

Soil compaction affects sunflower and Paiguas palisadegrass forage productivity in the Brazilian savanna

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Abstract

Integrated crop-livestock systems maximize land use, infrastructure and labor; diversify production; and minimize costs, thereby reducing risks and adding value to agricultural products. However, growing mechanically harvested crops can negatively affect soil structure, reducing plant biomass productivity. The present study aimed to evaluate soil compaction and its effects on the forage productivity of sunflower and *Brachiaria brizantha* cv. BRS Paiguas during the second cropping period. The experiment was conducted as a split-plot randomized complete block design with four replications. Four compaction levels represented by traffic from an agricultural tractor were established: 0 (absence of compaction), 2, 10 and 30 passes over the same spot. Two forage systems were established in the subplots: sunflower grown solely as a monocrop (40,000 plants ha⁻¹) or intercropped with Paiguas palisadegrass (10 plants linear m⁻¹). The following parameters were quantified: soil bulk density, plant height, capitulum diameter and 1000-achene weight for sunflower; stem length and the leaf/stem ratio for Paiguas palisadegrass; and total and partitioned forage productivity. The results showed that sunflower was highly sensitive to soil compaction and that the development and productivity of this species decreased in response to the greatest bulk density, which in turn affected the Paiguas palisadegrass. Overall, intercropping is recommended for increased forage productivity.

Keywords: *Helianthus annuus* (L.); *Brachiaria brizantha*; second cropping period; crop-livestock integration; soil structural degradation

Abbreviations: Aw_hot or humid tropical climate; Bd_soil bulk density; Bdb_beneficial bulk density; Bdc_{LLWR}_critical bulk density for plant growth based on the least limiting water range; Bdc_{MAC}_critical bulk density for a reduction in macroporosity to 0.10 dm³ dm⁻³; Bdi_initial bulk density; Bd_{T0}_bulk density in the absence of additional compaction; Bd_{T2}_bulk density under two passes of the tractor; Bd_{T10}_bulk density under ten passes of the tractor; Bd_{T30}_bulk density under thirty passes of the tractor; CLI: crop-livestock integration; DAS_days after sowing; GO_Goias state; Ki_SiO₂/Al₂O₃ molar ratio; Kr_SiO₂/Al₂O₃ + Fe₂O₃ molar ratio; LLWR_least limiting water range; Pd_particle density; T₀_absence of additional compaction; T₁₀_ten passes of the tractor; 0, 2, 10 and 30 passes; T₃₀_thirty passes of the tractor

Introduction

The Brazilian response to the increased global food demand includes land use intensification, which, in the Cerrado, is achieved via exploitation of Latosols (Santos et al., 2018; Oxisols according to the U.S. Soil Taxonomy or Ferralsols in the World Reference Base for Soil Resources). These soils are potentially apt for mechanized agriculture with high operational yield because of the relatively noncompact nature of that region (Silva et al., 2014).

However, intensive land use resulting from indiscriminate traffic of agricultural machinery and/or cattle can cause soil

compaction. During soil compaction, the soil bulk density (Bd) increases as the air-filled pore space decreases, thereby decreasing water infiltration and storage in the soil and increasing the resistance to crop root penetration (Severiano et al., 2011).

It is therefore crucial to adopt technological innovations that allow the recovery of degraded areas and reduce climate and business risks throughout the year. Crop-livestock integration (CLI) plays a unique role in the sustainability of both agriculture and cattle raising (Macedo et al., 2009;

Martha Júnior et al., 2011). CLI can facilitate the recovery of soil productivity on the basis of soil loosening via biological processes and the formation of straw for no-tillage systems in succession (Flávio Neto et al., 2015).

In order for a soil to both be an essential component of the environment and support plants for the production of food, its structure needs to be preserved. Quality indicators can be used to measure soil structure, which can be determined from the association of simple soil attributes with the use of pedotransfer functions. However, the association of these types of mathematical models with crop productivity is rare. Information concerning soil clay content, for example, allows the establishment of critical values of Bd on the basis of the least limiting water range (LLWR) (Severiano et al., 2011).

In the Brazilian savanna, a second grain crop is grown immediately after the summer crop is harvested; this second cropping period is characterized by a change in season, from the rainy summer to the dry winter, while the sowing stage is extended from January to March. Traditionally, corn and sorghum are cultivated via monocropping or intercropping with grasses, especially those of the genus *Brachiaria* (Trin.) Griseb. (syn. *Urochloa* P. Beauv.) (Cecon et al., 2012); however, for the second crop, owing to its rapid growth and resistance to water stress, sunflower (*Helianthus annuus* L.) is a better option for late planting when water scarcity increases crop risks (Silva et al., 2009). The recently released *Brachiaria brizantha* cv. BRS Paiaguas is a promising forage cultivar for use in CLI because it presents high interharvest production; the plants do not flower during this period, thus allowing the increase of the nutritional quality of the forage, and the plants are readily desiccated, facilitating the formation of the straw layer (Machado and Valle 2011).

Combined with the high tolerance to water stress of sunflower (Dutra et al., 2012), intercropping with this species therefore, shows high potential for the production of grain or silage (Mafakher et al., 2010) with high energy and protein content (Mello et al., 2006; Martin et al., 2014). The detrimental effects of soil compaction on forage productivity for silage production in both monocropping and intercropping systems of second crops are poorly known, especially considering that the relations between soil structural changes resulting from compaction and crop productivity are complex. The present study aimed to evaluate both the compaction of a Dystroferic Red Latosol from the Brazilian savanna and its effects on the forage productivity of sunflower grown in a monocropping system or in an intercropping system with Paiaguas palisadegrass, as a second crop.

Results

Soil physical properties for forage productivity

Bulk density (Bd) was affected by machine traffic (Figure 2). The highest increase in Bd ($\Delta B_{T_0-T_2} = + 17.5\%$) occurred under two passes of the tractor (T_2), whose impact was diminished under subsequent passes ($\Delta B_{T_2-T_{30}} = + 11.2\%$). When the Bd results under each traffic intensity are compared to the pedotransfer models established by Severiano et al. (2011) (Figure 3), T_0 presents a Bd value (1.14 kg dm^{-3}) that is slightly greater than the initial bulk density (Bdi) expected (1.06 kg dm^{-3}) for the studied soil (clay = 562 g kg^{-1}).

In T_{10} , the Bd was only 2.1% lower than the critical bulk

density because of a reduction in macroporosity to $0.10 \text{ dm}^3 \text{ dm}^{-3}$ ($B_{d_{MAC}} (1.43 \text{ kg dm}^{-3})$). However, considering the mean standard error of the Bd values observed in T_{10} , there is no appreciable difference between $B_{d_{T_{10}}}$ and $B_{d_{MAC}}$ (Figure 3). In the same context, under thirty passes of the tractor (T_{30}), the value of Bd essentially decreased the LLWR to zero ($\Delta B_{d_{T_{30}}-B_{d_{LLWR}}} = + 1.3\%$).

Agronomic changes to crops in forage systems

Soil compaction due to tractor traffic affected the agronomic characteristics of the sunflower plants (Figures 4 and 5), which in turn altered the growth environment of Paiaguas palisadegrass in the intercropping system, thus affecting its development (Figure 6). The height of the sunflower plants was not affected by cropping system (mono- or intercropping). Significant differences in plant height were detected only between different soil compaction levels (Figure 4).

During flowering and achene-filling stages, the edaphoclimatic conditions increased competition with Paiaguas palisadegrass in the intercropping system. Both the sunflower capitulum diameter (Figure 5A) and weight of achenes (Figure 5B) were affected by the bulk density and by intercropping. The greatest values of these variables were observed in the monocropping system. The sunflower agronomic performance was therefore highly sensitive to the tested factors. Both vegetative (Figure 4) and reproductive (Figure 5) plant development were lower in the intercropping system than in the monocropping system. In addition, the Paiaguas palisadegrass development in the intercropping system was also affected by the Bd (Figure 6). Paiaguas palisadegrass development was affected by sunflower development. According to the quadratic polynomial curve fitted to the sunflower height (Figure 4), the stem length of the Paiaguas palisadegrass was greater (Figure 6A) and the leaf/stem ratio was lower (Figure 6B) in treatments in which the sunflower height was greater. Grass etiolation (stimulation of phototropism) was therefore observed. The development of Paiaguas palisadegrass was strongly affected by light/shade, with 54% longer stems (Figure 6A) and a 58% lower leaf ratio (Figure 6B) for treatment T_0 compared with treatment T_{30} .

In general, the productivity parameters of sunflower and Paiaguas palisadegrass were greatest (Figures 4 to 6) in response to Bd values that were close to the estimated beneficial bulk density (B_{db}) value (1.29 kg dm^{-3}), with several exceptions. The exceptions were due to the capitulum diameter and the 1000-achene weight in the intercropping system (Figures 5A and 5B), under the assumption that their maximum values occurred when the bulk density was relatively low ($B_d = 1.24$ and 1.22 kg dm^{-3} , respectively). In contrast, the leaf/stem ratio of Paiaguas palisadegrass was minimal when Bd value approached the B_{db} (Figure 6B). Under this Bd, maximum sunflower plant performance occurred (Figure 4), which negatively affected the adequate growth of the Paiaguas palisadegrass (interspecific competition).

Production of forage for ensiling

In addition to changes in the plant growth parameters, the soil physical properties and cropping system affected forage yields. Figure 7 shows the total dry matter (DM) productivity

in response to both the different levels of soil compaction and the forage cultivation system of sunflower during the second cropping period, with polynomial quadratic fits to the data.

For the two cropping systems tested, the DM production increased with increasing Bd, up to 1.28 kg dm^{-3} , which corresponds to 4.50 and 5.51 Mg ha^{-1} productivity for sunflower grown as a monocrop or intercropped with Paiaguas palisadegrass, respectively.

Across the entire evaluated productivity range, greater productivity was observed for the intercropping system than for the monocropping system (Figure 7). Notably, the productivity losses due to soil compaction were lower for the intercropping system (54%) than for the monocropping system (86%).

Although intercropping resulted in increased productivity, there were changes in the partitioning of total DM with increasing soil compaction (Figure 8A). Initially, sunflower was responsible for 76% of the ensiling mass, but this percentage decreased with increasing soil compaction. Until the Bd reached 1.38 kg dm^{-3} , the sunflower DM predominated, and from then on, the Paiaguas palisadegrass accounted for the largest forage fraction, reaching 72% (Figure 8A).

The percentage of the forage weight constituted by achenes decreased by 66% with increasing bulk density in the intercropping system. Moreover, no significant effects of bulk density on this parameter were observed in the monocropping system (Figure 8B).

Discussion

Two tractor passes were enough to increase the Bd, which indicates a very high susceptibility to compaction of this Latosol, which is essentially inevitable (Severiano et al., 2013). For the Latosol under study (Figure 3), according to linear regressions for estimating the levels of Bd critical for plant growth proposed by Severiano et al. (2011) and according to clay content values determined via ultrasonic dispersion (clay content = 562 g kg^{-1}), the soil compaction classification (statistical moments of Bd) increased with increasing numbers of passes of the tractor.

The studied soil presented T_0 values higher than those estimated for the Bdi. This finding can be explained by the soil having been subjected to agricultural practices for several years, which affects the Bdi of that soil compared with a nonanthropized soil. Under T_2 , the value of Bd (1.34 kg dm^{-3}) is extrapolated to 3.9% of the estimated Bdb proposed by Severiano et al. (2011).

The LLWR represents a range of soil moisture in which the physical restrictions on plant growth are minimal in relation to the parameters described by it. The Bdb value is greatest under the LLWR because of the change in a portion of the soil macropores into micropores, improving soil water retention. This phenomenon suggests that slight compaction of an Oxidic Latosol may be beneficial for agricultural systems because it improves the redistribution of water in the soil profile (Severiano et al., 2011). Unlike that which occurs in soils under natural conditions, this redistribution increases both the surface area of roots in contact with the soil and the efficiency of water and nutrient uptake (Souza Neto et al., 2013). The increase in Bd obtained in T_2 in relation to the estimated Bdb, although not very remarkable, confirms the high susceptibility to compaction

of the Oxidic Latosols of the savanna (Severiano et al., 2013). Nevertheless, the efficiency of edaphic functions under T_2 was not severely affected by the traffic of the tractor.

In contrast, in T_{10} , the Bd reached limiting values in terms of the minimum $0.10 \text{ dm}^3 \text{ dm}^{-3}$ macroporosity required for full plant growth (Bd_{MAC} , Severiano et al., 2011). This finding means that, under these conditions, both the infiltration of water into the soil and root respiration may be impaired.

Similarly, the estimated critical bulk density for plant growth based on the least limiting water range (Bd_{LLWR}) was practically achieved with thirty tractor passes (T_{30}). These conditions imposed physical limitations on the plants at all soil water contents in terms of air supply, water availability, and, the resistance of the soil matrix to root growth.

Soil compaction due to tractor traffic affected the agronomic characteristics of the sunflower plants (Figures 4 and 5), which in turn altered the growth environment of Paiaguas palisadegrass in the intercropping system, thus affecting the development of the latter (Figure 6). The height of the sunflower plants was not affected by cropping system (mono- or intercropping); differences in plant height were detected only between different soil compaction levels (Figure 4).

The lack of response of sunflower in terms of plant height between the different cropping systems occurred because sunflower development initially responds to crop management practices, in particular, topdressing. In addition, Paiaguas palisadegrass, which was sown at a greater depth than was sunflower, emerged slowly and did not effectively compete with the sunflower plants during the vegetative stage. This behavior is in agreement with the results of Kichel et al. (2009).

The deleterious effects of increasing Bd and intercropping on the sunflower capitulum diameter and 1000-achene weight indicate that these two variables affected the reproductive development of sunflower and demonstrated interspecific competition effects. These results are in agreement with those of Alves et al. (2013).

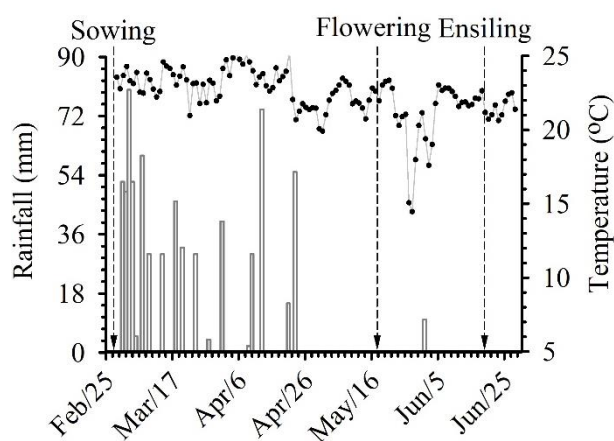
Our results showed that Bd affected the development of Paiaguas palisadegrass in the intercropping system (Figure 6). However, several studies have demonstrated the resilience of *B. brizantha* to soil compaction (Bonelli et al., 2011; Flávio Neto et al., 2015). Considering the capability of *B. brizantha* roots to penetrate compact soil, shading caused by sunflower plants was more likely responsible for the morphological changes in the grass rather than an increase in Bd.

As a result of the different soil structural conditions and the differential growth of the plants in the intercropping system, the changes in the stem length and in the leaf/stem ratio of Paiaguas palisadegrass may affect the final quality of the forage. Leaves are the main nutritive components of grass, whereas stems are fibrous components with lower digestibility and lower use by animals (Machado and Valle 2011). Therefore, in *B. brizantha*, these morphological changes due to the interspecific competition caused by Bd may alter the forage quality of this specie. In general, most of the plant growth parameters of the evaluated species peaked when the Bd approached the estimated Bdb. This fact reinforces the relevance of the Bdb indicator (Severiano et al., 2011), which was not applicable to only a few productivity parameters evaluated in the intercropping system when interspecific competition began to be the primary influence on sunflower performance.

Table 1. Physical and chemical properties of the Dystroferric Red Latosol from the Brazilian savanna.

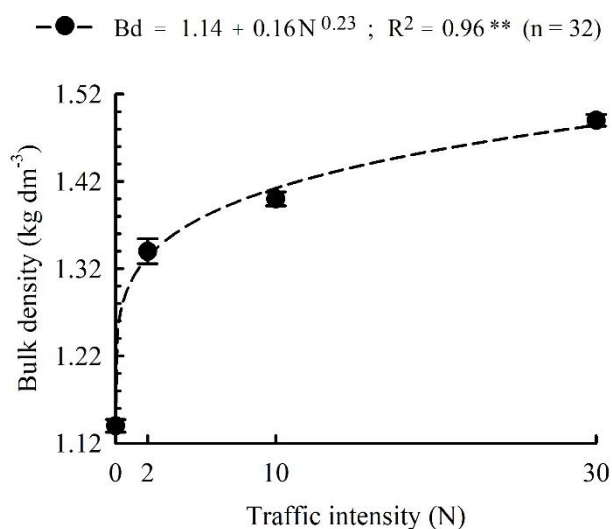
Layer (m)	Pd ⁽¹⁾ (kg dm ⁻³)	Soil texture ⁽²⁾			Sulfuric acid digestion				
		Sand	Silt	Clay	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	Ki	Kr
		----- (g kg ⁻¹) -----							
0-0.2	2.80	344	94	562	40.5	203.6	204.0	0.34	0.21
0.2-0.4	2.82	336	96	568	38.8	200.5	214.7	0.33	0.30

Note: ⁽¹⁾ Pd: The particle density determined via the volumetric flask method; ⁽²⁾ The soil texture was determined via the pipette method and ultrasonic dispersion (Vitorino et al., 2003); Ki: SiO₂/Al₂O₃ molar ratio; Kr: SiO₂/Al₂O₃ + Fe₂O₃ molar ratio.

**Fig 1.** Daily rainfall (mm) and temperature (°C) during the sunflower cropping cycle in the experimental area.**Table 2.** Soil chemical breakdown of a Dystroferric Red Latosol from the Brazilian savanna⁽¹⁾.

Ca	Mg	Al	H+Al	P	K	S	Zn	B	Cu	Mn	Mo	V ⁽²⁾	m ⁽³⁾	OM ⁽⁴⁾	pH
----- cmol _c dm ⁻³ -----				----- mg dm ⁻³ -----								--- % ---		g kg ⁻¹	
1.8	1.3	0.0	4.1	2.3	52	2.4	1.4	0.2	4.0	51.6	0.1	43.3	0.0	40	5.2

Note: ⁽¹⁾ 0.2 m depth; ⁽²⁾ V: base saturation; ⁽³⁾ m: aluminum saturation; ⁽⁴⁾ OM: organic matter. P: determined using the Mehlich test. The pH was measured in CaCl₂.

**Fig 2.** Traffic effects of an agricultural tractor [soil bulk density (Bd) as a function of the number of passes (N)] on a Brazilian savanna Latosol.

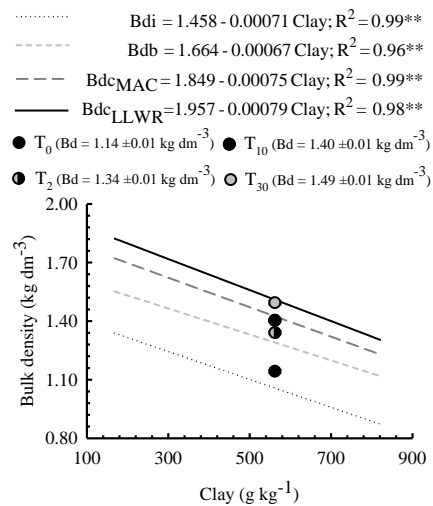


Fig 3. Initial bulk density (Bdi), beneficial density in terms of increased soil water retention (Bdb), critical density for a reduction in macroporosity to $0.10 \text{ dm}^3 \text{ dm}^{-3}$ (Bdc_{MAC}), and critical density for plant growth and yield based on the least limiting water range (Bdc_{LLWR}) as a function of the clay content of Latosols of the Brazilian savanna (adapted from Severiano et al., 2011). $T_0 = 0$, $T_2 = 2$, $T_{10} = 10$ and $T_{30} = 30$ passes over the same spot. The bulk density values calculated for the Dystroferic Red Latosol were evaluated on the basis of their clay content (562 g kg^{-1}).

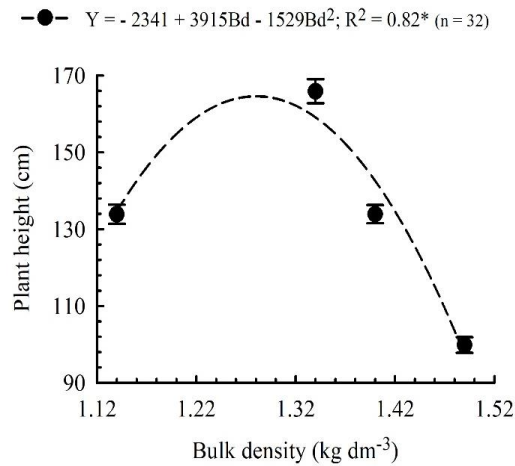


Fig 4. Sunflower plant height in response to different bulk densities resulting from compaction levels of a Latosol under a second crop in the Brazilian savanna.

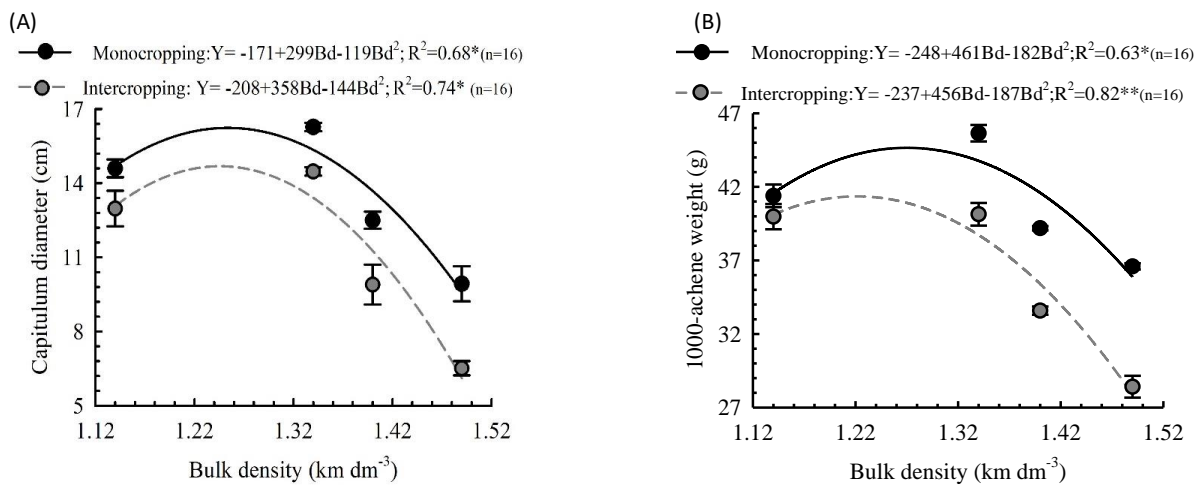


Fig 5. Capitulum diameter (A) and 1000-achene weight (B) in response to different bulk densities resulting from different compaction levels of a Latosol under sunflower grown via monocropping or intercropping as a second crop in the Brazilian savanna.

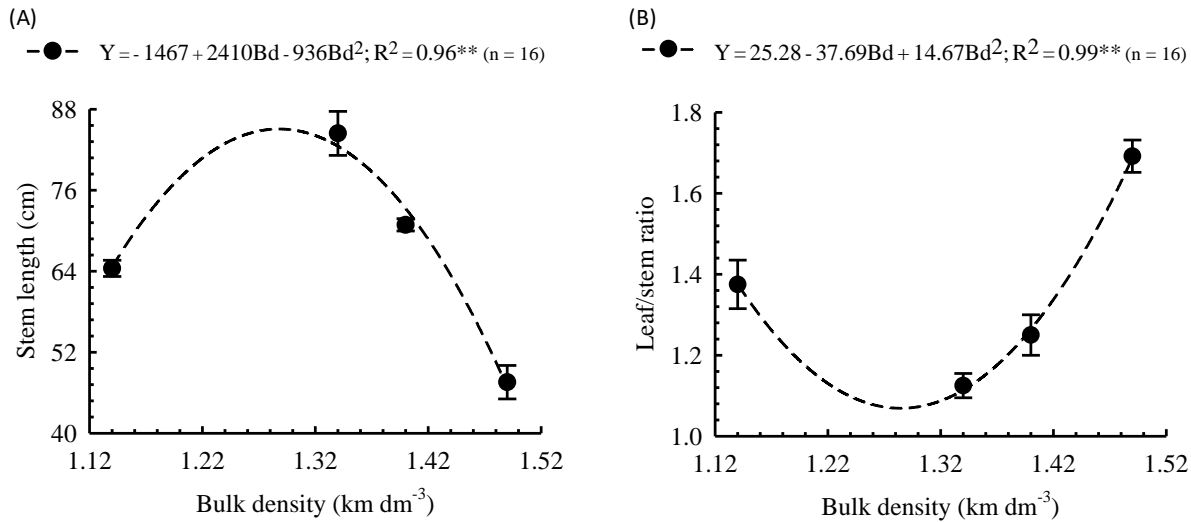


Fig 6. Stem length (A) and leaf/stem ratio (B) of Paiguas palisadegrass grown via intercropping with sunflower as a second crop in response to different bulk densities that resulted from different compaction levels of a Latosol in the Brazilian savanna.

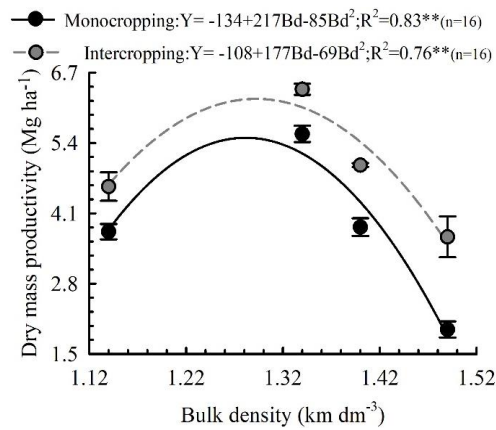


Fig 7. Dry mass productivity of sunflower grown via monocropping or intercropping in response to different bulk densities resulting from different levels of soil compaction of a Latosol in the Brazilian savanna.

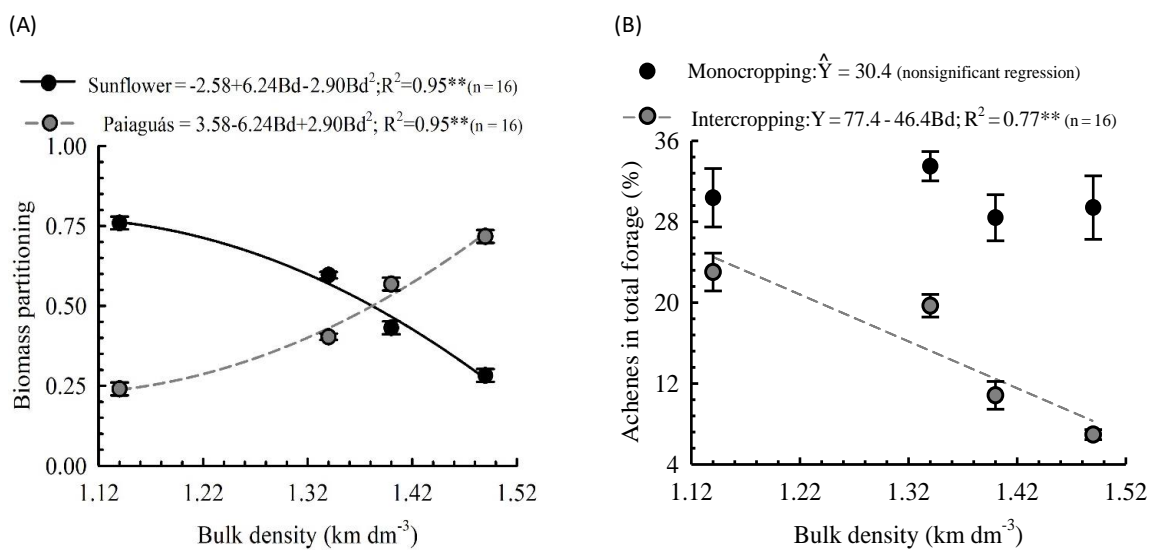


Fig 8. Biomass partitioning of forage plants grown via intercropping (A) and the percentage of sunflower achenes in the total forage of sunflower grown via monocropping or intercropping (B) in response to different bulk densities resulting from different levels of soil compaction of a Latosol in the Brazilian savanna.

When the Bd approached the estimated Bdb, the DM production was maximized. Notably, sunflower productivity was also affected by the limitations previously discussed. The increase in DM production with increasing compaction shows that, in these soils, slight compaction can benefit plant development because it promotes nutrient diffusion and increases soil/root contact, thereby increasing crop yields (Severiano et al., 2011). In this context, the applicability of the pedotransfer models (Figure 3) for sunflower cultivation in Latosols is shown for the first time. Moreover, this fact highlights the need for new research relating the critical Bd indexes studied with different plant species because of the amount of agronomic information that can be inferred from simple soil texture analyses.

The sunflower productivity values obtained were similar to those reported by Rezende et al. (2007) and Martin et al. (2014) for second crops. These productivity levels demonstrate the risk of using sunflower for ensiling because other crop species such as corn and sorghum present higher productivity potential (Mafakher et al., 2010).

However, under conditions of a late second crop, intense water stress may occur, which limits corn and sorghum growth more than sunflower growth. Possatto Júnior et al. (2013) made suggestions for agronomic planning and suggested that sunflower could be a supplement to forage productivity in regions and during seasons with relatively high risks of water deficit to generate income and increase potential land use. These ideas apply to the case for second crops in the Brazilian savanna.

The climate conditions during the evaluated period are considered an important factor for the dry mass yield obtained. Water stress, especially during the sunflower flowering stage, may have compromised crop productivity. This effect was previously reported by Martin et al. (2014), who obtained sunflower yield losses that were more pronounced because of the strong dry periods beginning during the flowering stage.

Water stress causes a series of physiological changes that reduce photosynthesis, thus compromising plant development (Dutra et al., 2012). The productivity results were therefore expected for a second crop, especially in the absence of rain during the inflorescence (58-71) and flowering [72-85 days after sowing (DAS)] stages, including only 10 mm of rainfall during achene filling at 93 DAS (Figure 1).

The greater dry mass productivity of the intercropping system compared with the monocropping system (Figure 7) was due to the increase in grass biomass, which negatively affected sunflower development but resulted in higher total forage yields for ensiling, i.e., increased biomass of both forage species. The differential productivity losses due to soil compaction observed in both cropping systems were likely due to the particular characteristics of the two studied crop species in terms of soil compaction. Sunflower sensitivity to soil compaction results in reduced plant height, stem diameter, capitulum diameter, and, in particular, achene production (Bayhan et al., 2002). In contrast, soil compaction has little influence on the development of *B. brizantha* (Sousa Neto et al., 2013).

It is therefore evident that in intercropping systems comprising sunflower and *Paiaguas* palisadegrass, when soil physical conditions are adequate, sunflower plants grow better than the grass plants do and limit the growth of the latter because of shading. Under conditions of relatively high

Bd, grass limits the development of sunflower because of competition, thereby resulting in the agronomic changes observed. The changes in the partitioning of total DM with increasing soil compaction (Figure 8A) were observed because, compared with the *Paiaguas* palisadegrass, the sunflower plants more sensitive to soil compaction. Thus, the proportion of sunflower in the resulting forage decreased with increasing Bd, with a consequent increase in the proportion of grass. These results are in accordance with those of Bonelli et al. (2011). A decrease in the percentage of achenes in the total forage as a function of Bd was observed in the intercropping system but not in the monocropping system (Figure 8B) because soil compaction proportionally decreased the development of the whole sunflower plant. Because the seeds of sunflower are oil seeds, this decrease is expected to alter the nutritional quality of the resulting silage produced, especially in the components in which *Paiaguas* is deficient. Finally, it should be highlighted that adopting the intercropping of sunflower with *B. brizantha* in CLI systems in the Brazilian savanna meets the needs of land use intensification by producing forage for animals via off-season cultivation.

It is therefore suggested that planning of forage systems consider historical land use. The previously discussed potential productivity losses and forage partitioning resulting from soil compaction indicate that agricultural activity may be compromised.

Materials and Methods

Experimental area characterization

The field experiment was conducted at the Federal Institute of Education, Science and Technology Goiano, Rio Verde Campus, Goiás state (GO) (17°48'34.25" S; 50°54'05.36" W; 731 m altitude), Brazil. The region's climate is hot or humid tropical (Aw) according to the Köppen classification, and the subtype is a tropical savanna. It has dry winters and rainy summers. The average annual temperature is 25°C, and the average annual rainfall is approximately 1600 mm. The rainy season lasts from November until April, and the months with the least amount of rainfall are June, July and August (< 50 mm month⁻¹).

The soil in the experimental area is a Dystroferic Red Latosol with a clayey texture (Santos et al., 2018). Its physical and mineral composition, according to Vitorino et al. (2003) and Teixeira et al. (2017), is presented in Table 1. Before the experiment was performed, the soil acidity was adjusted by the addition of 1.5 Mg ha⁻¹ dolomitic limestone on the basis of the results of soil analysis (Table 2) and in accordance with the methods of Sousa and Lobato (2004).

The soil preparation and initial weed control were performed via subsoiling at a depth of 0.45 m, followed by plowing and harrowing to a depth of 0.2 m at 120 days before sowing at the moment of liming; this alleviated any previous soil compaction. Thirty days before the experiment was initiated, 3.0 L ha⁻¹ of glyphosate was applied for the chemical control of weeds that originated from the soil seed bank.

Experimental design and conduction of the study

A split-plot randomized complete block design with four replications was used. The plots were 12.0 m long and 6.0 m

wide. Four different compaction levels were tested. The levels were quantified in terms of traffic from a John Deere 6605 tractor pulling a 4.9 Mg load. The wheel set consisted of diagonally marked tires with the following technical characteristics: front axle, 14.9-24 Pirelli TM 95°, 14.9-inch tire width and 24 inch wheel diameter, with an inflation pressure of 95 kPa and a mean contact pressure of 68 kPa; rear axle, 18.4-34 Pirelli TM 95°, 18.4-inch tire width and 34-inch wheel diameter, with an inflation pressure of 165 kPa and a mean contact pressure of 72 kPa.

The following traffic intensities (numbers of passes of the tractor over the same spot) were used to create soil compaction: T₀, absence of compaction; T₂, two passes; T₁₀, ten passes; and T₃₀, thirty passes. The tractor passes covered the entire soil surface of the experimental plots. The traffic treatments were performed in February when the soil water content was close to field capacity because of rainfall that occurred prior to the experiment, in accordance with the procedure described by Guimarães Júnnyor et al. (2015).

Three forage systems were established in the subplots: 1. sunflower (*H. annuus* L.) (Charrua hybrid) grown solely as a monocrop; 2. sunflower and Paiaguas palisadegrass (*B. brizantha* cv. BRS Paiaguas) grown in an intercropping system; and 3. Paiaguas palisadegrass grown solely as a monocrop. In this study, the treatments with Paiaguas palisadegrass as a monocrop were not evaluated; only treatments that included sunflower were considered in the present study.

The subplots were composed of 13 lines that were 4.0 m long and spaced 0.5 m apart. Mechanical sowing of the second crop was performed on February 28, 2014. Sunflower seeds were sown at a depth of 0.03 m. Paiaguas seeds were mixed with fertilizer and sown at an estimated depth of 0.07 m. For mechanical sowing, fertilizer that contained palisadegrass seeds was placed in an appropriate box. Fifteen kilograms of seeds, corresponding to 5 kg pure and viable seeds ha⁻¹, were premixed with a mixture of fertilizer (350 kg ha⁻¹); the fertilizer comprised 16.5 kg of N, 90 kg of P₂O₅, 35 kg of K₂O, 3.5 kg of Zn, and 3.2 kg of B and 0.32 kg of Mo, as urea, triple superphosphate, potassium chloride, zinc sulfate and Boromol®, respectively.

Thinning was performed at 21 DAS to adjust the sunflower population to 40,000 plants ha⁻¹ and the Paiaguas palisadegrass to 10 plants linear m⁻¹ in the intercrop subplots. In the monocrop subplots, all other plants were removed.

After the plants were established (22 and 42 DAS), fertilizer was topdressed according to the methods of Sousa and Lobato (2004), with 30 kg N ha⁻¹ applied as the first application and with 40 kg of N, 25 kg of K₂O and 24 kg of S ha⁻¹ as urea, ammonium sulfate and potassium chloride, respectively, applied as the second fertilization.

During the experiment, crop management practices and plant health control were performed as needed. At flowering, the capitula were covered to prevent bird attacks. Rainfall and temperature data, in association with the phenological development of sunflower, were monitored throughout the experiment (Figure 1).

Sampling and evaluation of soil physical properties

Nine intact soil samples were collected from all plots following sowing for the determination of bulk density via volumetric rings with a diameter of 0.064 m and a height of

0.05 m obtained with an Uhland sampler, with 3 sampling points along a diagonal line within three different soil layers (0-0.05, 0.05-0.1 and 0.1-0.15 m), thereby yielding a total of 144 samples. Nonintact samples were also collected at the described sampling points and depths and were used for determination of the soil texture (Teixeira et al., 2017).

After they were collected, the samples were wrapped in polyvinyl chloride plastic film. In the laboratory, the excess soil on the edges of the aluminum cylinders was discarded, and soil samples were then dried in an oven at 105 °C for 48 h to determine their bulk density (Teixeira et al., 2017). As a way of interpreting the Bd in each treatment, we adaptations of the Bd critical indexes proposed by Severiano et al. (2011). The pedotransfer functions suggested by those authors were again estimated from the values of total clay of all their evaluated Latosols, which we quantified by ultrasonic dispersion (Vitorino et al., 2003). The adaptation of these mathematical models was due to the presence of pseudosilt in the studied Latosol, evidencing the difficulty of dispersing the soil particles (Vitorino et al., 2003).

Agronomic characteristics and ensiling

The forage productivity was quantified in terms of the increase in biomass, and ensiling was performed at 112 DAS, when the DM concentration for both species was approximately 35%, according to the methods of Leonel et al. (2008) and Toruk et al. (2010). At the moment of ensiling, ten individuals of each species per subplot were collected, and the plant morphological development was evaluated by quantifying the following parameters: plant height (cm), capitulum diameter (cm) and 1000-achene weight (g) for sunflower and stem length (cm) and the leaf/stem ratio for Paiaguas palisadegrass.

The plants were cut at a height of 0.2 m from an area of 4.0 m². The forage was then weighed to determine the total biomass, which was subsequently extrapolated to megagrams per hectare. Forage samples from the sunflower plants grown via intercropping with grass were kept separate, and their DM partitioning was quantified.

Statistical analysis

The results of the agronomic and productivity parameters of the forage versus the mean Bd of the 0-0.15 m layer were subjected to analysis of variance. When significant effects were observed (p<0.05), regression models were fitted to the variation in the parameters measured for the different Bd values via the SigmaPlot 11.0 software package.

Conclusions

The Dystroferic Red Latosol was highly susceptibility to soil compaction, which could be predicted by the proposed pedotransfer functions. These mathematical models were validated for the cultivation of sunflower in Latosols. The development and productivity of the sunflower plants displayed drastic and differential effects under each soil structure condition, and soil compaction led to an increased percentage of Paiaguas palisadegrass in the ensiled forage. The resulting forage productivity may be considered low, but it is appropriate for the late second crop and for the soil physical conditions evaluated. Thus, intercropping is recommended because of its increased productivity and the

possibility of indirect pasture renewal following the forage harvest.

Conflicts of interest

The authors declare that no financial or other competing conflicts of interest exist.

Acknowledgments

We would like to thank the Instituto Federal Goiano for financial support and the Fundação de Amparo a Pesquisa do Estado de Goiás (Foundation for Research Support of the State of Goiás - Edital 003/2013) for granting scholarships to the first author.

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