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Morphological response of *Crotalaria juncea* L. and *Crotalaria spectabilis* Roth to soil compaction

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A B S T R A C T

The physical degradation of soil due to compaction is a critical process that increases density, limits porosity, and raises mechanical resistance, potentially restricting crop development. In this context, the present study aimed to evaluate the effect of increased soil compaction on the morphological traits of *Crotalaria juncea* L. and *Crotalaria spectabilis* Roth, grown in dystrophic Red Argisol. The experiment was conducted in a protected environment, using a randomized block design (5 × 2 factorial), with five soil density classes (1.3; 1.4; 1.5; 1.6; and 1.7 Mg m^{-3}) and four replications. Stem diameter, plant height, and number of leaves were evaluated at 15, 30, 45, and 60 DAP, along with leaf area at 60 days. The results indicate that plant height was not affected by the soil compaction levels. However, increasing the density from 1.3 to 1.7 Mg m^{-3} reduced the stem diameter (from 3.13 to 2.75 mm), the number of leaves (from 18.94 to 14.30 leaves per plant), and the leaf area (from 411.20 to 278.89 cm^2). Differences were also observed between species, with *Crotalaria juncea* showing a greater reduction in biometric variables, while *Crotalaria spectabilis* showed less variation, indicating greater tolerance to compaction conditions. It is concluded that *Crotalaria spectabilis* has a greater adaptive capacity to compacted soil, making it potentially more suitable for conditions with physical soil restrictions.

R E S U M O

A degradação física do solo por compactação é um processo crítico que eleva a densidade, restringe a porosidade e amplia a resistência mecânica, podendo limitar o desenvolvimento das culturas. Diante desse contexto, o presente estudo teve como objetivo avaliar o efeito do aumento da compactação do solo sobre atributos morfológicos de *Crotalaria juncea* L. e *Crotalaria spectabilis* Roth, cultivadas em Argissolo Vermelho distrófico. O experimento foi conduzido em ambiente protegido, em delineamento de blocos casualizados (fatorial 5 × 2), com cinco classes de densidade do solo (1,3; 1,4; 1,5; 1,6 e 1,7 Mg m^{-3}) e quatro repetições. Foram avaliados diâmetro do caule, altura de plantas e número de folhas aos 15, 30, 45 e 60 DAP, além da área foliar aos 60 dias. Os resultados indicam que a altura das plantas não foi influenciada pelos níveis de compactação do solo. Entretanto, o aumento da densidade de 1,3 para 1,7 Mg m^{-3} reduziu o diâmetro do caule (3,13 para 2,75 mm), o número de folhas (18,94 para 14,30 folhas planta^{-1}) e a área foliar (411,20 para 278,89 cm^2). Observou-se ainda diferença entre as espécies, com *Crotalaria juncea* apresentando maior redução das variáveis biométricas, enquanto *Crotalaria spectabilis* apresentou menor variação, indicando maior tolerância às condições de compactação. Conclui-se que *Crotalaria spectabilis* apresenta maior capacidade adaptativa ao solo compactado, sendo potencialmente mais indicada para condições de restrição física do solo.

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Introduction

Soil compaction is recognized as one of the main physical degradation processes in agricultural areas. This happens because of the rearrangement of the soil's solid particles, leading to increased density and decreased total porosity. As a result, the mechanical resistance to penetration rises, which can limit root growth and affect the vegetative development of plants (Fu et al., 2025).

Soil moisture conditions can also intensify the effects of compaction, because in low-moisture environments, the increase in physical resistance makes it harder for roots to spread through the soil profile (Schmidt, 2022). On the other hand, when the soil has too much water, the reduction in macroporosity limits oxygen diffusion, which harms root respiration. These factors can also reduce water infiltration in the soil profile and increase the soil's susceptibility to erosion (Correia, 2014).

In assessing soil physical quality, soil density is widely used as a structural indicator because it reflects changes in porosity and particle organization resulting from the management practices used (Araújo et al., 2012; Stefanoski et al., 2013). This attribute is influenced by factors such as texture, organic matter content, mineralogy, and biological activity, and it can be altered by machine traffic and the intensive use of agricultural implements, which promote compaction and degradation of the soil structure (Ohland et al., 2014; Farias et al., 2013).

As an alternative to reduce the effects of soil compaction, the use of cover crops has been widely recommended in agricultural production systems (Gentsch et al., 2024). These species help improve the physical properties of the soil through the action of their root systems, which promote the formation of biopores, in addition to adding organic matter. Additionally, they help reduce erosion and restore degraded areas, creating better conditions for the root growth of subsequent crops and contributing to the sustainability of production systems (Carmo et al., 2019).

In addition to the physical benefits provided by cover plants, these species help improve the soil's chemical properties through nutrient cycling, biological nitrogen fixation, and increasing organic matter content, supporting fertility maintenance and the gradual availability of nutrients during biomass decomposition (Fonseca, 2017; Nascente et al., 2015; Sugai et al., 2024). Among the legumes used for this purpose, the most notable are *Crotalaria juncea* L. and *Crotalaria spectabilis* Roth due to the high biomass production and the ability to accumulate nutrients in the aerial part (Oliveira et al., 2023). Although they belong to the same genus, they have morphological and growth differences that can influence their behavior under the constraints imposed by soil compaction (Pacheco et al., 2015; Fonseca et al., 2023).

Despite the widespread use of Crotalaria species as cover crops and their well-known contribution to improving soil physical properties, information about their behavior in environments with different levels of compaction is still limited. Moreover, studies directly comparing the responses of *Crotalaria juncea* and *Crotalaria spectabilis* to increased soil density are scarce, making it harder to understand the adaptation potential of these species to physically restricted conditions.

Given this context, the present study aimed to evaluate the effect of increased soil compaction on morphological attributes of *Crotalaria juncea* L. and *Crotalaria spectabilis* Roth, grown in dystrophic Red Argisol.

Materials and Methods

The study was conducted in a controlled environment at the Federal University of Alagoas (*Universidade Federal de Alagoas* - UFAL), Arapiraca Campus, from April 21st to June 20th, 2015. The experimental area is located in the Agreste region of Alagoas, at an altitude of 245 meters, with coordinates 9°48'40.3" S and 36°37'19.7" W. According to Köppen's classification (1948), the regional climate is of the As type, characterized by most rainfall occurring between April and early August and a predominantly dry season from September to March. The average annual precipitation is 854.27 mm, with December being the month with the lowest rainfall (Xavier; Dornellas, 2005).

The soil used in the experiment was identified as typical Dystrophic Red Argisol, with the material collected from the 0-20 cm and 20-40 cm layers in the experimental area at UFAL. After sampling, the soil was air-dried, manually disaggregated, and sieved through a 2 mm mesh to remove plant residues and coarse fragments. Then, a representative 0.5 kg sample was taken for chemical and physical analyses, with the results shown in Tables 1 and 2.

Table 1.
Results regarding the chemical characterization of the soil used in the study.

Results - Chemical Analysis (0-20 cm and 20-40 cm)										
Depth (cm)	pH	P	K	Ca	Mg	Al	H+Al	S.B.	T	CTC
	mg/dm³			cmolc/dm³						
0-20	4.10	18	54	0.60	0.40	0.63	4	1.20	1.83	5.20
20-40	3.90	4	32	0.30	0.10	1.23	3.90	0.56	1.79	4.46
	Na	Fe	Cu	Zn	Mn	V	m	Na/CTC	PST	M.O.
	mg/dm³					%				
0-20	15	179.30	0.80	2.76	4.84	23.10	34.40	1.30	2.70	0.90
20-40	17	233.50	0.96	2.35	1.80	12.50	68.90	1.70	1.90	0.52

Note: Analytical Center (2015).

Table 2.
Results regarding the physical characterization of the soil used in the study.

Results - Soil Physical Analysis (0-20 cm and 20-40 cm)						
Depth (cm)	Fine Sand	Coarse Sand	Total Sand	Clay	Silt	Textural Class
	---- g kg^{-1} ----					
0-20	418	467	885	144	14	F. Sandy
20-40	313	460	773	123	7	F. Sandy

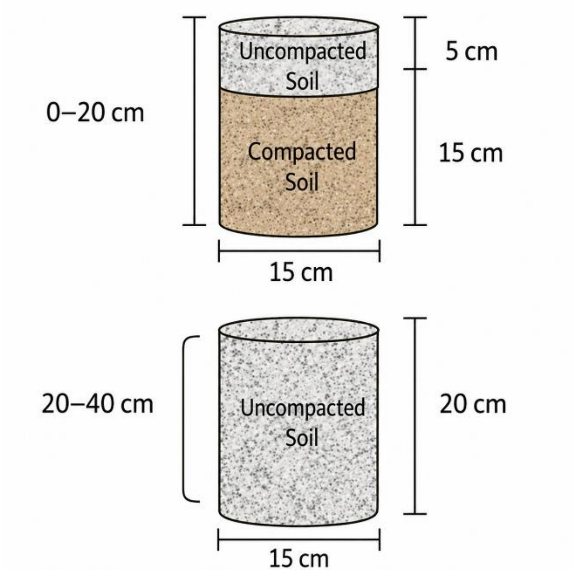
Note: Analytical Center (2015).

The experiment was conducted using a randomized block design (RBD), with four replications, totaling 40 experimental units. The treatments were arranged in a 5 × 2 factorial design, involving five soil densities (1.3; 1.4; 1.5; 1.6, and 1.7 Mg m^{-3}) and two species from the Fabaceae family. Each experimental plot consisted of two plants of *Crotalaria juncea* L. or *Crotalaria spectabilis* Roth.

The experimental units were set up with two overlapping PVC rings (20 cm high and 15 cm in diameter), held together with Silver Tape. The lower ring was filled with soil from the 20-40 cm layer, keeping its natural density (1.3 Mg m^{-3}). In the upper ring, soil from the 0-20 cm layer was used, previously weighed and compacted according to the established density levels and as per the proposed treatments (Figure 1).

Figure 1.

Schematic representation of the experimental units, detailing the storage of soil collected from the 0-20 cm and 20-40 cm layers in the respective stacked rings.



Note: Authors (2026).

To get the compaction levels, the amount of soil needed for each treatment was calculated based on the volume of the compacted layer, determined by the equation $V = \pi r^2 h$, where r corresponds to the inner radius of the ring (7.5 cm) and h to the height of the compacted layer (17 cm), resulting in a volume of 3002.62 cm^3. The soil mass was then obtained using the formula $M = Ds \times V$, where M is the soil mass (g), Ds is the desired density (g cm^{-3}), and V is the volume of the compacted layer (cm^3). In this way, approximate masses of 3.9; 4.2; 4.5; 4.8; and 5.1 kg of soil were used, corresponding to densities of 1.3; 1.4; 1.5; 1.6; and 1.7 Mg m^{-3}, respectively.

The compaction was done using a Charlotte PH5T hydraulic press, keeping the top 3 cm of the upper ring uncompacted to help seedling germination and early growth. At the bottom of the pots, 1 mm anti-aphid mesh was installed and secured with nylon ties. The density levels were set based on the soil mass calculated for the known volume of the compacted layer, and no additional measurement of soil density was done after setting up the experimental units.

No chemical correction of the soil was carried out, since it was decided to keep the same characteristics present when it was left fallow. This decision was made to preserve the natural conditions of the soil and allow the evaluation of the effects of different compaction levels on the growth of the studied species, without interference from the application of soil amendments or fertilizers.

On April 21^{st}, 2015, direct sowing was carried out in the pots, with each experimental unit receiving seven seeds. After the seedlings emerged, thinning was done, leaving two plants per pot, selected based on vigor and uniformity. Until the plants were established (20 days after sowing), daily surface irrigation was performed. Afterwards, soil moisture was maintained through capillarity by adding water to containers placed under the pots, aiming to stimulate root growth through the compacted layer in search of water and nutrients. Water management was carried out uniformly across all treatments.

The measurement of growth parameters was done at 15, 30, 45, and 60 days after planting (DAP), evaluating the number of leaves produced, stem diameter, and plant height. Height was measured from the plant collar to the tip of the main stem, while stem diameter was measured 4 cm above the collar using a digital caliper, with readings given in millimeters (mm). For leaf counting, only leaves with a central blade at least 3 cm long were considered.

For the leaf area (LA) variable, evaluations were carried out at 15, 30, 45, and 60 days after planting (DAP). In the first three evaluations, leaf area was estimated by measuring the length (L) and width (W) of the leaf blade using a millimeter ruler, and then the product of these variables was calculated (W × L).

At 60 DAP, 200 leaves of *Crotalaria spectabilis* were collected to determine the actual leaf area using a LI-COR leaf area integrator, model LI-3100, with results expressed in cm^2 per plant. Based on this data, a linear regression model was fitted between the leaf area determined by the integrator (dependent variable) and the product of the length (L) and width (W) of the leaflets (independent variable), resulting in the equation used to estimate the leaf area of the species. For *Crotalaria juncea*, the leaf area estimate was done using the model proposed by Cardozo et al. (2011). The equations used to estimate the leaf area of *C. spectabilis* and *C. juncea* are shown in Equations 1 and 2, respectively.

$$AF\ (Crotalaria\ spectabilis) = 0.6837 \times (C \times L) + 0.4275 \mid R^2 = 0.9781 \quad \textbf{(1)}$$

$$AF\ (Crotalaria\ juncea) = 0.7160 \times (C \times L) \mid R^2 = 0.9712 \quad \textbf{(2)}$$

Where:

- AF = Leaf area;
- C = Leaflet length;
- L = Leaflet width.

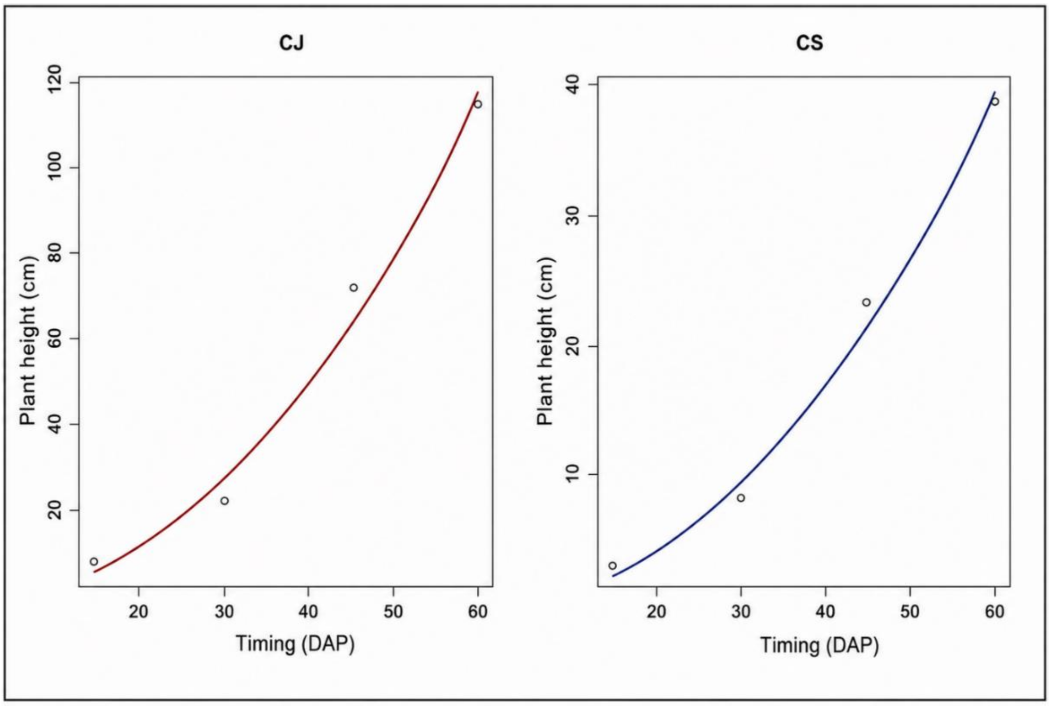
The data obtained were submitted to analysis of variance (ANOVA), using the statistical software R, adopting a significance level of 5%.

Results and Discussion

Plant Height

Considering the variable plant height, no significant effect of soil compaction levels was observed ($p > 0.05$) for the two species evaluated. However, a significant effect of the evaluation time on plant growth was found ($p < 0.001$), with the data being adequately described by quadratic models. For *Crotalaria juncea*, the fitted model showed a determination coefficient of $R^2 = 0.9466$ and an F value of 683.00, while for *Crotalaria spectabilis*, $R^2 = 0.9601$ and F = 926.48 were obtained. At the end of the experimental period (60 DAS), *C. juncea* reached an average height of 115.12 cm, while *C. spectabilis* had an average of 39.35 cm, showing the larger size of the first species (Figure 2).

Figure 2.
Height of *C. juncea* and *C. spectabilis* plants depending on soil compaction at 15, 30, 45, and 60 DAP.



Note: Authors (2015).

When evaluating wheat behavior under compressive stress, Mondal and Chakraborty (2023) found that height growth was severely affected, especially at densities close to 1.8 Mg m^{-3}. According to the authors, this happens because the physical barrier prevents root exploration and, consequently, limits the above-ground part. This effect is linked to restricted water and nutrient supply, as well as reduced photosynthesis and transpiration, resulting in less cell expansion and vegetative growth.

However, the result obtained does not support the findings of Paludo et al. (2014), who observed a significant influence of soil compaction on plant height in the cowpea crop. Similarly, Farias et al. (2013) also recorded a significant reduction in plant height as soil density increased, with a decrease of 51.07% between the lowest and highest compaction levels at 33 days just after emergence.

Different results were reported by Zhu et al. (2024), who found a decrease in plant height as soil density increased. According to the authors, compaction limited root growth and the uptake of water and nutrients, affecting plant growth. These results suggest that species' responses to compaction can vary depending on the conditions studied and the adaptive traits of each species.

Stem diameter

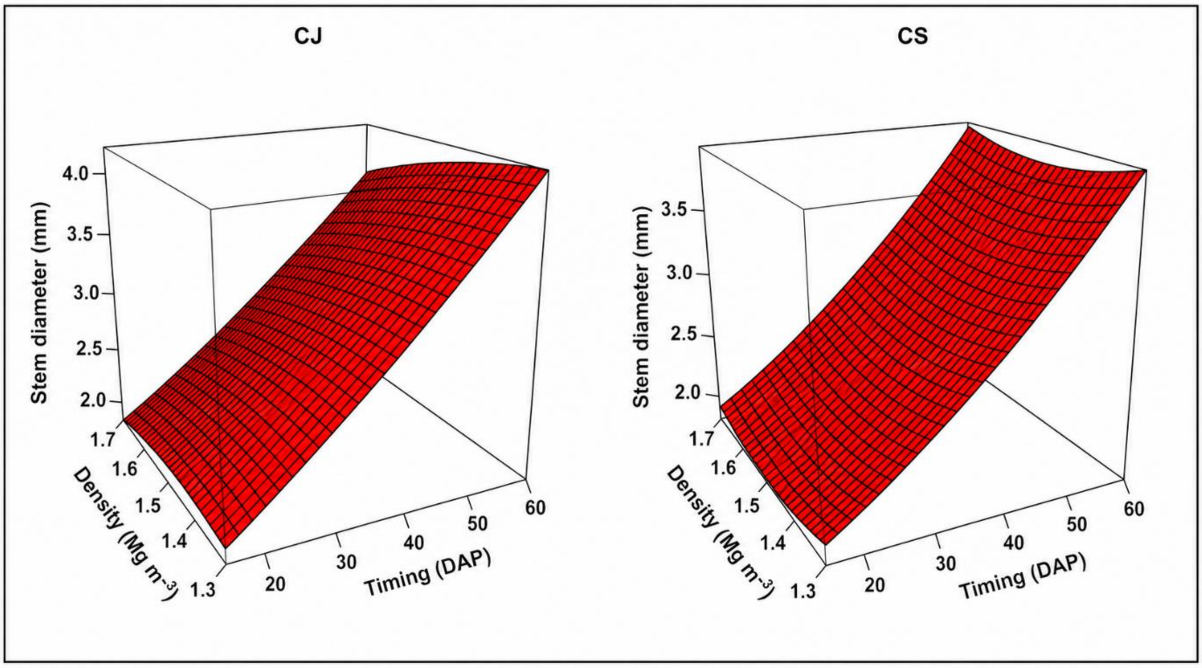
A significant effect of soil compaction on the stem diameter of the evaluated species was observed ($p < 0.001$). The fitted models showed a high fit to the observed data, with coefficients of determination of $R^2 = 0.9227$ ($F = 176.76$) for *Crotalaria juncea* and $R^2 = 0.9330$ ($F = 206.21$) for *Crotalaria spectabilis*. A difference in response between the species was observed, indicating distinct behavior in relation to the increase in soil density.

In *Crotalaria juncea*, a reduction in stem diameter was observed with increasing soil compaction, with the effects becoming more noticeable from a density of 1.5 Mg m^{-3}. This behavior may be related to the higher mechanical resistance of the soil, which makes it harder for the root system to expand and reduces water and nutrient uptake. As a result, there is less growth of the aerial parts, directly affecting stem development.

In *Crotalaria spectabilis*, a reduction in stem diameter was observed up to a density of 1.5 Mg m^{-3}. However, at higher levels of compaction, the plants showed relatively better performance, suggesting a possible ability to adapt to the physical conditions imposed by the soil. This behavior may be related to the root system's ability to explore micropores, allowing it to partially bypass the more compacted layer, which could have helped with water and nutrient uptake, supporting growth even under greater mechanical restriction (Figure 3).

Figure 3.

Stem diameter of *C. juncea* and *C. spectabilis* as a function of soil compaction at 15, 30, 45, and 60 DAP.



Note: Authors (2015).

According to the results presented by Cavalcante et al. (2025), in a study with *Stylosanthes* cv. Campo Grande, it was found that the increase in compaction applied caused significant changes in stem diameter, with this behavior being linked to physical restrictions that limit root elongation and branching. The authors found that restricted root growth impaired water and nutrient uptake, reducing the supply of essential resources for plant development and, consequently, the accumulation of biomass in stem tissues.

Almeida et al. (2021), when studying how compaction directly affects the biometrics and the aerial and root architecture of corn, observed that increased density led to a reduction in stem diameter. The restrictions imposed by the compacted layer raised the soil's mechanical resistance, limiting root system penetration and, consequently, the uptake of water and nutrients. This limitation in resource supply compromised the vegetative growth of the crop, directly reflecting in the reduced structural thickening of the stem.

These results contradict those obtained by Pacheco et al. (2014), who, when evaluating the response of *Crotalaria spectabilis* to compaction in an experiment conducted on a Latossolo soil, observed that the increase in density caused severe restrictions on its vegetative growth. In the cited study, the soil used was previously corrected and fertilized, and three stacked rings, each 15 cm high, were used. This setup favored the establishment of plants in the upper layer of the pot, reducing the need to explore the compacted layer just below.

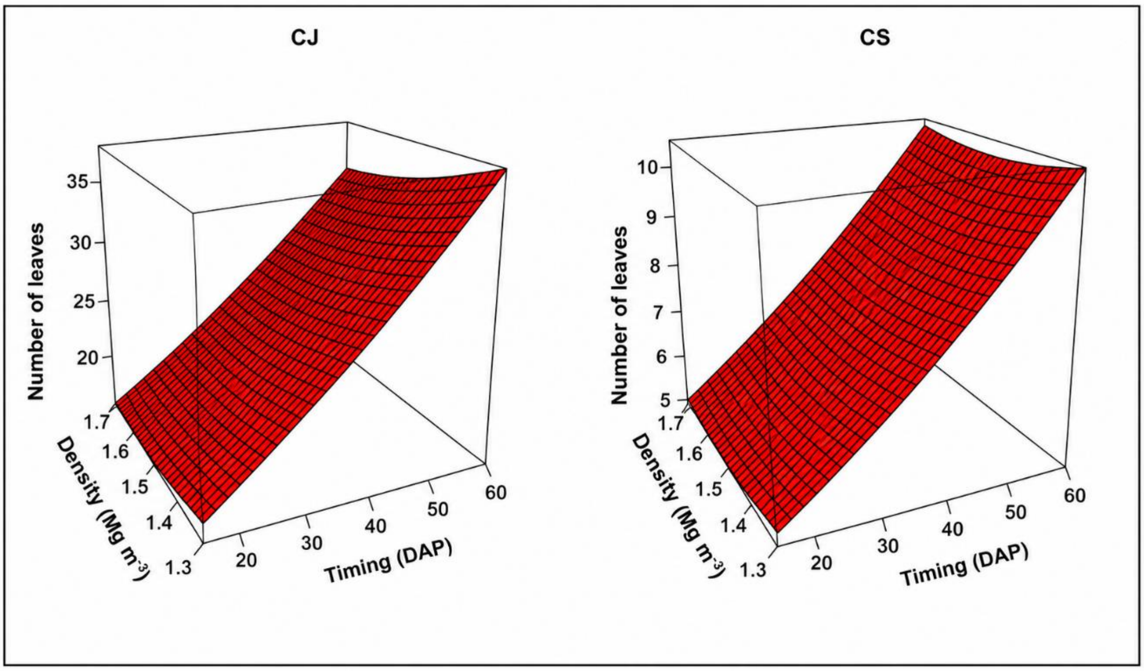
Number of leaves

Regarding the number of leaves variable, a significant effect of the evaluated factors was observed ($p < 0.001$), with models showing determination coefficients of $R^2 = 0.9220$ ($F = 174.98$) for *Crotalaria juncea* and $R^2 = 0.9214$ ($F = 173.48$) for *Crotalaria spectabilis*. In general, the number of leaves increased throughout the experimental period in both species, following the vegetative growth of the plants. However, in *Crotalaria juncea* there was a trend of reduced leaf production under higher compaction levels, especially in the later stages of development.

For *Crotalaria spectabilis*, a distinct behavior was observed, with the number of leaves remaining consistent across the different compaction levels and steadily increasing over the evaluations. This result suggests that the species is more tolerant of the physical constraints imposed by the soil, allowing vegetative growth to continue even under higher density conditions (Figure 4).

Figure 4.

Number of *C. juncea* and *C. spectabilis* leaves according to soil density at 15, 30, 45, and 60 DAP.



Note: Authors (2015).

This behavior can be attributed to the physical resistance caused by soil compaction, which limits root growth and, consequently, reduces the ability to absorb water and essential nutrients for plant growth. Although leaf production increased as the cycle progressed, higher soil densities tended to restrict this increase, especially in *C. juncea*, a species that showed greater vegetative growth throughout the experiment.

Similar behavior was observed by Santos et al. (2025), who, while studying different compaction levels in *Crotalaria juncea*, found a decrease in the number of leaves as soil compaction increased. According to the authors, the compaction of the surface layers creates a mechanical barrier that limits root expansion, leading to reduced vegetative growth and lower above-ground vigor.

Analyzing the initial growth of corn cultivated in sandy- and clay-textured soils under different levels of compaction, Souza and Gomes (2025) found that the variable number of leaves remained stable, ranging from six to seven during the evaluated period, with no significant influence from either soil type or the adopted density. According to the authors, during the initial stages of the crop cycle, the plant exhibits lower sensitivity to physical changes in the soil, indicating that leaf emergence at this stage tends not to respond significantly to variations in soil compaction.

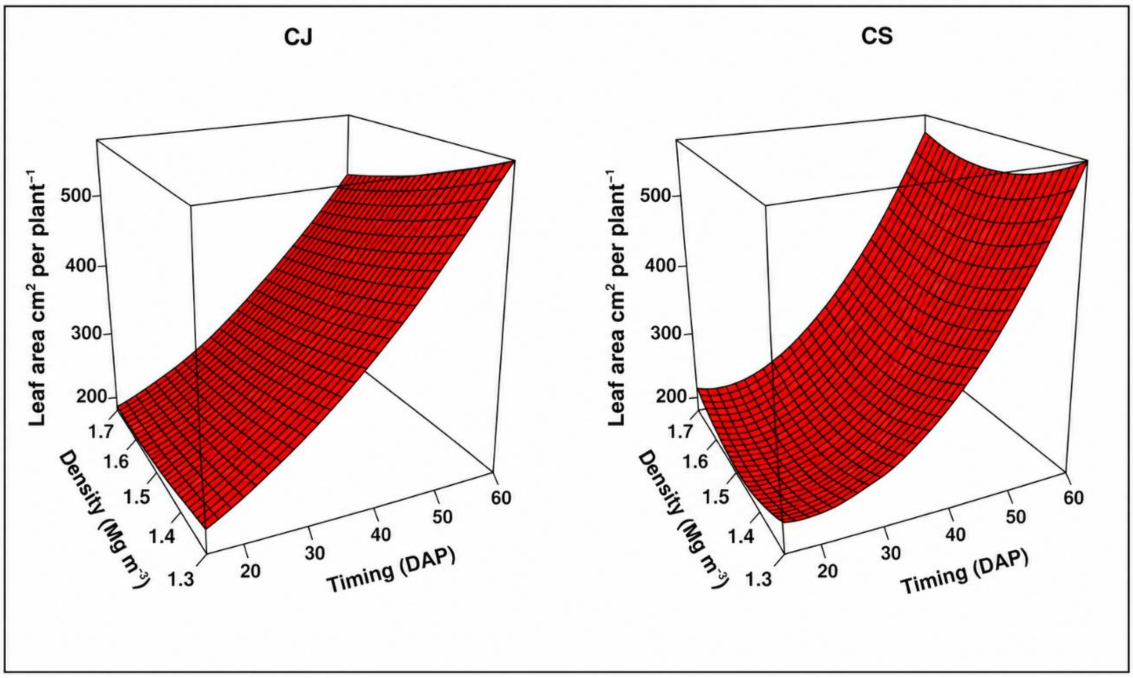
Considering both species, it is important to highlight the differences in plant size and resource demand during development. Due to its more vigorous growth, *Crotalaria juncea* tends to require a greater supply of water and nutrients, making it potentially more sensitive to the effects of soil compaction. Under these conditions, restricted root expansion may impair the absorption and transport of water and nutrients to the shoot, directly affecting leaf emergence and maintenance.

Leaf area

Regarding the leaf area variable, a significant influence of soil compaction was observed in both species analyzed ($p < 0.001$). The fitted models showed determination coefficients of $R^2 = 0.8446$ ($F = 80.44$) for *Crotalaria juncea* and $R^2 = 0.9500$ ($F = 281.43$) for *Crotalaria spectabilis*. Overall, *C. juncea* showed a greater reduction in leaf area in response to increased compaction levels. For *C. spectabilis*, a smaller increase in this variable was observed in the initial evaluations, which may be related to the species' slower growth during the early developmental stages (Figure 5).

Figure 5.

Leaf area of *C. juncea* and *C. spectabilis* in relation to soil compaction at 15, 30, 45, and 60 DAP.



Note: Authors (2015).

Although water supply was provided daily, keeping similar water conditions between the treatments, a reduction in leaf area was observed with increased soil density. This result suggests that compaction may have limited plant growth, directly affecting the expansion of the leaf surface.

Similar results were observed by Carneiro et al. (2018), who, when evaluating the initial growth of corn crops subjected to different soil compaction intensities and depths, found a reduction in the plants' leaf area, especially when the compacted layer was located in the upper soil layers. Similarly, Lima et al. (2010) found that the soil's mechanical resistance to penetration directly influenced the leaf area index and the height of the bean plants, with reductions of 46.51% and 59.00%, respectively.

Results presented by Cavalcante et al. (2025) also show that higher levels of soil compaction affect the vegetative growth of plants, directly impacting the development of the above-ground parts. According to the authors, the increase in the soil's physical resistance can reduce plant growth and limit the use of available resources in the environment.

Conclusion

It was observed that the height of the evaluated species is not limited by soil compaction up to 60 days after planting. However, increasing soil density causes reductions in stem diameter, as well as in leaf area and the number of leaves of *Crotalaria juncea*, showing its greater sensitivity to mechanical obstruction.

The species *Crotalaria spectabilis* stood out for maintaining good growth even under critical conditions, showing a greater ability to adapt to these conditions. Despite its slower initial growth, this species can tolerate compaction levels of up to 1.7 Mg m^{-3}, indicating its potential for use in crop rotation systems aimed at improving soil physical structure.

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