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Biopores, soil decompacting potential, and biomass of *Brachiaria* cultivars

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ABSTRACT: Grasses of the *Brachiaria* genus are widely used as cover crops in no-tillage areas of the Brazilian Cerrado. This study aimed to evaluate the ability of six *Brachiaria* cultivars to produce shoot and root biomass, and the potential of the root system to grow through a 0.01 m thick wax layer with 1.5 MPa penetration resistance. The plants were grown in PVC columns with a diameter of 0.1 m and a height of 0.7 m. The column was divided into an upper part measuring 0.25 m (top) and a lower part measuring 0.45 m (bottom). The wax layer was positioned between the two parts of the column as a physical barrier to be perforated by the roots. The columns were filled with peaty substrate. The *Brachiaria* cultivars used were: *Brachiaria brizantha* cv. BRS Piatã, *Brachiaria decumbens* cv. Basilisk, *Brachiaria brizantha* cv. BRS Paiaguás, *Brachiaria ruziziensis* cv. Ruziziensis, *Brachiaria brizantha* cv. Xaraés and *Brachiaria brizantha* cv. Marandu. The Ruziziensis cultivar accumulated a high root dry mass, but the Xaraés cultivar presented the highest wax layer perforation capacity (80 %). Decumbens is the species with the lowest wax layer perforation capacity (10 %). Brachiaria species and cultivars demonstrated differences in their responses to high root penetration ability, which can be used for recommended different species of Brachiaria in different proposes used changes in shoot, leaves, and root dry matter and the distribution of roots in the soil column profile. Xaraés cultivar has potential to be used as a management strategy in soil recovery for degraded lands with mechanical impedance.

Keywords: *Brachiaria* grass, cover crops, forage production, penetration resistance, hard paraffin disk.

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INTRODUCTION

Soil compaction induced by machine and animal trampling is one of the main causes of soil degradation characterized by increased soil density (Kunz et al., 2013). Increasing soil density in no-tillage system areas is a recurring reality (Büchi et al., 2017; Moura et al., 2021). In grain areas without machine traffic control, 40-50 % of the area is trafficked during a cycle (Bluett et al., 2019), in addition, the use of increasingly larger machines exacerbates this problem (Braunack and Johnston, 2014). Among the damages to crops grown in compacted soil, which results in higher soil penetration resistance (PR), decreased microporosity, a reduction in root growth in depth, and increased growth in the surface layer, increasing the water deficit susceptibility to crops (Rosolem et al., 2002; Silva et al., 2015).

Cover crops used with a vigorous root system can increase the number of pores that could be potentially exploited by the following crops (Rosolem and Pivetta, 2016). Grasses, in particular the genus *Brachiaria*, have been widely used for this purpose due to their handling ease and their positive results in improving the soil physical quality (Moura et al., 2021), with a longer-lasting effect than subsoiling mechanics interventions (Calonego et al., 2017). *Brachiaria* root activity improves the soil structure by favoring pore size distribution and increasing the hydraulic conductivity and the least limiting water range (LLWR) when used as an intercrop or cover crop (Flávio Neto et al., 2015; Silva et al., 2019, 2021).

Among the most cultivated species as cover crops, with or without grazing during the dry season, are *Brachiaria ruziziensis*, *Brachiaria decumbens*, and *Brachiaria brizantha* (Pariz et al., 2010). *However, especially in integrated systems, other forages of the genus Brachiaria*, such as cultivars Piatã (Pezzopane et al., 2019), Paiguas and Xaraés, have a high potential for forage production, increasing the yield of integrated systems (Gobbi et al., 2018). Its fasciculated and abundant root system promotes improvements in soil structure, superior to plants with a pivoting root system (Salton et al., 2008). Cavallini et al. (2010) found soil penetration resistance values from 2.15 to 6.08 MPa, limiting the root growth of *Brachiaria brizantha* (cv. Marandu), resulting in the pasture crude protein and dry matter reduction.

Flávio Neto et al. (2015) experimentally proved through least limiting water (LLW) results that Xaraés and Piatã grasses provide greater soil loosening and increase water availability to successive soybean crops. *Brachiaria* production as a cover crop has been used without distinction for straw production or soil structure recovery. Our purpose is to investigate the differences between *Brachiaria* cultivars to propose the most suitable one according to the expected objective of its management in cultivated areas (Clark et al., 2003). For that, we used a methodological proposal of crop development evaluation under a paraffin hardpan disk barrier (wax layer), tested before for rice, wheat, soybean, and corn crops (Bolaños et al., 1993; Clark et al., 2000; Acuña et al., 2012; Gao and Lynch, 2016; Fried et al., 2018; Lynch, 2018; Rut et al., 2022). This method proved to be an effective screening technique for selecting resistant and sensitive corn hybrids (Rut et al., 2022). This barrier of inert material aims to eliminate the known effect of soil moisture on the PR it offers to roots. Wetter soils have reduced PR (Bengough et al., 2011), and as the soil dries, the PR tends to increase and impose restrictions on plant growth (Bayat et al., 2017). There are no studies testing this method for brachiaria species or cultivars aiming to find the one with the greatest root penetration capacity under mechanical impedance.

We hypothesized that *Brachiaria* cultivars have different capabilities in overcoming hardpan limitations and have different potentials for structural recovery of degraded soils. This study aimed to evaluate six *Brachiaria* cultivars regarding their biomass production and root penetration capacity under the mechanical impedance of a wax layer and then indicate the better one for soil structure recovery.

MATERIALS AND METHODS

The experiment was carried out in a greenhouse at the Federal Institute of Mato Grosso, in the municipality of Cáceres, Brazil, at coordinates 16° 08' 11.7" S, 57° 41' 26.9" W with 120 m of altitude. Biomass production and root growth of six *Brachiaria* (Trin.) Griseb. spp. (syn. *Urochloa* P. Beauv. spp.) cultivars were studied: 1) Piatã (*Brachiaria brizantha* cv. BRS Piatã); 2) Paiaguás (*Brachiaria brizantha* cv. BRS Paiaguás); 3) Xaraés (*Brachiaria brizantha* cv. Xaraés); 4) Marandu (*Brachiaria brizantha* cv. Marandú); 5) Decumbens (*Brachiaria decumbens* cv. Basilisk); 6) Ruziziensis (*Brachiaria ruziziensis* cv. Ruziziensis).

To evaluate the root growth of the cultivars, PVC tube columns with a diameter of 0.1 m and a height of 0.7 m were used. Columns were divided into two parts, bottom and top, with heights of 0.45 and 0.25 m, respectively (Fried et al., 2018). A bottom plastic cap was adjusted with a central hole of 0.005 m for drainage.

Root penetration capacity in a compacted environment was tested by a hardpan disk composed of paraffin and solid vaseline mixture (wax layer), with 0.11 m in diameter and 0.01 m in thickness. This wax layer was placed on the upper part of the column bottom as suggested in previous studies (Bolaños et al., 1993; Gao and Lynch, 2016; Fried et al., 2018; Lynch, 2018), but with other species, such as corn, wheat, and soybean. The wax layer was produced with the proportion (mass of product) of 85 % paraffin and 15 % solid vaseline, to obtain a 1.5 MPa penetration resistance (PR), measured with a soil bench-top electronic penetrometer equipped with a 45° and 4 mm diameter circular cone tip, with rod displacement set at a constant speed of 2 mm sec^{-1} with 50 mm penetration (TE-096 model, TECNAL brand), at 30 °C of temperature. The mixture (paraffin/vaseline) was melted at 80 °C, poured into cylindrical molds, and allowed to stand to solidify at room temperature. The value of 2 MPa has been taken as an indicator of mechanical impedance limiting root elongation (Bengough et al., 2006; Cavallini et al., 2010). Therefore, the PR of 1.5 MPa was adopted to create a partially resistant but not insurmountable barrier to root growth (Yu et al., 1995; Bayat et al., 2017), and the peat substrate was used as a low-resistance environment for the roots.

The adhesive tape joined the bottom and top parts of the column containing the disc (wax layer) between both, placed at 0.25 m deep (Figure 1). The greater diameter of the disc than the tube diameter prevented the bypassing roots from this barrier. A peat substrate filled the column to facilitate the separation of the roots on the substrate at evaluation time, as used by Zhu et al. (2010). Our study aims to comprehend the effect of the wax layer (with a known resistance of 1.5 MPa). If soil were substituted for the peat substrate, this could introduce an uncontrolled factor of root growth resistance. Furthermore, employing compacted soil as an impedance layer would complicate moisture control. Other studies of a similar nature conducted their experiments in a nutrient solution (Clark et al., 2000).

The top of the column was fertilized with Osmocote 18:06:12 (N: P_2O_5:K_2O), a controlled-release fertilizer, using 20 g per column before grass planting, adapted from Novais et al. (1991). Soil moisture content ranged between 60 and 70 % of the total porosity of the substrate on the top part. Water was added through a small bottom irrigation pipe fitted to the PVC column structure (Figure 1).

Columns were kept for 88 days in a greenhouse, with a thermostat adjusted to maintain the temperature between 28 and 32 °C. The natural photoperiod for the latitude studied varied from 11 hours and 15 minutes on June 5, at the beginning of the experiment, to 11 hours and 22 minutes, on July 27, the time of the first cut, and 11 hours and 48 minutes, on August 31, date of the second cut and final evaluation of the experiment.

The experiment design used was randomized blocks, with six treatments (*Brachiaria* grass cultivars), *with* and *without* wax layer, and five replications. The experimental unit was a column filled with substrate cultivated with five *Brachiaria* plants, which tillered and "merged" forming a clump per column. More pictures are presented in the Supplementary Data file.

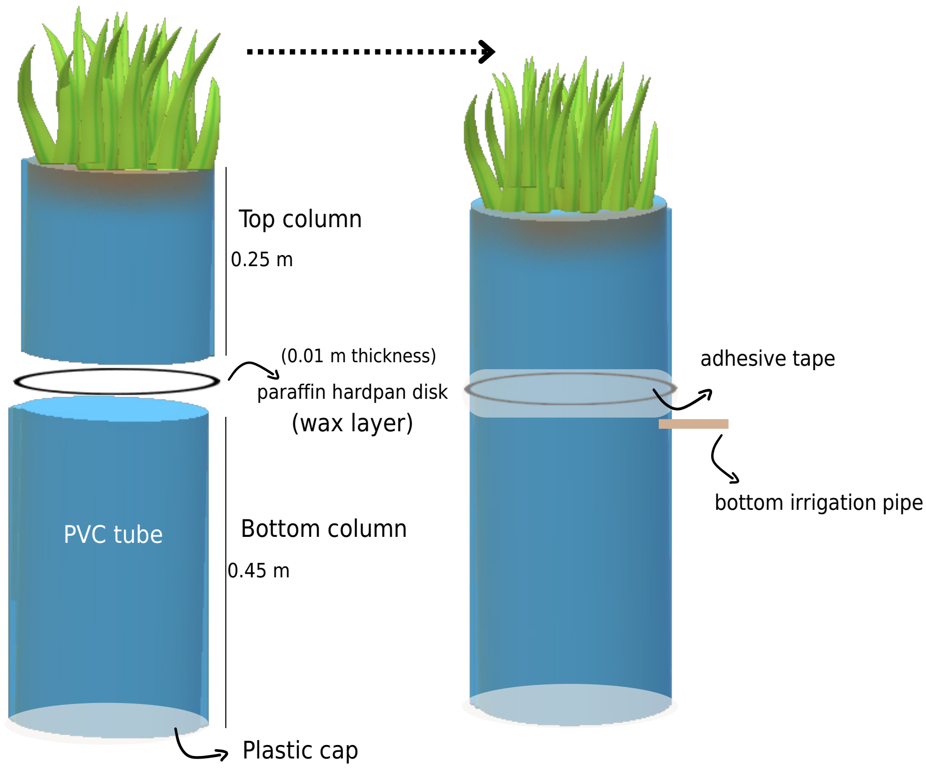

Figure 1. Experimental unit scheme with *Brachiaria* cv. crop in the PVC tube with peat substrate filled. Experimental details in Supplementary Data.

Data collect

The following variables were obtained: leaves dry mass (g) and stem dry mass (g) for the cuts 1st and 2nd; Root dry mass after the second cut (g); Rooting score, which is the degree note of rooting just in the wax layer at the end of the experiment.

The rooting score followed an ordered multinominal scale was used to assign a note, ranging from I to VI: I – the roots did not cause any perforation in the wax layer; II – the roots made shallow holes of less than 5 mm (0-4 mm) in the wax layer; III - medium holes up to half of the wax layer (5-6 mm); IV – shallow holes (0-4 mm) and abundant medium holes (5-6 mm); V – medium holes (5-6mm) and deep holes (7-9 mm); and VI – deep holes (7-9 mm) and roots that have completely crossed the wax layer.

The first cut was performed 53 days after sowing, 0.15 m above the clump base. The material collected was separated into stem and leaf, and the dead material was negligible or non-existent. The material was dried in an oven at 65 °C for 72 hours and obtained the dry mass. The second cut was to harvest the available forage, and the final harvesting of the experiment was carried out 38 days after the first cut. The grass cut was made at 0.15 m above the clump base, and the material dried in the same way as the first cut. Then, the clump was cut close to the substrate surface to collect the residual forage, and the dry mass obtained after the dried material. The root growth was evaluated at the end of the experiment. To harvest the roots the adhesive tape joined the top and bottom of the columns was removed. The roots at the column bottom, below the wax layer, were not quantified separately from the top, as they represent less than 1 % of the total roots, but their importance was quantified by the rooting score, since plants whose roots crossed the wax layer received maximum grade (VI). Roots and substrate were carefully separated by hand using a 4 mm mesh sieve to avoid root loss, compressing the root mass lightly. The wax layers were separated for visual analysis of root penetration, considering the number and depth of holes in the wax layer. After harvesting, each plant root system was washed and dried in an oven to constantly weigh at 65 °C to obtain the dry mass.

Data analysis

The variables of leaves and stem dry mass, where there is the cutting effect, were submitted to data analysis considering a split-plot model in a complete randomized block design with cultivar *vs* wax layer in the plot and cut in the subplot. For root dry mass after the second cut, cultivar *vs* cut was evaluated by the usual complete randomized block model. For these variables, a normal distribution is assumed. The assumptions of the analysis of variance were evaluated, and when deviations were refuted, attesting to the non-normality of the data, transformations were followed by the Box-Cox method (Box and Cox, 1964). When detected a significant effect the F test ($p<0.05$) was applied with multiple means comparisons by the Tukey test at 5 % probability for the leaf dry mass (LDM), stem dry mass (SDM) and root dry mass (RDM).

For the rooting score, the proportional probability ordinal logistic regression model was considered (Venables and Ripley, 2002). The predictor accommodated the blocks and cultivars effect, considering this response was only evaluated in experimental units with wax layer present and after the last cut. The effect of cultivars was evaluated by the chi-square statistics of the likelihood ratio at the 10 % probability level. If cultivar effects were detected, the parameters were compared to the logarithm of the probability ratio between cultivars, using Tukey's correction for pairwise contrasts. Subsequently, the probability of the rooting score of the cultivars in the wax layer was estimated. Therefore, the higher the value of this parameter (higher values on the scale of 0-1), the greater the probability that the roots will penetrate the wax layer.

RESULTS

The leaves dry mass accumulated until the first cut was statistically similar among the six cultivars studied. In the second cut, the Xaraés cultivar stood out among the other forages in this study and was superior to the Marandu cultivar, which had the worst regrowth performance (Figure 2).

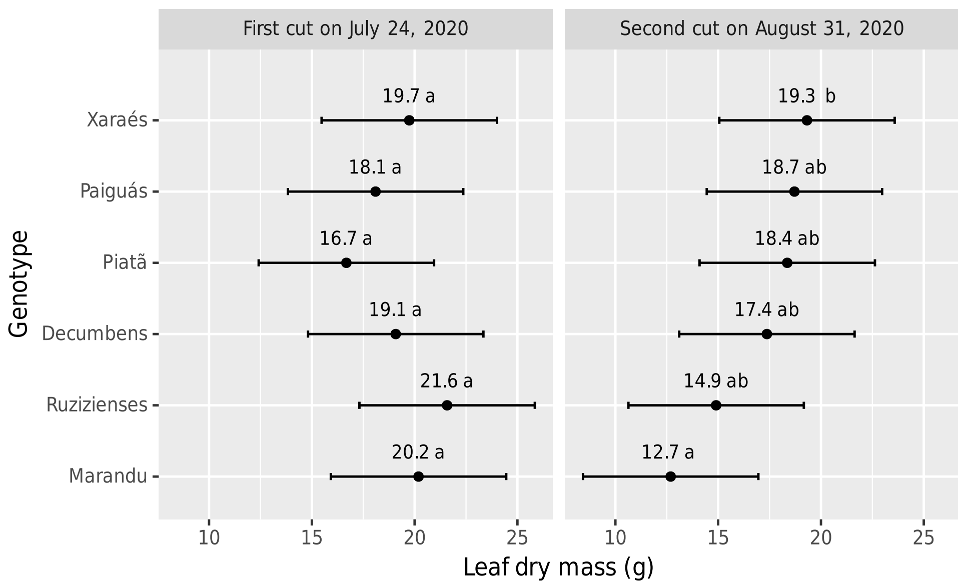

Figure 2. Production of leaves dry mass (in horizontal bars), in the first cut (53 days after sowing) and in the second cut (38 days after regrowth). Means followed by the same letter within each cut did not significantly different ($p<0.05$) by the Tukey test.

For the accumulated stem's dry mass between the sowing and the first cut, there was no significant difference (Figure 3). The Marandu cultivar, on the other hand, had the lowest stem elongation above the residue remaining after the first cut, with a value close to zero, not differing statistically from the Xaraés cultivar. The cuts were analyzed separately since the residual variance was quite different in the cuts. In the second cut, the Paiguás cultivar had a significantly higher stem accumulation.

Ruziziensis cultivar showed higher root accumulation, while cultivars Piatã and Paiguás with less accumulation (Figure 4). Considering the underground growth restriction factor valued, there was no effect of the wax layer in either of the two cuts for the leaf and stem dry mass production. However, an effect was verified for the root dry matter, which accumulated greater mass in the columns without a wax layer (Table 1). Evaluating the root development only in the hardpan disk factor, it is observed the the Xaraés cultivar stood out for its root growth capacity, with a higher degree of rooting score on the paraffin disk than *B. decumbens*. However, both did not differ statistically from the Ruziziensis, Marandu, Paiguás and Piatã cultivars (Figures 4 and 5).

When estimating the probability of the rooting score, a remarkable performance of penetration in the wax layer was observed by Xaraés roots, whose probability of total perforation of the wax layer exceeded 80 % (Figure 6). The Ruziziensis and Marandu cultivars showed an intermediate performance, close to 50 %. *B. decumbens*, on the other hand, showed the worst rooting performance, below 10 %.

DISCUSSION

As observed in this experiment, Bauer et al. (2011) also observed Xaraés better performance compared to other Brachiaria cultivars, mainly during the dry season. Xaraés is less sensitive to temperature drops and low soil and air humidity, maintaining some regrowth even under adverse conditions (Costa et al., 2010), which justifies its best regrowth performance (Figure 2).

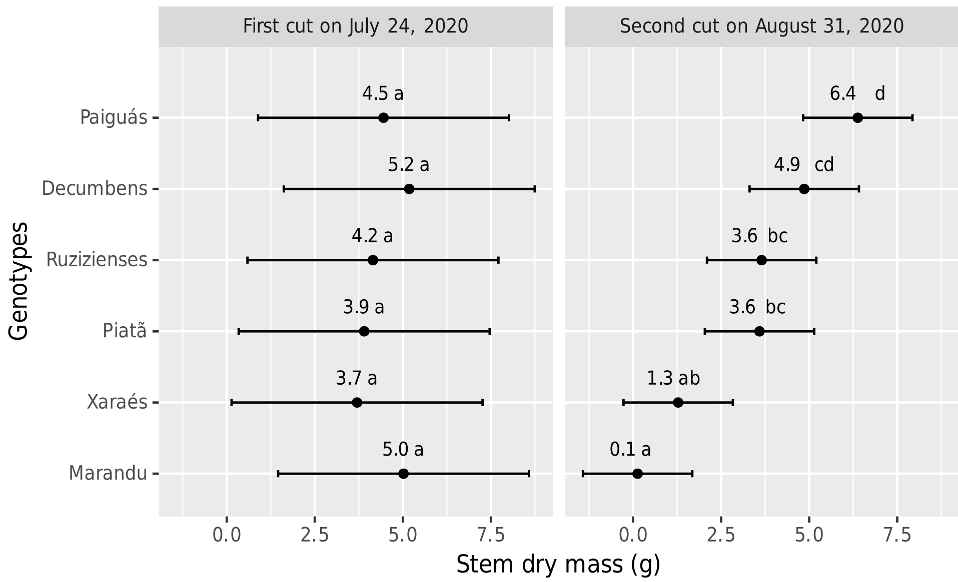

Figure 3. Stem dry mass, in the first cut (53 days after sowing) and in the second cut (38 days after regrowth). Means followed by the same letter within each cut did not significantly different (p<0.05) by the Tukey test. The cuts were analyzed separately due to the large difference in residual variance.

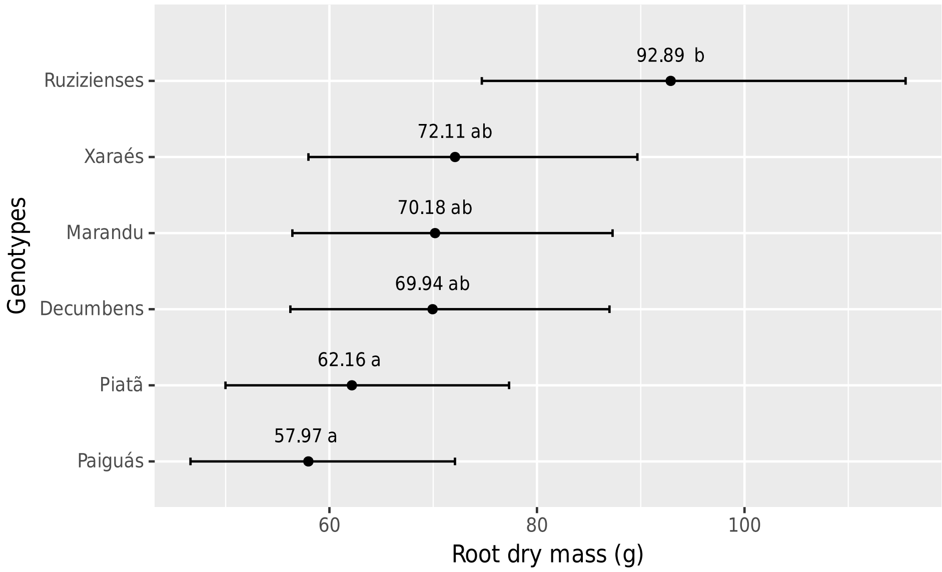

Figure 4. Root dry mass production at 88 days. Means followed by the same letter did not significantly different ($p<0.05$) by the Tukey test. The logarithm of the roots mass was analyzed to meet the assumptions. Data was converted to the original scale to facilitate the interpretation.

Table 1. Means of Leaf Dry Mass (LDM), Stem Dry Mass (SDM), and Root Dry Mass (RDM) in the first and second cut, *with* and *without* wax layer for all cultivars

Variable	Cut	***With* wax layer**	***Without* wax layer**
		g	
LDM	1st	20.4a[(1)]	18.0a
	2nd	15.7a	18.1a
SDM	1st	4.3a	4.5a
	2nd	2.9a	3.8a
RDM	1st	--	--
	2nd	1.8a	1.9b

[(1)] Means of each response variable, followed by the same letter in the lines, were not significantly different ($p<0.05$) by the Tukey test; (--): Not collected data.

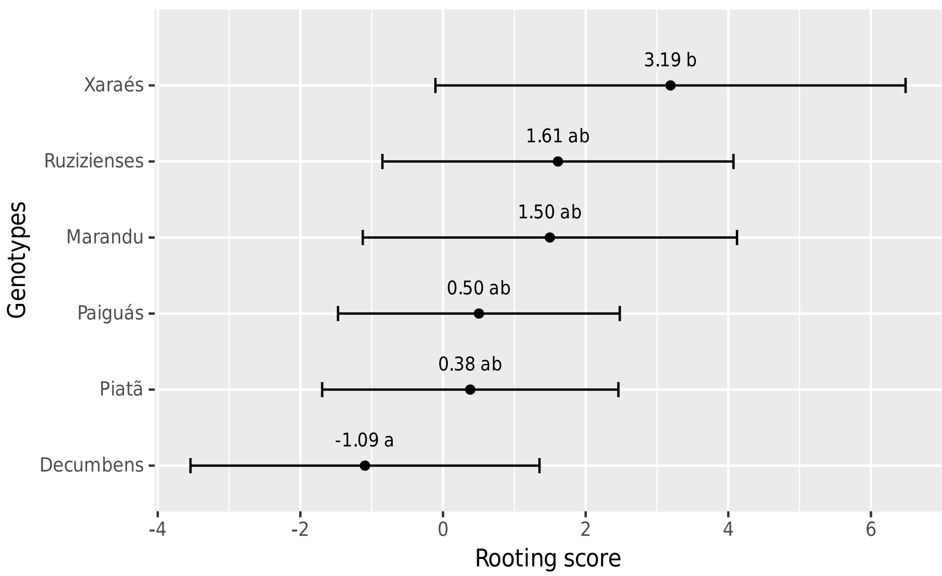

Figure 5. Estimation of the parameter logarithm of the odds ratio for degrees of rooting of six cultivars of the genus *Brachiaria* in wax layer with 1.5 MPa soil penetration resistance at 30 °C. Means followed by the same letter were not significantly different ($p<0.10$) by the Tukey test.

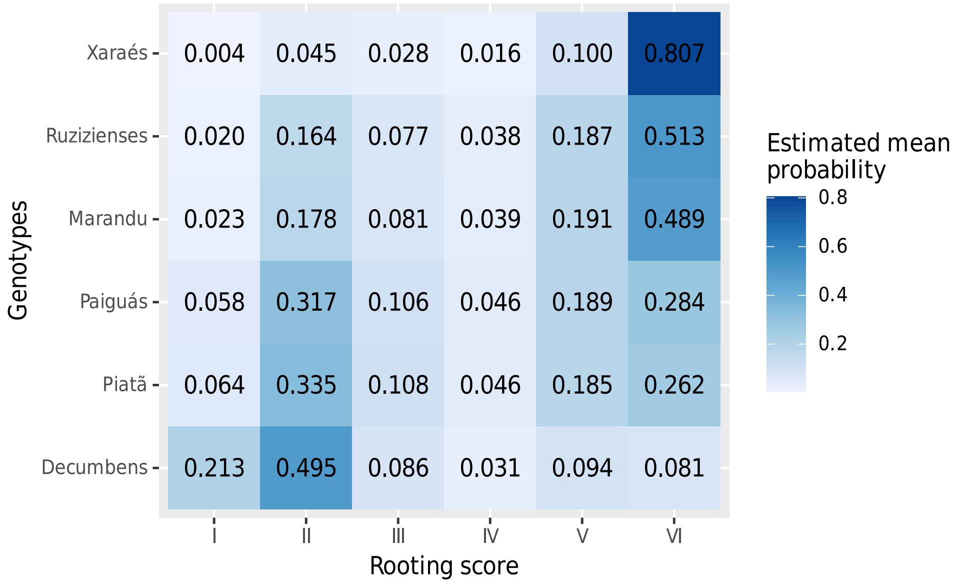

Figure 6. Estimated probabilities for rooting scores of six genus Brachiaria cultivars in wax layer with 1.5 MPa penetration resistance at 30 °C. Rooting score: I – the roots did not cause any perforation in the wax layer; II – the roots made shallow holes of less than 5 mm in the wax layer; III - medium holes up to half of the wax layer; IV – shallow holes and abundant medium holes; V – medium holes and deep holes; and VI – deep holes and roots that have completely crossed the wax layer.

B. *brizanta* species presented, in general, the best aerial and root growth performance. Between B. *brizanta*, in the figure 3, corroborant with the leaf mass accumulation observed the lowest stem elongation after the first cut for the Marandu cultivar, but the Xaraés presented higher leaf mass accumulation (Figure 2) despite stems dry mass production not statistically different from Marandu. According to Euclides et al. (2005), the Xaraés cultivar has a faster regrowth and higher forage production, guaranteeing a higher support capacity and higher productivity per area, and Piatã, characterized by high nutritive value and consequently high animal performance. Flores et al. (2008), studying these two cultivars, point out that these grasses require differentiated management due to their structural differences, but both did not differ in forage production.

Piaguas cultivar, despite the higher stem production, could not surpass the leaf mass average production Xaraés. A higher stem accumulation in Paiguás, also reported by Gobbi et al. (2018), did not differ statistically from *B*. *decumbens*, demonstrating greater sensitivity to photoperiod and stem elongation stimulation. This is also a cultivar that presents better growth during the dry season and better forage quality at that time, resulting in better animal performance according to Euclides et al. (2005) findings, compared to Piatã cv.

The volume and total mass of roots are characteristics of interest when the main objective of *Brachiaria* crop production is to increase soil carbon (Barber and Navarro, 1994; Rossi et al., 2012). The root mass of *B. ruziziensis,* Xaraés, and the Marandu cultivar (Figure 4) did not differ statistically, which was also observed by Galdos et al. (2020), in cultivation carried out in columns filled with soil. *B. ruziziensis* has high growth potential and root volume (Rosolem and Pivetta, 2016). What has not been confirmed by Silva et al. (2019), where the *B*. *ruziziensis* indicated limited potential for soil physical recovery, offering less amount of total organic carbon (TOC) in the soil layer of 0.00-0.20 m, consistent with the less biomass added to the soil by the root systems.

The wax layer affected the root dry matter production (Table 1) due to the greater space available promoted in the *Without* wax layer in relation to the columns with the wax layer presence, which constituted a barrier to the roots. This result shows that even with similar biomass production of the shoot, the cultivars differ in the root biomass production. According to Clarck et al. (2003), in one review about root penetration in compacted soil, differences between species in their ability to penetrate more resistant soil layers are not related to differences in the maximum root growth pressure but appear to be due to differences in the diameter of these roots. Differences between species or cultivars in their ability to penetrate resistant layers may be due to differences in the tendency of roots to deviate or bend when growing from a more porous medium as compared to a more restrictive medium with fewer pores and higher pore density.

B. decumbens had the worst statistical performance, inferior to Xaraés in the wax layer perforation capacity. The superior result of the Xaraés cultivar was also observed in an Oxisol (bulk density: 1.2 Mg m^{-3}) by the Silva et al. (2019), who reported positive effects of the cover crop on the least limiting water range (LLWR), followed the descending order: Xaraés, Piatã, Marandu, and Decumbens cultivars. This finding is particularly significant, as a penetration resistance (RP) of 2.5 MPa was used in determining the LLWR.The use of B. *brizanta* has has been for many years as a potential tillage tool. The biopores formed by these crop roots are important and frequently result in four-fold or greater increases in infiltration rates, and an increase in the number of pores in the dense subsoil horizon (Barder, Navarro, 1994). These authors identified the Brachiaria genus, among other cover crops, as one that provides beneficial effects on subsoil structure due to its high root mass production and ability to penetrate compacted soil layers with ease.

In a study carried out by Flavio Neto et al. (2015), the cultivar Xaraés also presented the highest growth capacity in a compacted soil layer, promoting soil physical. In this same study, grades were assigned for the physical recovery promoted by each grass cultivar, and the better scores were for Xaraés and Decumbens, and the worse results were for Ruziziensis. This differs from our study, in which the Ruziziensis did not differ from Xaraés, with scores approximately 3 to >6, and Decubens 1.5 to – 3.5 with poor and average performance. Studies conducted by Favilla et al. (2020) indicated that cultivating *B. ruziziensis* between corn rows alleviated soil compaction by reducing soil density by 18 % and increasing pore system continuity by up to 490 %, in addition to improving the balance between water and air storage in this system. This strategy has the potential to enhance the physical functions of the soil surface layer, creating a more favorable physical environment for crop development.

The cultivar Xaraés has a high climatic adaptation to the Cerrado conditions, capable of maintaining its regrowth and growth superior to the other cultivars (Costa et al., 2010), which is reflected in the vigor of its root system for wax layer perforation. According to our results, the *Brachiaria* cultivars have different characteristics that confer distinct purposes in their use as a cover crop. As was observed in this study, Xaraés stood out in the role of biological decompaction by its potential to create biopores throughout the hard wax layer, which is structural relief. Meanwhile, Ruziziensis stood out in root biomass production, which contributes to increasing the carbon contribution in the soil. Plant tolerance to different soil physical stresses can be enhanced by selecting specific root traits that facilitate root growth in compacted soil, as proved in Colombi and Keller (2019).

The total perforation capacity of the wax layer by the Xaraés cultivar, above 80 % (Figure 6), it is according to the good biomass production shown by the data in figure 2, as well as the worst biomass development of the Marandu cultivar in the second cut and its lower drilling capacity (50 %) compared to Xaraés. According to Colombi and Keller (2019), increasing root growth in compacted soil may mitigate crop productivity losses and recover soil structure since plant roots are major drivers of soil structure dynamics.

We would recommend the Xaraés cultivar for its superior biomass production and greater ability to penetrate the hard disk, and the Ruziziensis cultivar for its notable root biomass production and high likelihood of penetrating the hard disk. However, the biomass production of Xaraés had no discrepancy with the other cultivars, despite its greater wax layer perforation capacity, in relation to Decumbens and Piatã. So, this suggests that further studies should be carried out under adverse conditions to assess the root growth capacity with regard to these grasses' biomass. This comprises an important study given its potential scope in the cultivation of joint areas with the use of grasses and its stimulus to the structural improvements of cultivated soils, especially those found in the degradation stage, since 33 % of the land in the world, as warned by FAO (Montanarella et al., 2015).

CONCLUSIONS

The tested hypothesis was confirmed, as the *Brachiaria* cultivars exhibited varying biomass production under the restrictive conditions imposed by the wax layer. The presence of the wax layer did not reduce the production of shoot biomass but reduced the production of root biomass. *B. brizantha* cv. Xaraés and *Brachiaria ruziziensis* have the greatest potential to be used to protect and mitigate soil compaction, while *B. decumbens* has the lowest potential. The selection of the most suitable *Brachiaria* cultivar for use as a cover crop is a key component of management and planning strategies to promote sustainable agriculture and mitigate land degradation caused by anthropogenic soil compaction. This approach contributes to enhancing the longevity and sustainability of agricultural systems, particularly grain production, which represents a significant Brazilian commodity.

SUPPLEMENTARY DATA

Supplementary data to this article can be found online at https://www.rbcsjournal.org/wp-content/uploads/articles_xml/1806-9657-rbcs-49-e0240079/1806-9657-rbcs-49-e0240079-suppl01.pdf.

DATA AVAILABILITY

The data will be provided upon request.

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Resources: Milson Evaldo Serafim (lead).

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Supervision: Bruno Montoani Silva (supporting) and Milson Evaldo Serafim (lead).

Validation: Walmes Marques Zeviani (lead).

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Writing – original draft: Milson Evaldo Serafim (lead) and Samara Martins Barbosa (supporting).

Writing – review & editing: Bruno Montoani Silva (equal), Eduardo da Costa Severiano (equal), Kátia Aparecida de Pinho (equal), Luciano Recart Romano (equal), Milson Evaldo Serafim (lead) and Samara Martins Barbosa (lead).

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