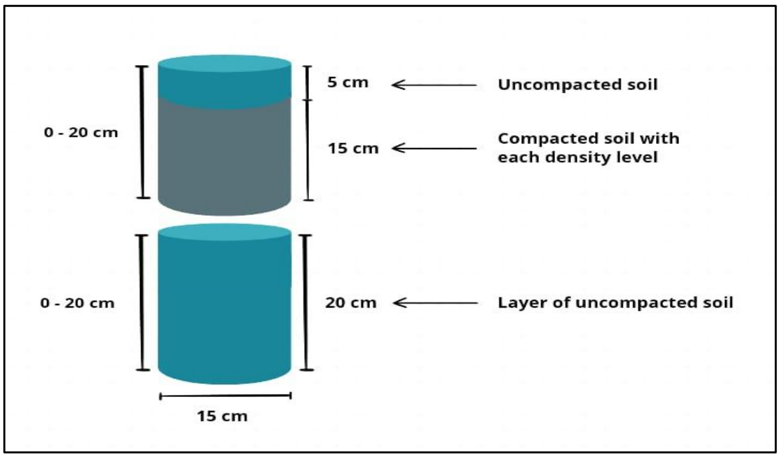
Source: Central Analítica (2023).

Treatments and plant material used

The treatments used consisted of five levels of soil density, designated T1, T2, T3, T4, and T5, corresponding to compaction densities of 1.3, 1.4, 1.5, 1.6, and 1.7 Mg m^{-3}, respectively. These levels were combined with a Fabaceae species, *Crotalaria juncea* L., using two plants per experimental unit. The experimental design adopted was completely randomized blocks, with four replications, totaling 20 plots.

The experimental plots consisted of two overlapping rigid PVC rings, each 20 cm high and 15 cm in diameter, which were joined with adhesive tape of the type "Silver Tape." For this, the assembly of the pots was carried out with the lower rings filled with soil collected from a depth of 0 - 20 cm, having a natural density of 1.6 Mg m^{-3}. The upper rings were filled with soil from the same 0 - 20 cm depth layer, whose mass was determined and compacted according to the soil density treatments for each experimental unit (Figure 1).

Figure 1.
Representative scheme of the assembly of the pots used in the experiment with the soil at the respective depth (0-20 cm) and its distribution in the upper and lower rings.



Source: Adapted from Santos (2016).

For the compaction densities, the following soil masses were used: 3.8; 4.2; 4.5; 4.8 and 5.2 kg corresponding to the respective treatments T1, T2, T3, T4, and T5. Each soil mass was compacted until reaching 15 cm of filling in the upper pot of the experiment.

To subscribe to the density levels, 15 cm of the upper rings was considered, reserving 5 cm of the surface with uncompacted soil to allow for the initial development of plants adequately. At the bottom of the plots, an anti-insect mesh with a 1mm mesh size was placed and secured with a nylon clamp. Regarding soil compaction, it was carried out using a hydraulic press, according to each density and mass level for each treatment. There was no soil correction, opting to maintain its original characteristics under environmental conditions.

The sowing was done directly in the pots, with the distribution of four seeds per treatment. After the germination of the culture, two seedlings were selected based on their vigor and better development.

Analyzed variables

The variables related to plant development, such as plant height (PH), stem diameter (SD), and number of leaves (NL) were evaluated at 20, 30, 40, 50, and 60 days after sowing (DAS). Plant height was measured in centimeters using a measuring tape from the soil surface to the apical meristem of the main stem. The stem diameter of the plants was determined with the help of a graduated caliper in millimeters, and in the leaf counting, only those with a central leaf length of at least 3 cm were considered.

The evaluated variables, such as fresh leaf mass (FLM), fresh stem mass (FSM), fresh root mass (FRM), dry leaf mass (DLM), dry stem mass (DSM), and dry root mass (DRM) at depths of 0 - 20 cm (upper ring) and 20 - 40 cm (lower ring) were analyzed at the end of the crop cycle, 60 days after planting. For FLM, all leaves of each treatment were manually removed, while for FSM, the stem was cut with the help of knives at the collar height. For FRM, at both depths of 0 - 20 cm and 20 - 40 cm, the material was washed to preserve its entire structure and avoid sample loss. Subsequently, all the variables were taken to the laboratory for weighing on a precision scale.

For the leaf area variable (AF), at the end of the experiment, a total of 200 leaves were collected from the plants using a destructive method, consisting of 10 leaves per repetition and 40 leaves per treatment. At this stage, the length (C) and width (L) of the blade of each leaf were measured with a millimeter ruler. Subsequently, the product of the length multiplied by the width of each leaf was calculated.

After completing these steps, the leaves were subjected to high-resolution scanning using an HP printing machine model 2360. To facilitate calibration by the software, a 10 cm red line was incorporated into the images. Subsequently, these images were processed and analyzed for leaf area using the ImageJ software, which is widely available for free on the internet (http://rsbweb.nih.gov/ij/). Using the data from the 200 leaves, a model was developed that relates the leaf area determined by the integrator (dependent variable) with the product of length (C) by width (L) (independent variable).

Statistical analysis

The obtained data were analyzed through analysis of variance using the statistical software SISVAR, and significance was assessed using the F test. The variables that showed significance were compared regarding their means using Tukey's test, with a significance level of 5%, and the quantitative factor was subjected to regression analysis.

Results and discussion

Growth indices: plant height, stem diameter, and number of leaves

The results obtained indicate that soil compaction influenced almost all the analyzed variables in nearly all planting times. However, no significant differences were observed in stem diameter between 30 days after sowing and in plant height at 30 and 40 days after sowing. Likewise, the number of leaves showed no significant difference between 20 and 60 days after sowing (Table 2).

The different levels of soil density significantly influenced the stem diameter. Twenty days after sowing, it was observed that soil density had a significant effect on the stem diameter of the plants, suggesting that soil compaction affected the initial growth in diameter. The regression presented behaved quadratically, indicating a moderate variation among the samples.

Table 2.
Analysis of variance of the growth variables of *Crotalaria juncea* L., based on different soil compaction densities.

VARIATION SOURCE	G.L.	MEAN SQUARES		
		20 days after planting		
		Diameter	Height	Number of Leaves
Soil Density	4	0.324*	5.075*	0.250^{NS}
Waste	5	0.019	0.774	0.300
C.V. (%)		8.35	7.81	7.30
		30 days after planting		
		Diameter	Height	Number of Leaves
Soil Density	4	0.075^{NS}	66.28^{NS}	13.35*

Waste	5	0.033	22.86	1.10
C.V. (%)		10.66	29.33	9.45
		40 days after planting		
		Diameter	**Height**	**Number of Leaves**
Soil Density	4	1.66*	232.74^{NS}	63.35*
Waste	5	0.057	52.89	7.10
C.V. (%)		8.81	21.36	12.06
		50 days after planting		
		Diameter	**Height**	**Number of Leaves**
Soil Density	4	1.95*	516.66*	183.10*
Waste	5	0.132	81.27	11.60
C.V. (%)		12.27	13.94	11.13
		60 days after planting		
		Diameter	**Height**	**Number of Leaves**
Soil Density	4	2.70*	1429.81*	411.75^{NS}
Waste	5	0.261	120.75	83.50
C.V. (%)		15.30	13.08	25.74

G.L. - Degrees of freedom, C.V. - Coefficient of variation, NS - Not significant, * - Significant by the F test (p < 0,05). Diameter - Diameter of the stem, Height - Height of the plant, Number of Leaves - Number of leaves per plant.

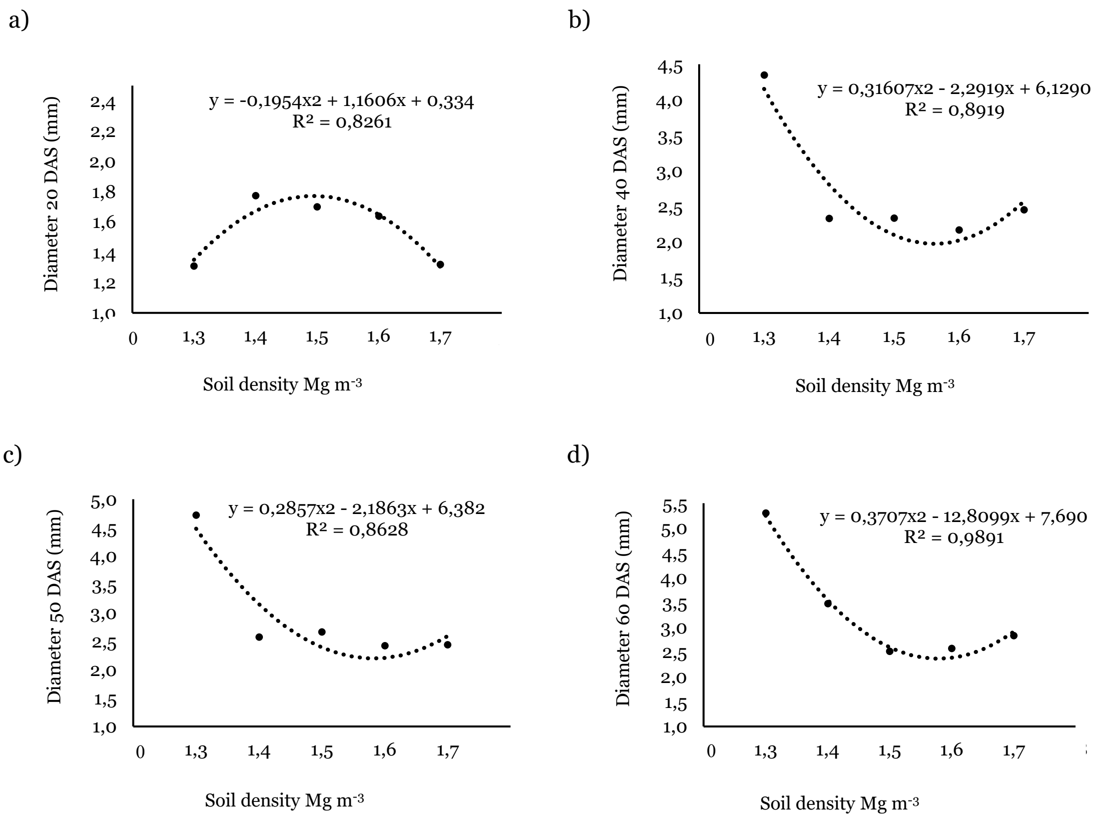
Source: The authors (2024).

At 40 days after sowing, soil density showed a significant effect on stem diameter, with a decrease observed in the regression. This indicates that over time, soil density began to impact the diameter of the plants. At 50 days after sowing, stem diameter continued to be significantly influenced by soil density, with the regression graph maintaining a decreasing pattern, reflecting greater variability among the samples. In the final phase of the experiment, at 60 days after sowing, soil density also had a significant effect on stem diameter, with the highest value for this variable obtained at a density of 1.3 Mg m^{-3}, measuring 5.30 mm, while at compaction levels of 1.4, 1.5, 1.6, and 1.7 Mg m^{-3}, the values were 3.47 mm, 2.51 mm, 2.57 mm, and 2.83 mm, respectively.

The stem diameter (SD) variable exhibited a quadratic behavior in response to soil density treatments. It was observed that treatments with higher soil densities (1.6 and 1.7 Mg m^{-3}) resulted in the lowest outcomes at different planting times, indicating that soil compaction negatively affected this variable. Specifically, the stem diameter proved to be more sensitive to high soil densities, reflecting a significant reduction in its growth with increasing compaction (Figure 2). In the study by Santos *et al.* (2018), conducted with *Crotalaria juncea* and *Crotalaria spectabilis*, a significant reduction in stem diameter was observed in response to different levels of soil compaction, especially in cases of high compaction density.

Figure 1.

Comparison of the significant values of stem diameter variable of *Crotalaria juncea* L., as a function of soil compaction: a) diameter at 20 DAS; b) diameter at 40 DAS; c) diameter at 50 DAS; d) diameter at 60 DAS.

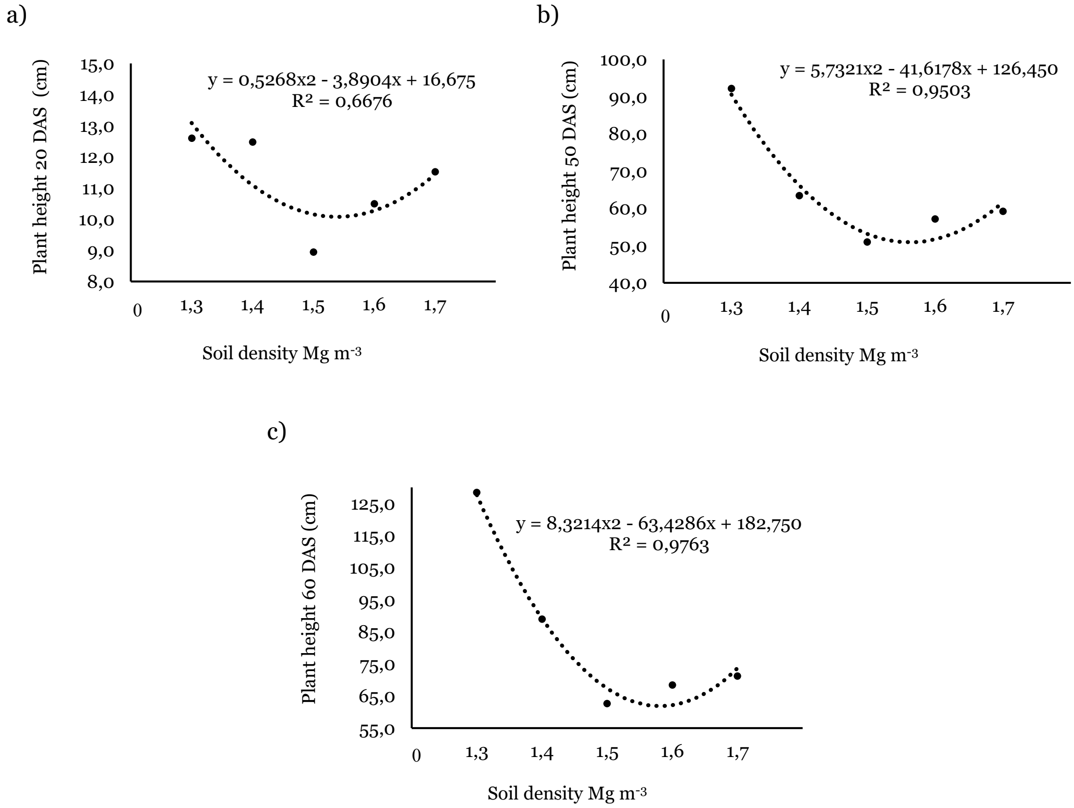


Source: The authors (2024).

For plant growth, it was observed that soil compaction influenced this variable throughout the experiment. At 20 days after sowing, it was observed that plants in less compacted soils (1.3 Mg m^{-3}) had greater height, reaching about 13 cm, while in more compacted soils (1.7 Mg m^{-3}) the plants only reached 8.5 cm. At 40 days, the plants in the lower density soil reached 92 cm, while in soils with densities (1.5 and 1.6 Mg m^{-3}) they grew only about 51 cm and 40 cm, respectively. In the final phase, at 60 days, the effect of compaction was even greater, as the plants in less compacted soil reached approximately 125 cm, while in more compacted soils, the heights were limited to 65 cm and 55 cm (Figure 3). These results demonstrate that soil compaction negatively affects plant growth due to the restriction on root development and access to essential resources, such as water and nutrients.

Figure 2.

Comparison of the significant values of the plant height variable of *Crotalaria juncea* L., according to soil compaction: a) Plant height at 20 DAS; b) Plant height at 50 DAS; c) Plant height at 60 DAS.

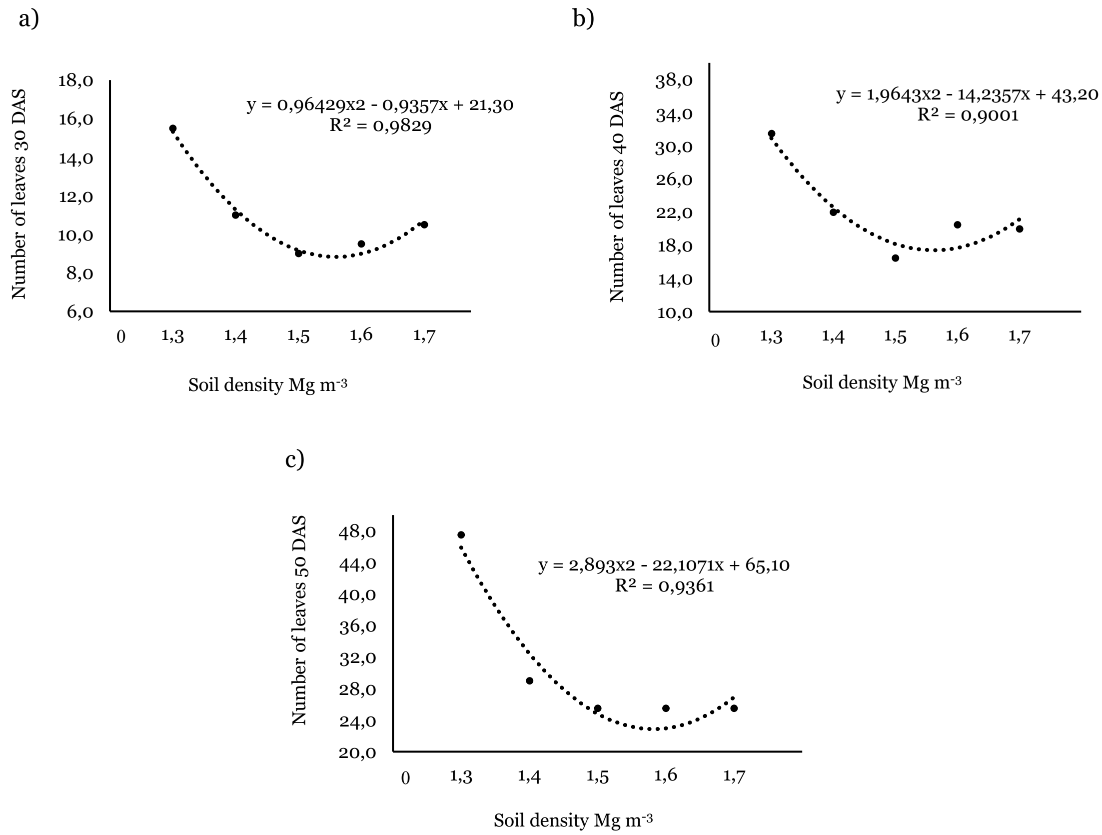


Source: The authors (2024).

Pacheco *et al.* (2015) emphasize that *Crotalaria* is recognized as one of the leguminous species with the fastest initial growth. Due to this characteristic, *Crotalaria* performed well up to 40 days after sowing, during which the species demonstrated a tall stature, with longer and heavier stems, and also showed a high branching potential. The results suggest that Crotalária can develop more robustly in both the vegetative and root parts when exposed to slight soil compaction, as observed by Silva *et al.* (2006).

The number of leaves showed a trend similar to the other variables, with a decrease observed due to the increase in compaction levels, especially from a density of 1.5 Mg m^{-3}. In the 30 days following sowing, soil density had a significant effect on this variable, behaving quadratically and achieving values of 15.5 leaves at the lowest compaction (1.3 Mg m^{-3}), 11 leaves at the compaction (1.4 Mg m^{-3}), 9 leaves at the compaction (1.5 Mg m^{-3}), 9.5 leaves at the compaction (1.6 Mg m^{-3}), and 10.5 leaves at the highest compaction (1,7 Mg m^{-3}).

Figure 3.
Comparison of the significant values of the variable number of leaves of *Crotalaria juncea* L., according to soil compaction: a) number of leaves at 30 DAS; b) number of leaves at 40 DAS; c) number of leaves at 50 DAS.



Source: The authors (2024).

At 40 days after sowing, the number of leaves was significantly affected by soil density, showing a decreasing regression in its results and obtaining a significant reduction in the density treatments of 1.5 and 1.7 Mg m^{-3}, indicating an increase in variability. At 50 days after sowing, soil density had a significant effect, presenting a quadratic regression in its results, and the number of leaves was higher at the lowest compaction with 47.5 leaves. In subsequent compactions, the observed values were 29 leaves for 1.4 Mg m^{-3}, 25.5 leaves for both 1.5 and 1.6 Mg m^{-3}, and for 1.7 Mg m^{-3} (Figure 4).

These results confirm the findings of Bonelli *et al.* (2011) who observed a reduction in leaf production in grasses when exposed to higher soil densities. In addition, Santos *et al.* (2012), in their study with the physic nut, also identified a negative influence on the number of leaves as soil density increased.

Fresh pasta and dry pasta

According to the results of the variance analysis, the variables showed significance and interaction among the results. For both variables, it is noted that the increase in soil compaction densities affected the results (Table 3).

Table 3.

Result of the analysis of variance of the variables: Fresh root mass (0 - 20 cm) (FRM), fresh root mass (20 - 40 cm) (FRM), fresh leaf mass (FLM), fresh stem mass (FSM), dry root mass (0 - 20 cm) (DRM), dry root mass (20 - 40 cm) (DRM), dry leaf mass (DLM), and dry stem mass (DSM) as a function of increased soil compaction.

VARIATION SOURCE	G.L.	MEAN SQUARES			
		MFC	***MSC***	***MFF***	***MSF***
Soil Density	4	450.32*	35.71*	161.77*	7.27*
Waste	5	4.37	0.80	0.74	0.22
C.V. (%)		8.28	12.87	4.77	14.44
		MFR 0-20	***MFR 20-40***	***MSR 0-20***	***MSR 20-40***
Soil Density	4	930.57*	1100.82*	29.94*	30.47*
Waste	15	12.75	9.41	2.15	1.17
C.V. (%)		11.96	13.38	21.22	20.22

G.L. - Degrees of freedom, C.V. - Coefficient of variation, NS - Not significant, * - Significant by the F test (p < 0,05). MFC - Fresh Mass of Stem, MSC - Dry Mass of Stem, MFF - Fresh Mass of Leaf, MSF - Dry Mass of Leaf, MFR (0-20) - Fresh Mass of Root from 0 to 20 cm depth, MFR (20-40) - Fresh Mass of Root from 20 to 40 cm depth, MSR (0-20) - Dry Mass of Root from 0 to 20 cm depth, MSR (20-40) - Dry Mass of Root from 20 to 40 cm depth.

Source: The authors (2024).

The development of the root system of the crop showed significant differences between the soil layers and density treatments. In the upper layer of the pot (0 - 20 cm), a higher accumulation of fresh root matter was observed in the soil density treatments of 1.3, 1.4, and 1.5 Mg m^3, with values of 67.71, 26.10, and 22.66 grams, respectively. In the lower layer (20 - 40 cm), the results followed a similar pattern to that of the upper layer, except in the density treatment of 1.6 Mg m^3, which recorded the lowest value, with only 3.0 grams of fresh matter. These data indicate that higher densities restrict root development, especially in deeper layers, limiting the crop's ability to explore available resources.

Clark *et al.* (2003) state that the increase in compaction reduces root growth due to the increased resistance of the soil to penetration, which can result in losses in crop productivity by restricting the root's access to the reservoir of water and nutrients.

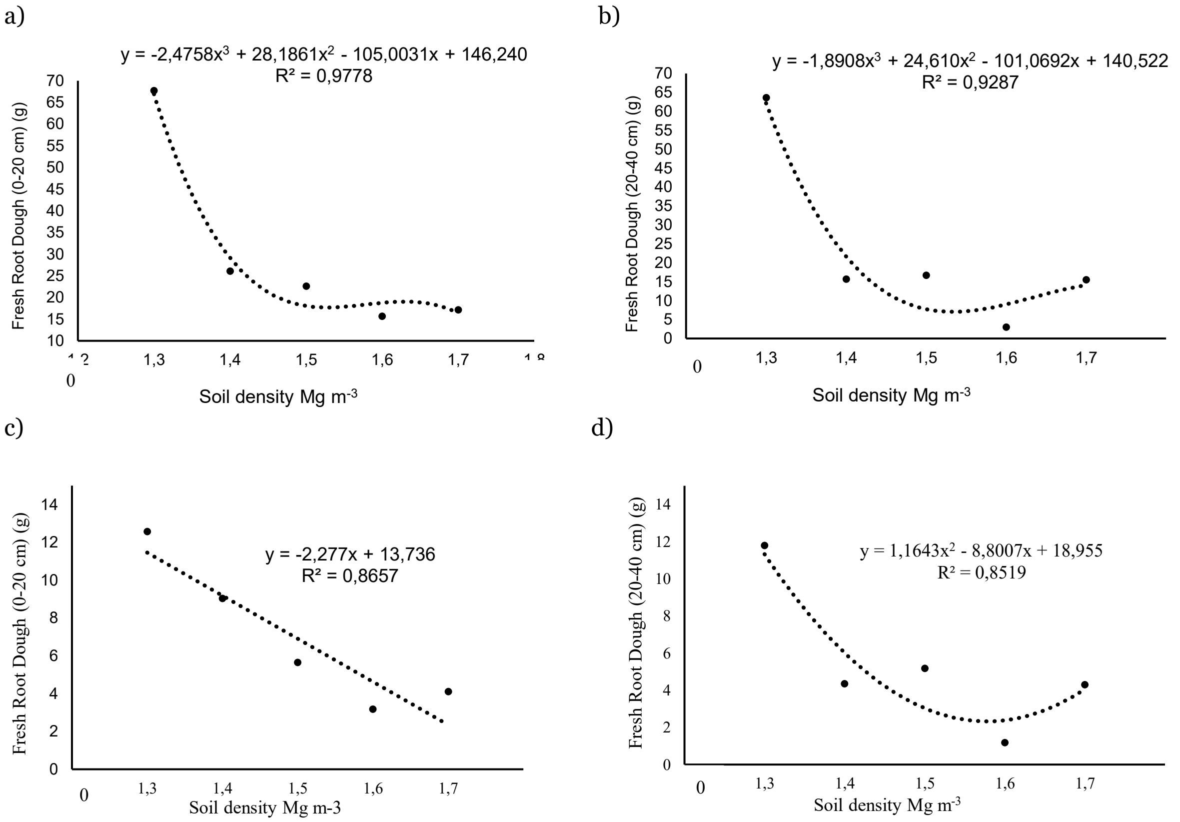
For the dry mass of the root (0 - 20 cm), it was noted that *C. juncea* recorded the highest values at densities of 1.3, 1.4, and 1.5 Mg m^{-3}, with amounts of 12.56, 9.03, and 5.65 grams, respectively. These results demonstrate that soil compaction negatively impacted the development of the plant's root system. These findings corroborate the results presented by Dezordi *et al.* (2013), which confirmed that the increase in soil density had an adverse effect on the performance of millet species (*Pennisetum glaucum*), *U. brizantha* and *C. spectabilis*.

These researchers also demonstrated that densities higher than 1.5 Mg m^{-3} represent a limitation for the growth of the roots of these species.

Regarding the accumulation of dry mass of the roots in the lower part of the pot (20 - 40 cm), the results are similar to those in the upper part, where the treatment with a density of 1.6 Mg m^{-3} recorded the lowest value of 1.18 grams, indicating a minimal amount of the crop's roots (Figure 5). Similar results were observed by Ferraz *et al.* (2017), who identified a 32% reduction in the accumulation of dry mass of the bean roots under higher compaction levels, compared to the control treatment.

For the accumulation of fresh leaf mass (MFF), the results revealed a significant response, with high values in the initial soil compaction treatments. In the treatment with a density of 1.3 Mg m^{-3}, a value of 32.78 grams was observed. On the other hand, in treatments with higher compaction densities, there was a decrease, particularly lower at the density of 1.6 Mg m^{-3} compared to the others, recording a value of 8.37 grams.

Figure 4.
Comparison of the fresh mass and dry mass of the root system of *Crotalaria juncea* L., in response to different soil compaction densities: a) fresh root mass (0 - 20 cm); b) fresh root mass (20 - 40 cm); c) dry root mass (0 - 20).



Source: The authors (2024).

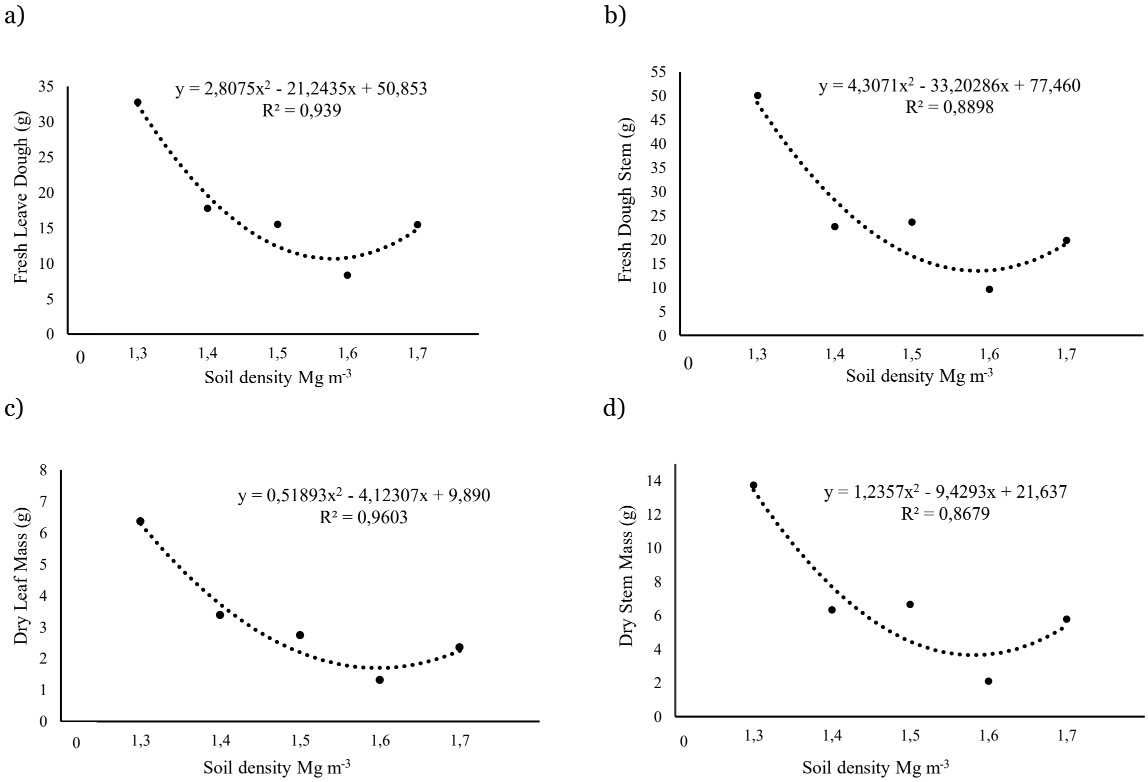
The fresh mass of the stem (FMS) showed comparable values to the other fresh mass measurements, with higher values in the initial treatments of soil densities, especially at 1.3, 1.4, and 1.5 Mg m^{-3}, where values of 50.15, 22.75, and 23.70 grams were recorded, respectively. However, at the more compacted soil densities, the values decreased, reaching 9.65 and 19.90 grams for the treatments 1.6 and 1.7 Mg m^{-3}, respectively.

Silveira *et al.* (2022), when studying the culture of Safflower in relation to soil density, found significant values for the fresh mass of the aerial part. Similarly, Fagundes *et al.* (2014) assessed the development of three varieties of sugarcane at five levels of soil density and found significant effects in their results. These findings corroborate the results of Guimarães *et al.* (2013), where soil compaction levels were observed as significant modifiers of the fresh mass of the aerial part of millet.

For the accumulation of dry leaf mass (DLM), the results revealed a significant response, with higher values in the initial soil compaction treatments. In treatments with higher compaction densities, there was a decrease, being particularly lower at the density of 1.6 Mg m^{-3} compared to the others, recording a value of 1.31 grams. Silva *et al.* (2011) emphasize that in highly compacted soils, the availability of water and nutrients to the root system can be quickly reduced, limiting its exploration area and resulting in lower production of the aerial part, including the leaves of the crops. However, in less dense soils, the larger pore space promotes root development and water absorption, which can lead the plant to direct more photoassimilates to the roots, potentially compromising the growth of the aerial part.

The dry mass of the stem (DMS) showed values comparable to those of the other dry mass measurements, with a greater effect observed in the initial treatments of soil densities, especially at 1.3, 1.4, and 1.5 Mg m^{-3}, where 13.76, 6.67, and 6.35 grams were recorded, respectively. However, in the more compacted soil densities, the values decreased, reaching 2.12 and 5.80 grams for the treatments of 1.6 and 1.7 Mg m^{-3}, respectively (Figure 6).

Figure 5.
Comparison of fresh mass and dry mass of the aerial part of *Crotalaria juncea* L., in response to different soil compaction densities: a) fresh mass of the leaves; b) fresh mass of the stem; c) dry mass of the leaves; d) dry mass of the stem.



Source: The authors (2024).

Leaf area

The results indicated that there was a significant difference in the final outcome of leaf area (LA) among the soil density treatments. The mean squares of the repetitions of treatments T1 to T5 were calculated and analyzed to determine the significance of the observed variations.

The statistical analysis showed that soil density significantly influenced most of the assessed variables, including T1, T2, T3, and T5. These variables showed consistent responses to increased compaction, indicating that changes in soil physical conditions directly impacted the performance of these characteristics.

However, the variable T4 did not show statistical significance, which indicates that compaction reduced the variability in plant growth, making the results more homogeneous. This effect suggests a uniform limitation in root development and resource absorption (Table 4).

Similar results were found by Zobiole *et al.* (2007), who used soybean cultivation at different soil compaction densities and found that the leaf area was affected by the interaction between soil compaction levels. In their study, at densities of 1.0 and 1.2 g cm^{-3}, the results were significantly higher compared to the densities of 1.4 or 1.5 g cm^{-3}.

Table 4.

Analysis of variance of the leaf area variable of *Crotalaria juncea* (CJ) based on densities 1.3, 1.4, 1.5, 1.6, and 1.7 Mg m^{-3} cultivated in a greenhouse on the Arapiraca Campus.

VARIATION SOURCE	G.L.	MEAN SQUARES				
		T1	T2	T3	T4	T5
Repetitions	3	59.45*	216.20*	160.02*	0.66^{NS}	66.67*
Waste	24	16.44	5.58	8.35	1.60	3.62
C.V. (%)		23.44	22.34	22.70	19.12	24.20

G.L. - Degrees of freedom, C.V. - Coefficient of variation, NS - Not significant, * - Significant by the F test ($p < 0.05$). T - Treatment, T1 - Density treatment 1.3 Mg m^{-3}, T2 - Density treatment 1.4 Mg m^{-3}, T3 - Density treatment 1.5 Mg m^{-3}, T4 - Density treatment 1.6 Mg m^{-3}, T5 - Density treatment 1.7 Mg m^{-3}.

Source: The authors (2024).

Conclusions

The growth of the root system and the aerial part of *Crotalaria juncea* L. was hindered by the increase in soil compaction, particularly evident from a soil density of 1.5 Mg m^{-3}.

The increase in soil compaction results in a decrease in stem diameter, plant height, a reduction in the number of leaves, and in leaf area *Crotalaria juncea* L.

Both the fresh biomass and the dry biomass of the aerial and root parts were reduced with the increase in compaction levels, negatively affecting the overall growth of the plant, compromising its ability to absorb nutrients and water from the soil, and consequently harming its performance and productivity.

The compacted upper layer of the treatments acts as a barrier that prevents the root system of the crop from penetrating and developing in the lower part of the soil.

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