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CROP PRODUCTION

Crop-livestock integration systems mitigate soil compaction and increase soybean yield

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ABSTRACT. The use of integrated agricultural production systems has been expanded due to the multiple functions they perform. Although soil structural studies have elucidated the relationship of these systems with plant development, adjustments are needed to incorporate the diversity of management systems employed. Thus, the hypothesis of this study was that integrated cropping systems mitigate soil structural degradation and increase the agronomic performance of crops. The objectives of this study were to evaluate the biological soil loosening potential containing paiaguás grass and the effectiveness of integrated systems in promoting the agronomic performance of soybean plants and to model the least limiting water range (LLWR) considering the adopted management regimes. An experiment was performed based on a randomized block and split-plot design. In the plots, the traffic intensity (0, 2, 10, and 30 passes of an agricultural tractor. In the subplots, soybean cultivation was performed under the three management systems (simple: monoculture grains; integrated: intercropping between grass and grains; and pasture in monoculture). The following soil physical quality indicators were determined: bulk density (Bd) and LLWR; these indicators are related to phenological development attributes and soybean productivity. The integrated agricultural production systems promoted biological soil loosening and improved soybean yield. The use of Paiaguás grass in monoculture enhanced edaphic benefits and enabled greater grain production compared to grain monocropping. The least limiting water range was an efficient parameter for modeling the physical behavior of the soil, and the application of the LLWR was improved by considering penetration resistance reference values specific to each management system. Our results highlight the soundness of using the LLWR in evaluating the response of soybean to physical changes in soil due to compaction, and the reference values for penetration resistance contribute to greater accuracy in the LLWR and the physical diagnosis of soil properties.

Keywords: *Glycine max*; *Brachiaria brizantha* cv. BRS Paiaguás; least limiting water range; biological soil loosening; sustainability.

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Introduction

Agricultural production has served as a major form of socioeconomic development in Brazil and the basis for international relations, contributing to trade and providing opportunities for the development of the country. Agricultural production is responsible for supplying food markets and contributing to global food security due to the technological revolution that has occurred in recent decades. Among cultivated species, soybean [*Glycine max* (L.) Merrill] is the main summer crop, and Brazil is the second largest producer of soybean in the world, with a 154.6 million ton harvest in the 2022/2023 season (Companhia Nacional de Abastecimento [CONAB], 2023), which was mainly aimed at export.

However, increased agricultural development was based on the use of inputs (products) that initially brought about increases in production but more recently generated obstacles to productivity and resulted in environmental degradation. This is because soil compaction has widely occurred in production fields due to the use of mechanized agricultural equipment in all stages of the production process (Peixoto et al., 2019; Torino et al., 2020). Compaction is characterized by a compression of the soil due to the application of pressure (machinery and animals) and is the greatest agro-environmental limitation worldwide (Keller, Sandin, Colombi, Horn, & Or, 2019), particularly in the Brazilian Cerrado, where the soils are most susceptible to soil compaction (Severiano et al., 2013).

However, management systems (processes) have been proposed to mitigate the effects of damage from machinery. Crop and livestock integration (CLI), for example, can enhance soil physical quality compared to simple cropping systems (Lemaire, Franzluebbers, Carvalho, & Dedieu, 2014). In these systems, forage plants are included to keep the soil permanently covered with plants in all seasons of the year and might provide opportunities for grazing. Therefore, for these systems to succeed, it is necessary to include plants with the potential for soil structural improvement (Calonego, Raphael, Rigon, Oliveira Neto, & Rosolem, 2017; Silva et al., 2019), and in this context, Flávio Neto et al. (2015) highlighted the cultivation of *Brachiaria brizantha* due to its aggressive root action in breaking compacted layers, which has several benefits for subsequent crops (Braida, Reichert, Veiga, & Reinert, 2006; Andrade, Segui, Carlesso, Trois, & Knies, 2011; Chioderoli et al., 2012; Silva et al., 2021; Muniz et al., 2021).

Additionally, the use of paiaguás grass (*Brachiaria brizantha* cv. BRS Paiaguás) is highly recommended in integrated agricultural production systems (Guarnieri et al., 2019; Silva et al., 2021) due to its potential for biological soil loosening, and understanding its effect is fundamental for adequate management, given its suitability for ILP, particularly its potential to mitigate damage from land use.

The least limiting water range (LLWR) has been widely adopted in characterizing the physical environment for plant root growth. Contemplates the soil water content in which matric potential, oxygen and mechanical resistance are not limiting for plant growth (Silva, Kay, & Perfect, 1994; Li et al., 2020; Oliveira et al., 2019; Silva et al., 2021; Moura et al., 2021). When limits are defined, it is possible to evaluate situations in which the crop is subject to water deficit or anoxia, as well as high mechanical resistance (Oliveira et al., 2019; Li et al., 2020). However, it is necessary to refine this indicator, considering the specificities of crops (Torino et al., 2020; Silva et al., 2021) or even soil management regimes (Moraes, Debiasi, Carlesso, Franchini, & Silva, 2014; Ferreira, Tormena, Severiano, Zotarelli, & Betioli Junior, 2020).

Therefore, the hypothesis of our study was that integrated systems would mitigate soil structural degradation and increase the agronomic performance of crops. The objectives were: i) to evaluate the potential of paiaguás grass to biological soil loosening, ii) to evaluate the effectiveness of integrated agricultural production systems on the agronomic performance of soybean plants relative to simple grain production systems, and iii) to model the LLWR considering the specific mechanical resistances of the adopted management systems (grains in monoculture, intercropping of grains, and pasture in monoculture).

Material and methods

Characterization of the site and soil studied

The field experiment was carried out at the experimental farm of the Instituto Federal Goiano (IF Goiano), municipality of Rio Verde, Goiás State, Brazil (17°48'34.25" S; 50°54'05.36" W; and 731 m altitude; Figure 1). The Brazilian Soil Classification System (Santos et al., 2018) classifies it as a *Latossolo Vermelho acriférrico típico* of clayey texture or Typic Haplustox (USDA - Soil Survey Staff, 2022). The southwestern region of the state of Goiás, where the experimental area is located, is an important agricultural region in Brazil due to its flat topography and because it is covered by the oldest soils in the world. Additional information on the rock geology, soil mineralogy and main systems and on the management of this soil was provided by Severiano et al. (2013).

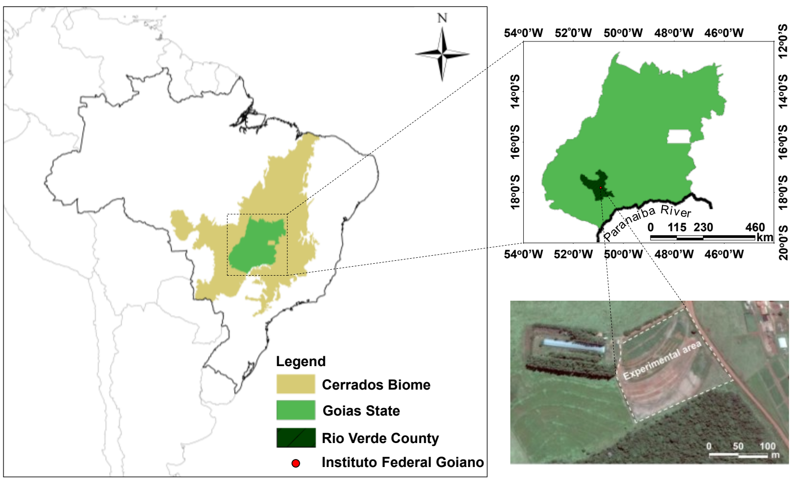

Figure 1. Location of the experimental area in Rio Verde, Goiás State, Brazil, Cerrado Biome.

The region's climate is Megathermal or Humid Tropical (Aw), Tropical Savannah subtype, with dry winters and rainy summers. The average annual temperature is 25°C, and the average annual rainfall is approximately 1,600 mm, with the maximum precipitation occurring in January and the lowest precipitation occurring in June, July and August (< 50 mm month^{-1}). Summer weather occurs in the middle of the rainy season; it normally lasts 10 to 15 days with no rain and may last for more than 30 days.

Field experiment description

The experiment was performed during the 2014/2015 harvest in an area that was converted to a production field in 1990. Initially, the soil use history was eliminated by carrying out two cross-subsoiling operations at a depth of 0.45 m and incorporating 1.5 Mg of limestone (relative capacity of total neutralization = 80%, CaO = 36% and MgO: 12%) by harrowing with 28-inch disks and a levelling tool at 0.20 and 0.10 m depth, respectively. The necessary fertilization was carried out according to Sousa and Lobato (2004) and was adjusted for the soybean crop according to soil analysis (Table 1). The soil analytical procedures were based on Teixeira, Donagemma, Fontana, and Teixeira (2017).

Table 1. Physical and chemical characterization of the *Latossolo Vermelho acriférrico típico* from the Brazilian Cerrado during soybean sowing, 2014/2015 harvest.

Layer	Pd[(1)]	Texture[(2)] Sand (2.00-0.05 mm)	silt (0.05-0.002 mm)	Clay (< 0.002 mm)	Oxides[(3)] SiO_2	Al_2O_3	Fe_2O_3	Soil chemical attributes Ca	Mg	Al	H+Al	P	K	V[(4)]	OM[(5)]	pH
(m)	(kg dm^{-3})	------------------ (g kg^{-1}) ------------						----- cmol$_c$ dm^{-3} -----				mg dm^{-3}		%	g kg^{-1}	
0-0.20	2.80	350	200	450	--	--	--	2.5	1.8	0.0	3.3	1.9	65	58	43	5.5
0.20-0.40	2.82	382	150	468	42	186	238	--	--	--	--	--	--	--	--	--

[(1)] Pd: particle density determined by the volumetric flask method. [(2)] Determined by the pipette method. [(3)] Determine via digestion with H_2SO_4 (standard method in Brazil) (Teixeira et al., 2017). [(4)] V: base saturation; [(5)] OM: organic matter. P: determined by the Mehlich extractor. pH was measured in a $CaCl_2$ solution.

The experiment was conducted with a randomized block design and in accordance with a split-plot design with four replicates. In the plots, which were 12 m in length and 6 m in width, four levels of compaction were evaluated through passes of an agricultural tractor with a mass of 4.5 Mg and a set of wheels made up of front and rear diagonal tires with inflation pressures of 95 and 165 kPa, respectively. Four traffic intensities were applied: T0: no additional traffic; T2: two passes; T10: ten passes; and T30: thirty passes of the tractor in the same place, covering the entire soil surface of the plot. The soil water content was close to field capacity (0.33 ± 0.01 dm^3 dm^{-3}), a condition in which the soil is highly susceptible to compaction (Severiano et al., 2013; Silva et al., 2021).

In the subplots, consisting of 13 planting rows spaced 0.50 m apart and 4.0 m long, soybean cultivation was performed in the summer of 2015 after the harvest of sunflower (*Helianthus annuus* L.) (selected treatment of grains in monoculture) and a paiaguás grass (*Brachiaria brizantha* cv. BRS Paiaguás) (pasture in monoculture). Additionally, the two species were intercropped; the grass was implanted during the second harvest and remained throughout the entire 2014 off-season. The agronomic performance of crops was described by Silva et al. (2021).

Sampling and evaluation of the soybean crop

When the experiment was initiated, before cultivation (February 2014) and at soybean harvest (November 2014), after the plots were treated with glyphosate herbicide (4 L ha^{-1}), soil samples were collected from all compression subplots for physical, chemical and grading analysis (Table 1), and undisturbed soil samples were collected with the aid of a Uhland-type sampler (confined in volumetric cylinders of 0.064 m diameter, 0.05 m height and packed in plastic film (PVC), at three diagonal points in the plot (one point per subplot) and in three layers (0-0.05; 0.05-0.10, and 0.10-0.20 m), for a total of 288 samples.

Mechanical implantation of the soybean crop was carried out on November 20, 2014, using a Massey Ferguson pivoted agricultural seeder (Model MF 500, regulated for a population of 360,000 plants per hectare, recommended for the cultivar M 7110). This cultivar has the following parameters: INTACTA RR2 PRO®, a relative maturity of 6.8, indeterminate growth, resistance to lodging, an average height of 71 cm, productive stability and moderate susceptibility to the Javan root nematode. The seeds were inoculated with 1 kg of *Bradyrhizobium japonicum* as the inoculant for 50 kg of seeds. The inoculant was homogenized and graphited, and Cropstar® fungicide and Cruiser® insecticide, which are specific for seed treatment, were applied.

Fertilization was carried out according to the soil analysis (Table 1), and the integrated management of pests and diseases was carried out according to the following steps: 45 days after emergence (DAE), the fungicide trifloxystrobin + cyproconazole (300 mL ha^{-1}); 50 DAE, the full insecticide Engeo (200 mL ha^{-1}) for pest control (*Colaspis* sp., *Bemisia tabaci*, *Megascelis* sp., *Spodoptera albula*, *Euschistus heros*); and ant control with granulated bait (pyrazole chemical composition fipronil 0.01%) throughout the crop cycle.

To determine the soybean yield, 112 days after sowing, plants were harvested in an area of 5 m^2 in the center of the plot, and 10 of these were separated for agronomic evaluation of the crop: (i) plant height; (ii) number of pods; and (iii) number of scars with and without pods. The plants were subsequently threshed, and the grains were weighed. The results obtained from each subplot were subsequently transformed into weights of 1,000 grains and yields (kg ha^{-1}) corrected to 13% moisture. During the experiment, rainfall and temperature were monitored in the field, and the results are shown in Figure 2.

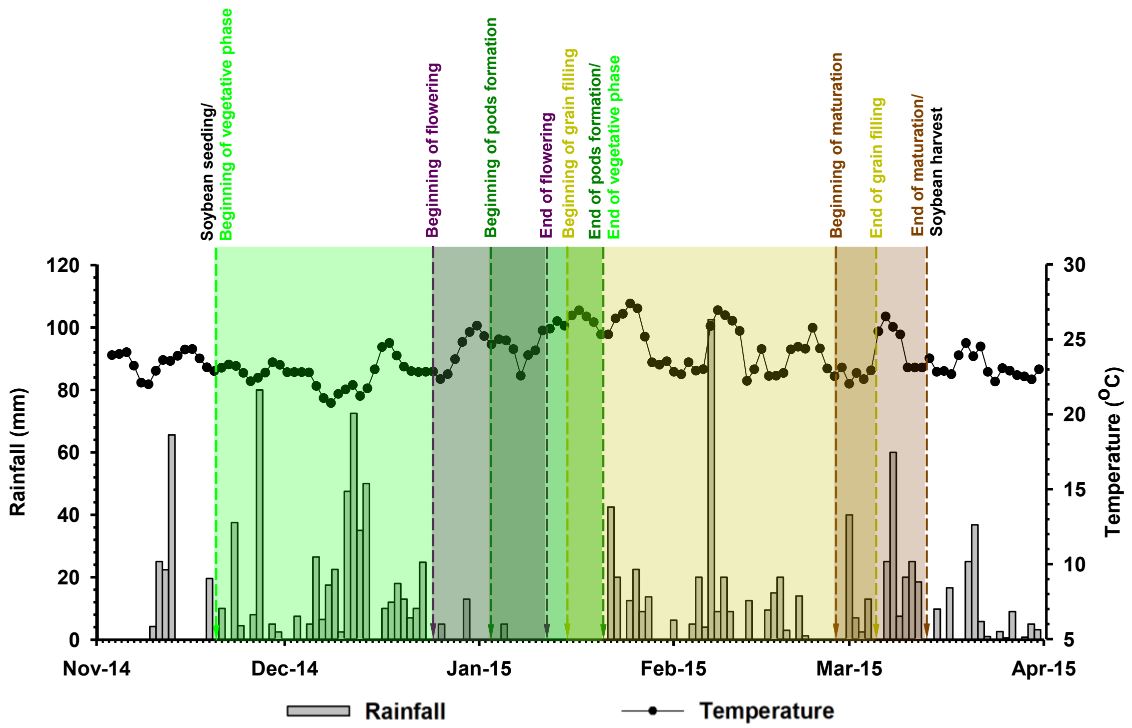

Figure 2. Precipitation (mm) and average daily temperature (°C) during the soybean cycle, 2014/2015 harvest, in the municipality of Rio Verde, Goiás State, Brazil.

Soil evaluation

The undisturbed samples were processed at the Laboratory of Soil Physics at IF Goiano, with excess soil removed from the edges of the cylinders. The surplus material was used to determine the permanent wilting point (matrix potential of -1.5 MPa) by subjecting the saturated soil to the Richards extractor apparatus (Teixeira et al., 2017). Afterwards, the samples were saturated by gradually raising the water level for 48h and then subjected to a matrix potential of -0.006 MPa until hydraulic equilibrium was reach. At this potential, the retained water content was considered equivalent to the field capacity for this Latosol, as suggested by Severiano et al. (2011) and Silva et al. (2021). Subsequently, the samples were air-dried to obtain water contents ranging from 0.03 to 0.36 dm^3 dm^{-3} in the samples, during which the penetration resistance (PR) was determined using a bench penetrometer with a displacement speed of 10 mm $min.^{-1}$ and automatic data logging. Afterwards, the soils were dried in an oven at 105°C for 48 hours to determine the soil bulk density (Bd). The total porosity (TP) was determined by Equation 1, with Pd being the particle (Table 1).

$$TP = [1 - (Bd/Pd)] \quad (1)$$

The adjustment of the water retention data according to Bd resulted in Equation 2, considering the soil water retention curve at field capacity (FC):

$$\theta_{FC} = \text{-}0{,}7842 + 2{,}1982\text{Bd} - 1{,}1565Bd^2; \quad R^2 = 0{,}83^{**} \quad (2)$$

The soil penetration resistance curve (SPRC) was obtained by adjusting the PR values for the water content (θ) and the Bd using the model proposed by Busscher (1990), with coefficients described in Equation 3:

$$PR = 0{,}036\theta^{-1{,}648}Bd^{7{,}341}; \quad R^2 = 0{,}75 ** \qquad (3)$$

The least limiting water range (LLWR) was calculated according to procedures described in Silva et al. (1994), considering as the upper limit (LS) the lowest value between the water content in the field capacity (θ_{FC} – Equation 2) or the water content in the restrictive aeration porosity (θ_{AP}) (0.10 dm^3 dm^{-3}), calculated using Equation 4.

$$\theta_{AP} = PT - 0.1 \qquad (4)$$

The lowest limit (LI) is the highest value between the water content retained at the permanent wilting point (θ_{PWP}), obtained from gravimetric to volumetric moisture correction ($\theta_{PWP} = U_{1,5MPa} * Bd$), and/or the water content corresponding to the soil penetration resistance, initially with a value of 2.5 MPa (θ_{PR}).

The value of Bd at which the first reduction in available water occurred between the FC and PWP was considered the structural alert Bd (Bd_{alert}). A Bd for which the LLWR = 0 was considered critical and highly restrictive to plant development, regardless of the soil water content (Silva et al., 1994).

Statistical analyses

To evaluate the potential for biological soil loosening as a result of the cultivation of paiaguás grass, comparisons were made between linearized regressions ($y = a + bX^c$, where $y = Bd$ and $x = passes^c$), according to Snedecor and Cochran (1989), of the impact of agricultural tractor traffic (bulk density as a function of the number of passes) before and after the implementation of the management systems. This statistical procedure is used to analyse the homogeneity of the data (F), the significance of the intercepts (a), the angular coefficients and the linearized regression (b). When there is homogeneity between the regressions and when the coefficients are not significant, they are grouped, and a new equation is generated considering all the previous results.

All the statistical analyses were performed using SAS software (SAS, 2002). The results of agronomic performance and soybean yield were subjected to analysis of variance using the PROC GLM routine and regression adjustment (PROC REG) when significance was demonstrated. In addition, the crop yield (yield/maximum yield) was normalized for each treatment, and the results were plotted in a contour graph as a function of PR and θ. The threshold PR in the θ_{FC} was defined considering 90% of the yield, after which the LLWR was estimated again for the soybean crop in the production system.

Results

Table 2 compares the curves for soil compaction resulting from the use of agricultural equipment during soybean cultivation under 3 management systems (grains in monoculture; intercropping and pasture in monoculture) and 4 levels of soil compaction (T0, T2, T10, and T30). According to statistical analysis, we grouped areas with the same structural conditions before the implementation of the systems and under grain cultivation in monoculture (after cultivation) > intercropping system > pasture in monoculture (Table 2) during the desiccation of Paiaguás grass.

Table 2. Comparison between the linearized regressions of curves of soil compression as a result of agricultural equipment traffic before and after the implementation of monoculture and intercropping management systems in a *Latossolo Vermelho acriférrico típico*[1].

System	F	F		Decision
		Linear coefficient, log a	Slope coefficient, b	
Grains in monoculture x intercropping	H	**	ns	do not group
Grains in monoculture x pasture in monoculture	H	**	**	do not group
Intercropped x pasture in monoculture	H	**	**	do not group
Compression before x grains in monoculture	H	ns	ns	Group
Compression before; grains in monoculture x consortium	H	**	ns	do not group
Compression before; grains in monoculture x pasture in monoculture	H	**	**	do not group

[1]Analysis performed according to Snedecor and Cochran (1989). NH: Nonhomogeneous; H: Homogeneous; ns: not significant; *: significant at 5%; **: significant at 1%.

The use of integrated agricultural production systems promoted increases in Bd in previously tilled soil (T0) and reductions in all traffic intensities, with Bd being more effective with pasturing in monoculture (Figure 3). This was verified by comparing the linearized equations (Table 2) and confirmed by the high coefficient of determination of the regression adjustments (R^2; $p < 0.01$).

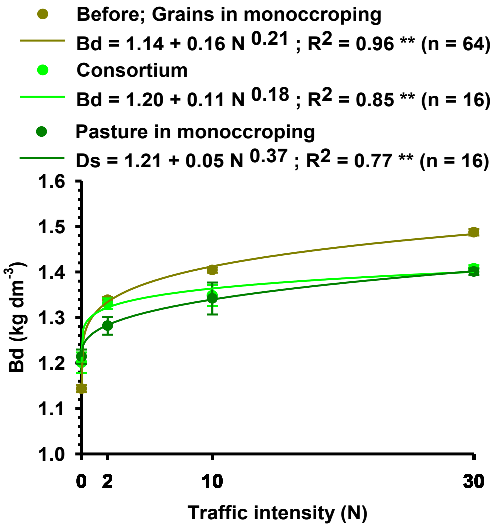

Figure 3. Impact of agricultural tractor traffic [Bulk density (kg dm^{-3}) as a function of the number of passes (N)] before and after the implementation of management systems in monoculture (grain and pasture) and intercropped in a *Latossolo Vermelho acriférrico típico* of the Brazilian Cerrado.

The relationships between water content and bulk density (Bd), considering the critical limits of the LLWR, are shown in Figure 4. The upper limit of the LLWR was represented by the θ_{FC} in almost the entire range analyzed, which was replaced by the θ_{AP} from Bd 1.46 kg dm^{-3} (Figure 4A). A change in lower limit contents occurred at 1.28 kg dm^{-3} from θ_{PWP} to θ_{PR} and the LLWR became null at 1.44 kg dm^{-3} (Figure 4B), which is considered the critical value.

Again, the effect of integrated agricultural production systems in mitigating soil compaction could be observed. There was an increase in the LLWR when Paiaguás grass was cultivated in the off-season in the T0 (main limitation: low water retention), T10 and T30 treatment (strongly affected by high PR). The highest value for the LLWR was observed in the T2 monoculture (Figure 4B).

Figure 5 shows the relationship between soil compaction and management system performance and between agronomic parameters and soybean yield.

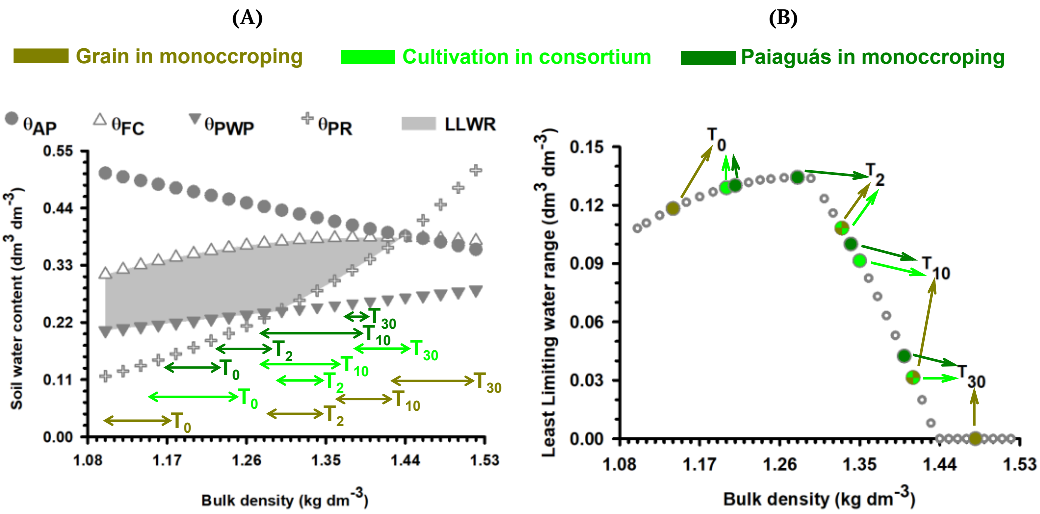

Figure 4. Variation in soil water content (θ) as a function of increasing bulk density (Bd) at critical field capacity (θ_{FC}: ψ_m = -0.006 MPa), permanent wilting point (θ_{PWP}: ψ_m = -1.5 MPa), aeration porosity of 0.10 dm^3 dm^{-3} (θ_{AP}) and penetration resistance of 2.5 MPa (θ_{PR}) limits (A) and variation in the least limiting water range (LLWR) with increasing Bd (B) in the 0-0.15 m layer of the *Latossolo Vermelho Acriférrico típico* of the Brazilian Cerrado due to agricultural tractor traffic in monoculture systems (grains and pasture) and intercropping systems. The hatched area represents the LLWR;ψ_m: matrix potential; Bd_{alert}: bulk density at which the first reduction in available water occurs; Bd_c: bulk density at which the LLWR = 0; T0 = 0, T2 = 2, T10 = 10, and T30 = 30 passes over the same area of an agricultural tractor weighing 4.5 Mg.

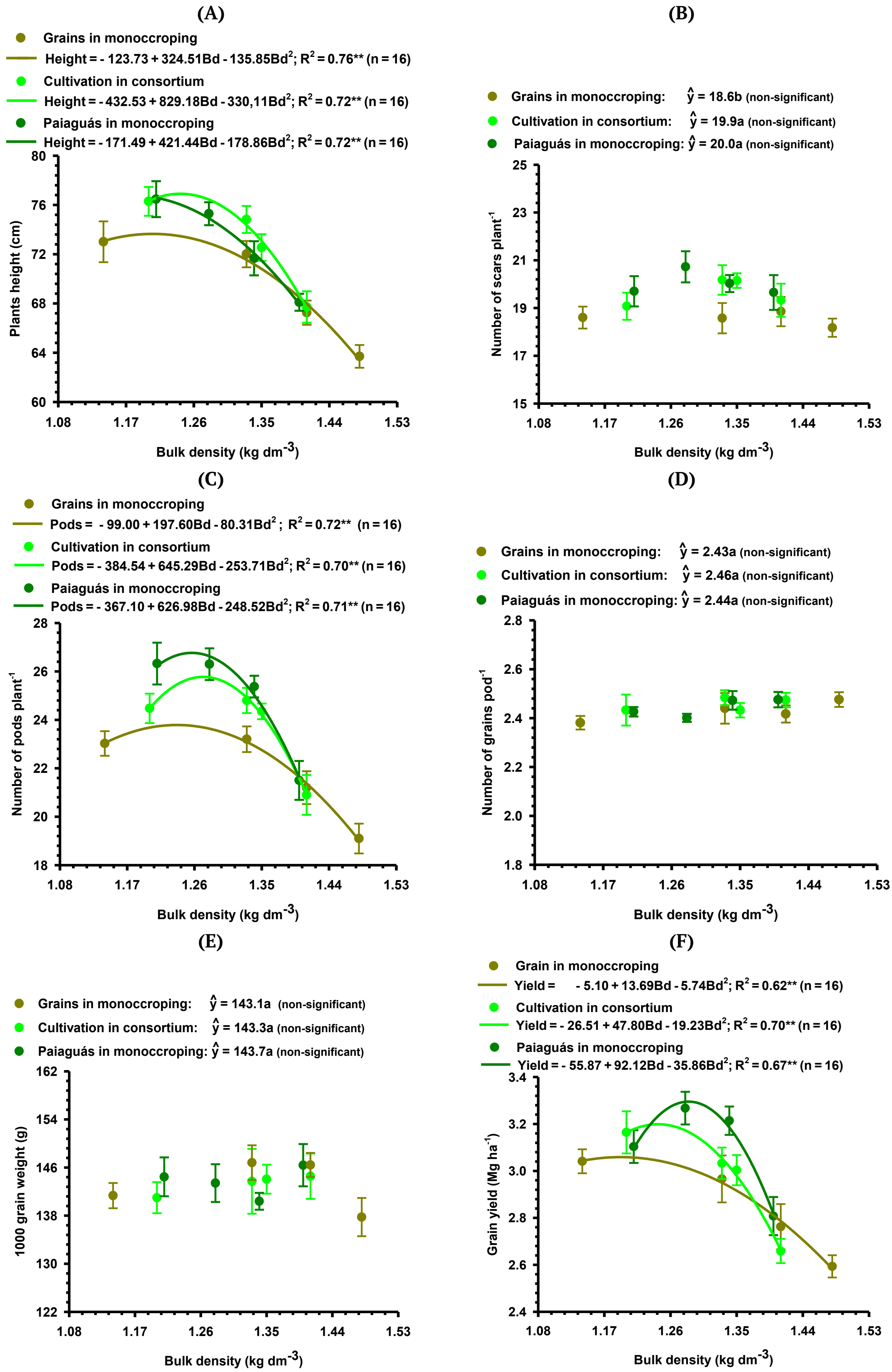

Figure 5. Phenological development and grain yield of soybean plants as a function of bulk density in monoculture (grain and pasture) and intercropped management systems in a *Latossolo Vermelho Acriférrico típico*. A: Plant height; B: number of scars per plant; C: number of pods per plant; D: number of grains per pod; E: weight of 1,000 grains and; F: grain yield per hectare.

Plant height (Figure 5A), number of pods per plant (5C) and grain yield (5F) were affected by the two factors evaluated, with superior performance for the intercropped system and pasture in monoculture. The maximum yield was 3.06 Mg ha^{-1} at a Bd of 1.19 kg dm^{-3} in the monoculture grain system, while the yield in the intercropping system reached 3.19 Mg ha^{-1} in 1.24 kg dm^{-3}; for the monoculture pasture system, the yield was 3.29 Mg ha^{-1} in 1.28 kg dm^{-3}.

For the number of nodes per plant (5B), only the crop-livestock integration systems had an effect; again, there was superior performance compared to grain monoculture, while for the number of grains per pod (5D) and weight of 1,000 grains (5E), no differences were found.

Figure 6 suggests that integrated management mitigated soil compaction and promoted yield performance of soybean, and the causes are presented in Figures 3, 4, and 5. The relative yield of soybean is exponentially related to the variation in PR as a function of θ. When the soil structure is preserved, even when the water content in the soil is close to the permanent wilting point, it is possible to obtain the maximum yield for PR values > 2.5 MPa. However, with increasing soil compaction, the influence of mechanical resistance increases with an increase in the amplitude of the evaluated moisture.

The analysis of relative soybean yields as a function of soil compaction and management systems clearly differentiates the edaphic environment of agricultural production. When the yield was greater than 90%, the PR was 1.6 MPa for grains in monoculture (Figure 6A), 2.0 MPa for intercropping (Figure 6B) and 2.4 MPa when only Paiaguás grass was cultivated throughout the off-season (Figure 6C) based on water content at field capacity.

Considering the biological response to these PR values, the LLWR was recalculated (Figure 7) rather than using the preestablished value of RR = 2.5 MPa (Figure 4). The new LLWRs increased in the following order: LLWRgrains > LLWRintercropped > LLWRpasture, with Bd_{alert} values of 1.19, 1.24 and 1.28 (Figure 7A) and Bd_c values of 1.36, 1.40, and 1.44 kg dm^{-3}, respectively (Figure 7B).

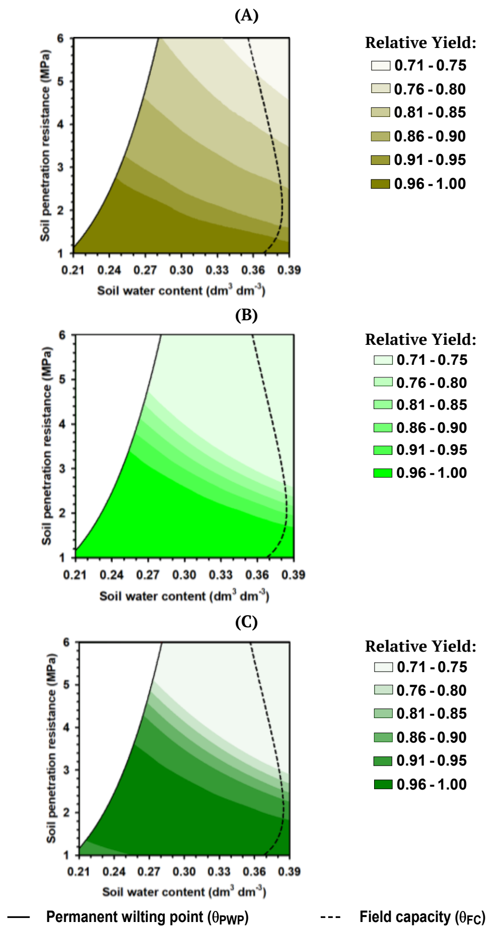

Figure 6. Variation in soil penetration resistance as a function of soil water content and relative yield of soybean plants in a grain management system under monoculture (A), integrated agriculture and livestock (B) and pasture in monoculture (C) in a *Latossolo Vermelho acriférrico típico* in the Brazilian Cerrado.

It is worth noting that the Bd_{alert} values (Figure 7) are consistent with the points of maximum soybean grain yield (Figure 5) and demonstrate an improvement in the accuracy of the LLWR based on the critical values of the PR.

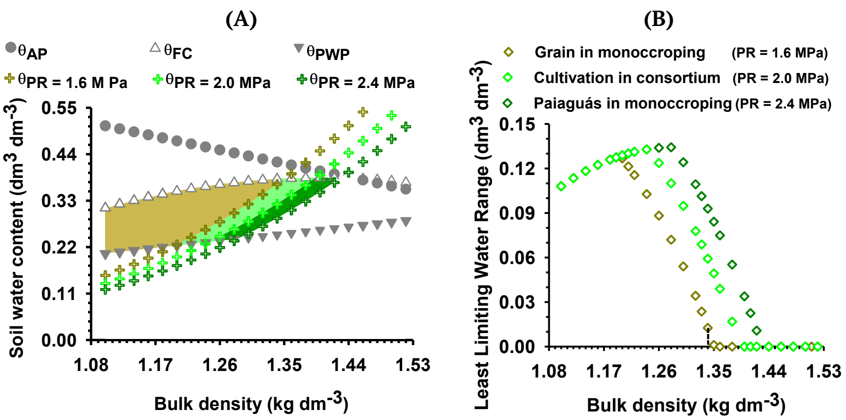

Figure 7. Variation in soil water content (θ) as a function of increasing bulk density (Bd) at critical field capacity (θ_{FC}: ψ_m = 0.006 MPa), permanent wilting point (θ_{PWP}:ψ_m:-1.5 MPa), aeration porosity of 0.10 dm^3 dm^{-3} (θ_{AP}) and penetration resistance (PR) of 1.6, 2.0 and 2.4 MPa (θ_{PR}) limits (A) and variation in the least limiting water range (LLWR) with increasing Bd (B) in the layer of 0-0.15 m of a *Latossolo Vermelho acriférrico típico* of the Brazilian Cerrado due to agricultural tractor traffic in monoculture systems (grains and pasture) and intercropped systems. The hatched area represents the LLWR.

Discussion

The effect of integrated management systems on soil physical properties

According to analysis by Snedecor and Cochran (1989) (Table 2), there was no difference in the soil compaction curves between a monoculture grain management system and an integrated management system, which demonstrated the limited effect of previously planted crops (in this case, sunflower in monoculture). The high susceptibility of the soil to compaction is clear, with a loss of yield capacity in more than 50% of achenes due to soil compaction and metabolic changes (Silva et al., 2021). However, the cultivation of Paiaguás grass pastures had effects, both in consortium and in monoculture; therefore, the models were adjusted separately (Figure 3). The physical properties of a soil can negatively impact the yield of successive crops (Derpsch et al., 2014; Buchi et al., 2017; Oliveira et al., 2019; Torino et al., 2020; Ferreira et al., 2023), particularly in the clayey soils of the Brazilian Cerrado (Severiano et al., 2011; Silva et al., 2015; Moura et al., 2021), where compaction is an unavoidable process [according to Severiano et al. (2013), worldwide, these soils are most susceptible to compaction].

The LLWR exhibited properties that are characteristic of soils in the Brazilian Cerrado (Severiano et al., 2011; Flávio Neto et al., 2015; Silva et al., 2021). In this study, poor aeration was not a problem, except under conditions of severe physical degradation, such as after BDc (Figure 4). The main limitations therefore occur due to low water retention under soil structural conditions that are close to the natural conditions and when the soils are compared with soils from other Brazilian regions (Ferreira et al., 2020) or even those in temperate climates. This is due to the granular structure of Latosols, in which structural pores (macropores) develop that, in turn, promote low capillarity, low water retention and, consequently, greater aeration (Severiano et al., 2013; Silva et al., 2022).

With increasing soil compaction, there was a significant increase in water availability (Figure 4B), which was beneficial for crops (Severiano et al., 2011; Silva et al., 2021). However, at high PR values, soil compaction is a serious physical problem, in agreement with the findings of Tormena, Karlen, Logsdon, and Cherubin (2017), and may harm plant development (Peixoto et al., 2019; Moura et al. 2021; Silva et al., 2021) and limit soybean yield (Ferreira et al., 2023), as well as the yield of other annual grain crops commonly used in rotation (Peixoto et al., 2019; Torino et al., 2020; Silva et al., 2021). High degrees of compaction limit root development (increase θ_{PR} and decrease LLWR), as compaction causes abiotic stress and leads to loss of crop yield (Keller et al., 2019).

Our results highlight the role of Brachiaria in soil structuring. With no traffic (T0), there was an increase in Bd of 5 and 6% in the intercropped and pasture in monoculture system relative to grains in monoculture (Figure 3), which increased the LLWR (Figure 4B). This may have occurred due to the formation of aggregates through adhesion between soil particles due to the cementing action of soil organic matter and root exudates which, in turn, stimulate soil microbial activity, inducing the formation of microbial byproducts that also stabilize soil aggregates; the mechanical action of roots can also bring soil particles together (Brandão & Silva, 2012; Borghi et al., 2013). It is worth noting that this plant has an extensive root system and is aggressive (Lima et al., 2023).

The Bd point that separates beneficial compaction ($LLWR_{max}$) from restrictive compaction was defined by Silva et al. (2021) as Bd_{alert}, with a value of 1.28 kg dm^{-3}. It corresponds to the condition under which θ_{PR} replaces θ_{PWP} as the lower limit of the LLWR (Figure 4). In addition, the effect of grass monoculture was best under moderate compaction (T2) conditions. This type of structural improvement has been reported by several authors (Brandão & Silva, 2012; Borghi et al., 2013; Crusciol et al., 2014; Flávio Neto et al., 2015; Calonego et al., 2017; Pariz et al., 2017; Silva et al., 2019; Moura et al., 2021).

The integrated agricultural production systems proved to be effective at mitigating soil compaction promoted by the most intense traffic condition evaluated (Figure 3). This process associated with forage plants was described by Flavio Neto et al. (2015) as biological soil loosening and was more intense with *B. brizantha* than with other grasses of the same genus (Silva et al., 2019). The use of paiaguás grass was effective; it promoted adequate forage production in the off-season for animal grazing and soil cover for no-till treatment, and the soil could tolerate nearly three times more compaction (measured by the authors as PR) compared to soils cultivated with annual grain crops (Silva et al., 2021). This practice also improved the edaphic environment for successive crops (Figure 4).

Therefore, Paiaguás grass contributed to an improvement in the root environment both in terms of soil restructuring (when the soil was freshly turned over) and biological soil loosening. The inclusion of this grass reduced Bd under high compaction conditions (Figure 3) and increased the LLWR by 68 and 74% at the site with 10 passes of the tractor and by 23 and 32% at the site with 30 passes, respectively, in the intercropped and monoculture systems. The lower performance of intercropped plants was due to interspecific competition during the initial establishment of the species, as noted by Silva et al. (2021) during the evaluation of the first crop of this experiment. Additionally, the full activity of the grass was limited; this in turn severely compromised sunflower production. Therefore, to use consortia, the structural conditions of the soil must be determined to enhance the ability of the system to repair the physical degradation of the soil and restore the productive potential of agricultural systems.

These results, although encouraging for agricultural planning, were less promising than those of Flávio Neto et al. (2015), who reported 54 to 88% physical recovery after the cultivation of *Brachiaria brizantha* grass in the off-season in a severely compacted soil. This discrepancy could to due to the following reasons: I - the paiaguás grass, here, was planted at the end of the rainy season, remained for seven months (in contrast to eleven months in the other work) and was exposed to lower soil water content at the time of establishment; and II - this is the first time that the biological loosening potential of this cultivar has been evaluated, and it may (or may not) have a lower performance in relation to other cultivars. Therefore, it was necessary to compare the grasses under the same experimental conditions to better support this finding.

Our results suggest that the aforementioned approach is justified, especially considering its effect under moderate degradation conditions (T10). The effects mainly involved improving soil water conditions, particularly under conditions of irregular rainfall. The agronomic performance of successive crops was improved by the grass since the soybean plants experienced a period of 22 consecutive days with no rain during the full flowering and pod formation stages (Figure 2).

Integrated systems, soil compaction and soybean agronomic performance

Among the soybean growth parameters (Figure 5), plant height reflects the edaphoclimatic conditions throughout the crop cycle, given the indeterminate growth of the variety. Soil compaction positively and negatively affected (quadratic polynomial adjustment) plant height, while integrated systems mitigated physical soil degradation by increasing the maximum point by up to 10% in relation to the system under monoculture (Figure 5A). The number of nodes, which was influenced only by the management system employed, showed up to 1.5 more axils per plant (Figure 5B) in the integrated systems, which is relevant because it is the point of insertion of the pods. Thus, an increase in the number of nodes (Figure 5C) of 13 and 20% was observed in the integrated systems, in addition to an increase in Bd at the maximum point from 1.23 to 1.27 kg dm^{-3}. This occurred due to the direct and indirect effects of foraging.

In addition to biological soil loosening (Figure 4), the inclusion of pastures in agricultural systems has multiple functions, as described by several authors: 1) cattle production in pastures; 2) maintenance of dead biomass for the no-tillage system; 3) provision of environmental services, according to Silva et al. (2021); 4) reduction of thermal oscillation in the surface soil layer (Braida et al., 2006; Chioderoli et al., 2012); 5) nutrient cycling (Muniz et al., 2021); and 6) maintenance of soil moisture (Andrade et al., 2011; Flávio Neto et al., 2015). The production of dead biomass for soil cover was determined by Silva et al. (2021), who reported values of 5.5 and 3.8 Mg ha^{-1} for intercropped systems and monoculture pastures, respectively, which were considered satisfactory for providing the aforementioned benefits.

Adequate grain formation was determined by the number of grains per pod (although this is a genetically controlled characteristic) and by the weight of 1,000 grains (not significant - Figures 5D and 5E) and coincide with the resumption of rain (Figure 2). Soybean yield losses with increasing soil compaction (Beutler, Centurion, Centurion, & Silva, 2006; Girardello et al., 2014; Moura et al., 2021; Botta et al., 2022; Ferreira et al., 2023). In this study, the yields were equivalents the Brazilian average for the crop and 5 and 8% greater, respectively, for the intercropping system and monoculture pasture, both for yield and Bd maximum (Figure 5F).

The quadratic relationship of the agronomic variables and, mainly, of grain yield reinforce the following findings: 1) Severiano et al. (2011) asserted that slight compaction in the Oxidic Latosols of the Brazilian Cerrado is beneficial, given the high porosity of the soil under natural conditions (Severiano et al., 2013; Silva et al., 2022); they noted that compaction improves water retention and availability (as seen in Figure 4); 2) paiaguás grass improved the edaphic environment by conditioning the soil structure towards the maximum and ideal LLWR from a physical point of view (that is, with maximum water availability, adequate contact area between roots and soil, sufficient and continuous pore space for the movement of gases and water and without excessive mechanical resistance), both under recent turning (T0) or excessive compaction conditions (T10 and T30).

Thus, it is essential to discuss the relevance of adopting integrated agricultural production systems for mitigating agro-environmental damage and maintaining the yield capacity of soils, especially considering that soybean performance is affected by the interaction between soybean genotype and the environment. The water demand of crops in rainfed systems is intimately influenced by the water retention capacity of soils and rainfall. In the flowering/grain filling period, the evapotranspiration demand can reach values of 8 mm day^{-1} (Buchi et al., 2017), a critical condition in terms of the observed lack of rainfall (Figure 2) and a factor that cannot be controlled by farmers. Although the agronomic response of soybean plants is affected by phenotypic plasticity [adaptability to management and environmental conditions, according to Balbinot Junior et al. (2016) and Carmo, Braz, Simon, Silva, and Rocha, (2018)], yield is reduced in some cases (Ferreira et al., 2020; Ferreira et al., 2023) but not in others (Secco, Reinert, Reichert, & Silva, 2009).

LLWR modelling based on the effects of soil management systems

LLWR represents an important advance in soil biophysics studies because it is the indicator that best correlates with plant growth (Tormena, Araújo, Fidalski, & Costa, 2007). However, it is necessary to refine it, particularly with respect to the reference values for limiting grades (Silva et al., 2015; Ferreira et al., 2020; Silva et al., 2021). The literature still lacks studies related to the biological responses of soybean plants to soil compaction, particularly in integrated agricultural production systems, and our results suggest different responses in soybean plants to soil compaction.

In addition to the increase in yield in the order of pasture in monoculture > intercropped system > grains in monoculture, there was also an increase in tolerance to compaction observed for Bd at the point of maximum yield in the same order (Figure 5F). In this context, an improvement in the LLWR can contribute to improved accuracy as an indicator of yield potential since its performance in the diagnosis of the structural condition of soil is improved (Silva et al., 1994; Reichert, Suzuki, Reinert, Horn, & Håkansson, 2009; Severiano et al., 2011; Flávio Neto et al., 2015; Tormena et al., 2017; Silva et al., 2019; Ferreira et al., 2020; Silva et al., 2021). Figure 6 demonstrates that the relative yield had an exponentially relationship to the variation in PR and θ in θ_{FC} and θ_{PWP}, as modelled by Equation 3. According to Peixoto et al. (2019), high plant productivity potential exists even when a soil has high PR; thus, determination of the θ_{FC} condition is recommended to standardize the effects of θ since there are no restrictions regarding mechanical resistance (θ_{AP} not being limiting, as already discussed) under these conditions. Considering that the penetration resistance value equates to 90% yield, as suggested by Silva et al. (2021), at a PR of 1.6, 2.0, and 2.4 MPa, soybean plants in monoculture, intercropped system and monoculture pastures, exhibit different biological responses.

The strategy of using PR values that affect agronomic yield in integrated systems recognizes the edaphic environment of production in a differentiated way, consistent with the magnitude of the soil quality indicator studied. In previous studies, preestablished values were used that varied in most cases between 2.0 and 2.5 MPa (which here would represent an overestimation of the mechanical resistance of the simple system of grain cropping; Figure 6), as in the case of results from Silva et al. (1994), Reichert et al. (2009), Severiano et al. (2011), Flávio Neto et al. (2015), Tormena et al. (2017), and Silva et al. (2019). In addition, to improve the LLWR, Moraes et al. (2014) and Ferreira et al. (2020) considered a critical limit for soils under long-term no-tillage, with a PR value equivalent to 3.5 MPa (higher than our results). According to the authors, under these conditions, the soil has root biopores from previous crops that partially compensate for the state of soil compaction. Despite these findings, the aforementioned studies did not involve dry spells during cultivation; thus, in the absence of water deficit, soybean plants develop even under high compaction conditions. Integrated agricultural production systems, therefore, mitigate climatic stresses associated with compacted soils.

Figure 7 demonstrates through the LLWR the growth environment in each management system, demonstrating that integration makes the system more resilient as it increases Bd_{alert} (1.19, 1.24, and 1.28 kg dm^{-3} for grains in monoculture, intercropped system and pastures in monoculture), the Bd_c (1.36, 1.40, and 1.44) and the entire range of the LLWR (θ_{AP} is not a problem for the studied soil). Our results provide guidance for the physical diagnosis of soil conditions and agronomic planning in terms of the management system to be adopted. By considering specific PR thresholds (the main factor reducing the LLWR), methodological advances can be made by describing the physical environment for the development of crops in succession (Figure 7B).

Conclusion

The integrated agricultural production systems reduced soil compaction and the effects of dry spells and contributed to the growth and yield of soybean. The use of Paiaguás grass in monoculture throughout the preceding off-season enhanced edaphic benefits, and soybean plants performed better by up to 10% compared to plants in a simple monocropping system. The least limiting water range (LLWR) proved to be efficient variable for modeling the physical behavior of the soil, and the application of the LLWR was improved by considering specific penetration resistance (PR) reference values for each management system. These results underscore the soundness of the LLWR in assessing soybean response to soil physical changes due to soil compaction. The PR reference values contribute to greater accuracy in the LLWR and soil physical diagnoses. Research of this nature contributes to a better understanding of soil management systems and serves as the basis for sustainable agricultural production.

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