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Modeling and quantification of soil compaction promoted by animal trampling in an integrated crop-livestock system

Modelagem e quantificação da compactação do solo promovida pelo pisoteio animal em sistema de integração lavoura-pecuária

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Highlights

Soil compaction by animal trampling is irrelevant in integrated systems.
Biological soil decompaction by forage plants may occur.
Crop-livestock integration contributes to agricultural sustainability.

Abstract

At critical levels, animal trampling can physically degrade soil, leading to the loss of sustainability of agricultural production. Therefore, it is becomes necessary to model and quantify the soil compaction potential. In this context, the objective was to evaluate the occurrence of soil compaction promoted by animal trampling in crop-livestock integration system (ICL). The study was conducted in a field at Centro Tecnológico da Comigo in the municipality of Rio Verde, Goias state, Brazil, during the agricultural off-season. The experimental area was composed of 1.97 ha, which was equally divided into eight paddocks. Soil was sampled before the grazing phase and after each of four grazing cycles. The compressive behavior of the soil was evaluated by determining the pre-consolidation and critical pressures. The results showed that only the first cycle of grazing showed additional compaction in 14.59% of samples. No critical compaction was observed in the evaluated area. Animal trampling under the studied conditions is not responsible for the dissemination of structural soil degradation in crop-livestock integration systems and may contribute to physical improvement resulting from biological soil loosening.

Key words: Soil degradation. Uniaxial compression test. Soil structure. Pre-consolidation pressure. Sustainability.

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Resumo

Em níveis críticos, o pisoteio animal podem degradar fisicamente o solo, levando à perda de sustentabilidade da produção agrícola. Portanto, torna-se necessário modelar e quantificar o potencial de compactação do solo. Neste contexto, objetivou-se avaliar a ocorrência da compactação do solo promovida pelo pisoteio animal em sistema de integração lavoura-pecuária (ILP). O estudo foi conduzido a campo no Centro Tecnológico da Comigo no município de Rio Verde, Goiás, Brasil durante o período da segunda safra da agricultura. A área experimental foi composta de 1,97 hectares, dividida igualmente em oito piquetes. O solo foi amostrado antes da fase de pastejo e após cada um dos quatro ciclos de pastejo. Foi avaliado o comportamento compressivo do solo, a partir da determinação da pressão de pré-consolidação e da pressão crítica. Os resultados mostraram que somente o primeiro ciclo de pastejo apresentou compactação adicional e em 4,59% das amostras. Não houve compactação crítica na área avaliada. O pisoteio animal nas condições estudadas não é responsável pela disseminação da degradação estrutural do solo em sistemas de integração lavoura-pecuária, podendo contribuir eventualmente até com a melhoria física decorrente da descompactação biológica do solo.

Palavras-chave: Degradação do solo. Ensaio de compressão uniaxial. Estrutura do solo. Pressão de pré-consolidação. Sustentabilidade.

Introduction

In Brazil, agricultural and cattle-raising activities are mostly performed in isolation. If on the one hand, the grain fields employ the world's highest production technology and not always with due conservation of natural resources (Silva et al., 2021), the areas destined for livestock have low yields and occupations lower than one head of cattle per hectare in more than 80% of the pastures (Feltran-Barbieri & Féres, 2021). The integrated crop-livestock systems (ICL) are a way to increase competitiveness and sustainability in rural properties through the synergism between these two activities. These systems aim to diversify land use with annual crops for grain production and pastures in succession for meat and milk production (Muniz et al., 2021; Simões et al., 2023; Silva et al., 2023).

However, although this production technology is accessible in several modalities (Linhares et al., 2020; Torino et al., 2020), many farmers and ranchers still do not adopt it. Resistance to ICL adoption lies in the potential damage to succeeding crops caused by animal trampling (Jordon, 2021). However, when well-managed, integrated systems can increase forage productivity, thus increasing the animal stocking rate, as well as provide benefits to the soil, such as by improving the physical, chemical, and biological properties; breaking the biotic cycles of pests and diseases; and resulting in better conditions for crop implementation during the summer harvest (P. C. F. Carvalho et al., 2018; Silva et al., 2019).

In areas in which grain crops are grown, intense traffic of agricultural machinery is responsible for the spread of soil compaction. This originates fromin the compression of unsaturated soil by the application of external pressures, and the ease with which it decreases in volume, with a consequent increase in bulk density, is called compressibility (Torino et al., 2020; Silva et al., 2021).

The introduction of animals in the production process can generate impacts resulting from soil compaction, mainly in the superficial layers of the soil, which may be associated with animal stocking rates above the carrying capacity of the pasture (Centeri, 2022) or grazing occurring at times of the year with high rainfall. This is because the water content of the soil is the factor that governs the amount of deformation that may occur, reducing the load bearing capacity of the soil with its increment (Severiano et al., 2011). However, the modality emerging in Brazil includes the cultivation of soybeans (spring/summer) and some forage plants (summer/autumn) in the rainy season, with animal grazing throughout the off-season, a period characterized by dry winters (M. B. C. Dias et al., 2020; Muniz et al., 2021).

According to Severiano et al. (2010a), an increase in soil compaction does not always cause agro-environmental damage. However, if it is generated by a critical pressure capable of compromising the soil porous system, soil structure degradation will occur, thereby limiting plant development. Modeling of compaction and quantifying its impacts through the evaluation of compressive behavior is fundamental for the sustainability of agricultural systems. Mathematical models have been used to estimate the load-bearing capacity of soils to quantify the maximum levels of pressure that can be applied to soil to avoid compaction (Severiano et al., 2010b; M. S. Dias et al., 2019).

In this context, the aim was to develop a load bearing capacity model of a Latossolo Vermelho Distrófico típico, aiming to quantify the effect of animal trampling in the ICL system on the soil compaction process in the off-season period corresponding to the dry season of the year. Such results are important forbecome important to establishing sustainable management integration of crop–livestock systems.

Material and Methods

The study was conducted at the Centro Tecnológico da Comigo (CTC), in the municipality of Rio Verde, Goias, Brazil. Collected samples were analyzed at the Soil Physics Laboratory of the Federal Institute of Education, Science, and Technology Goiano (IF Goiano), Rio Verde Campus.

The experimental area consisted of 1.97 ha, divided by an electric fence into eight equally sized paddocks. The soil was classified as Latossolo Vermelho Distrófico típico according to the Brazilian System of Soil Classification (Santos et al., 2018), with a loamy-clayey sandy texture (Table 1). Variations in the particle size distribution were related to the composition of the soil parent material.

Table 1
Physical attributes of Latossolo Vermelho Distrófico típico located in the Rio Verde region, Goias state, Brazil

Horizon(1)	Clay	Sand	Silt	Particle density	Critical bulk density(2)
	-----------	(g kg^{-1})	-----------	(kg m^{-3})	(kg m^{-3})
Ap	303	590	107	2,61	1,57
Bw	399	487	114	2,67	1,47

(1): Ap: Horizon A with anthropic origin disturbance, in the 0 to 5 cm layer; Bw: latosolic B horizon, in the 80 to 100 cm layer; (2): Defined by the pedotransfer function *Dsc* = 1.8426 - 0.00089 Argila proposed by Severiano et al. (2011). Soil particle size distribution was determined via rapid agitation according to the methodology described by Teixeira et al. (2017).

The climate is classified as Megathermal or Humid Tropical (Aw) in the Tropical Savanna subtype, with dry winters and rainy summers. The average annual rainfall is 1560 mm, with the maximum rainfall occurring in January and the lowest in June, July, and August. Figure 1 shows the average temperature and accumulated rainfall in the experimental area during the production cycle. The data were obtained from a meteorological station installed near the experimental area.

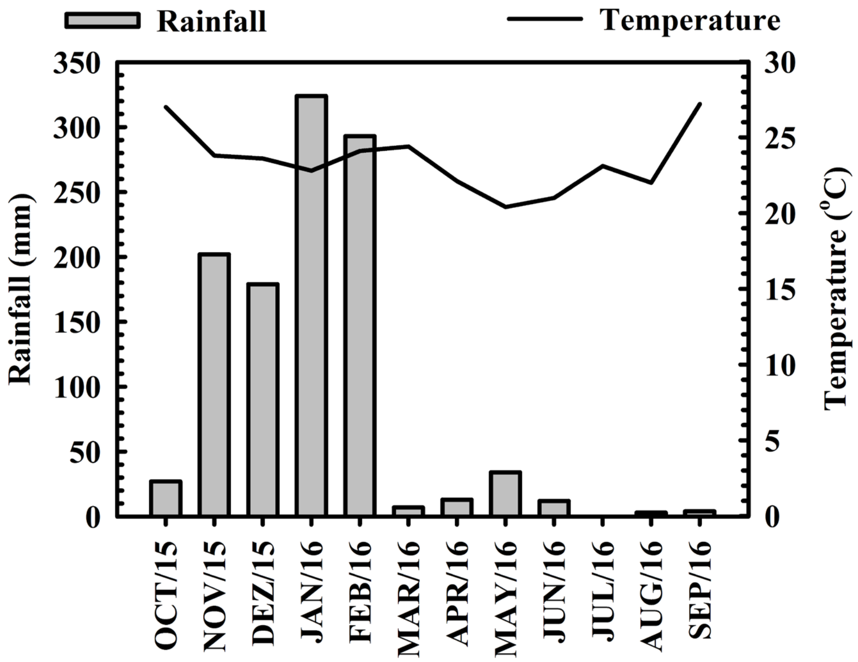

Figure 1. Monthly rainfall (mm) and temperature (ºC) in the municipality of Rio Verde, state of Goias, Brazil, evaluated during the conduct of the experiment.

The agricultural phase occurred during the summer harvest and, comprised of soybean cultivation between October 2015 and January 2016. In February 2016, after harvesting the grain, Brachiaria ruziziensis was mechanically sown at a spacing of 0.50 m between rows. To do so, 10 kg of forage seed mixed with 150 kg of simple superphosphate fertilizer per hectare was used.

The animal production cycle began with the first grazing on May 17, 2016, according to the forage supply, using uncastrated calves aged approximately eight months and coming from industrial crossbreeding (1/2 Canchim x Nelore) with an average weight of 220 kg. Initially, we used an intermittent stocking system with four days of occupation in the pasture and 28 days of rest. The stocking rate was adjusted according to the forage supply available to the animals. The livestock phase ended on September. 16, 2016.

Four paddocks (1, 3, 5, and 7) were selected for experimental evaluation. Soil sampling occurred prior to the livestock phase and during the four grazing cycles at nine points in each paddock at a shallow depth (0–5 cm) in a zigzag format, totaling 180 samples (9 samples x 4 plots x 5 collection periods). The undeformed samples were collected with a Uhland sampler in volumetric rings 0.064 m in diameter and 0.025 m in height. After field collection, the samples were wrapped in a plastic film to maintain their structure until they were analyzed in the laboratory.

The soil samples were collected from May to September 2016 (Table 2). To verify the water content in the soil at the time of each pasture in the paddocks, deformed samples were collected and dried in an oven at 105°C for 48 h to determine soil water content, as described by Teixeira et al. (2017).

The samples were subjected to a uniaxial compression test, being initially saturated by capillarity, and equilibrated to a tension of 6 kPa to determine the microporosity (Teixeira et al., 2017). In the sequence, they were adjusted to water contents ranging from 0.05 to 0.39 kg kg-1 by drying under natural conditions (Severiano et al., 2011).

Then, they were submitted to uniaxial compression test using a consolidometer model Terraload S-450 (Durham Geo Enterprises, USA), according to the methodology proposed by Teixeira et al. (2017). The samples were kept inside the compression cell of the equipment and submitted to successive and increasing pressures of 25, 50, 100, 200, 400, 800 and 1,600 kPa, without unloading the previously applied pressures. Each pressure was applied until 90% of the maximum deformation was reached.

Table 2
Sequence of grazing cycles and pastures with soil sampling date

Cycles	Paddock	Collection day	Stocking rate (AU ha^{-1})	Soil water content at the time of grazing (kg kg^{-1})
Before grazing	1	05/17/2016	--	0.09
	3	05/23/2016	--	0.07
	5	05/31/2016	--	0.09
	7	06/08/2016	--	0.16
1st cycle	1	05/23/2016	2.25	0.08
	3	05/31/2016	2.25	0.08
	5	06/08/2016	2.93	0.20
	7	06/15/2016	2.93	0.09
2nd cycle	1	06/24/2016	2.93	0.08
	3	07/01/2016	3.14	0.06
	5	07/11/2016	3.14	0.03
	7	07/18/2016	3.14	0.03
3rd cycle	1	07/22/2016	3.14	0.03
	3	08/01/2016	1.65	0.03
	5	08/08/2016	1.65	0.02
	7	08/15/2016	1.65	0.02
4th cycle	1	08/22/2016	1.65	0.02
	3	09/01/2016	1.77	0.07
	5	09/08/2016	1.77	0.09
	7	09/16/2016	1.77	0.02

After the test, the samples were dried in an oven (105°C for 24 h) and weighed to determine their bulk densities (Bd). The pre-consolidation pressure (σp) of each sample was obtained from the soil compression curve as described by Teixeira et al. (2017). Particle density was determined using the pycnometer method described by Teixeira et al. (2017).

The pre-consolidation pressure values of the samples obtained before grazing were adjusted as a function of soil water content for determination of the soil bearing capacity model, according to M. S. Dias et al. (2019), using Sigma Plot 11.0 software (Jandel Scientific, P.O. Box 7005, San Rafael, CA, USA), whereas those obtained after grazing were used to verify the impacts of trampling on the soil structure.

The 95% confidence intervals (95% CI) of the load-bearing capacity models were determined, and the three regions proposed by Severiano et al. (2010b) were used to monitor soil compaction resulting from animal trampling. Region “a” corresponds to pre-consolidation pressures determined after grazing that were greater than the upper limit of the confidence interval, a region, therefore, in which additional compaction has already occurred; region "b" corresponds to pre-consolidation pressures between the CI limits, indicating that there was neither compaction and nor biological soil loosening, i.e., no structural changes; and the region "c" corresponds to pre-consolidation pressures lower than the lower limit of CI, also determined after grazing, and characterizes the soil loosening promoted by the root action of the pasture.

To evaluate the occurrence of harmful compaction, pre-consolidation pressure values were fitted to a non-linear model as a function of soil water content (W) and Bd as proposed by Severiano et al. (2010a):

$$\sigma_p = 71.70W^{-0.45}Bd^{1.63}; R^2 = 0.76* \quad \text{Eq. (1)}$$

where σ_p is the pre-consolidation pressure (kPa), W is the soil water content (kg kg^{-1}), and Bd is the bulk density.

For the modeling of the bearing capacity at critical pressure (σ_{cr}), it was considered as critical bulk density (Bd_c), the pedotransfer function proposed by Severiano et al. (2011), whose reference value is shown in Table 1. The σ_{cr} was determined using as modeling parameters the Bdc and the soil water content adjusted in the sample for the compressibility test. For this, it was considered in this case, the criteria proposed by Severiano et al. (2010a), and, the samples located in region "a" limit the soil edaphic functions; in region "b" without critical compaction, although there is the possibility of occurrence of additional compaction, and region "c" as being without compaction.

Results and Discussion

Figure 2a shows the load-bearing capacity model of the soil at depths of 0–0.05 m, containing the 36 samples collected before the cattle-raising phase (before grazing). Notably, as the soil water content increased, the preconsolidation pressure decreased exponentially. The values of the estimated fit parameters of the load bearing capacity model, "a" and "b", were 2.75 and -1.67, respectively, and the coefficient of determination was 0.88, which was significant at 1%. Figure 2b represents the load-bearing capacity model with a confidence interval of 95%, which divides it into three regions and subsidizes the evaluation of the effects of animal trampling on soil structure during the livestock phase of the integration system.

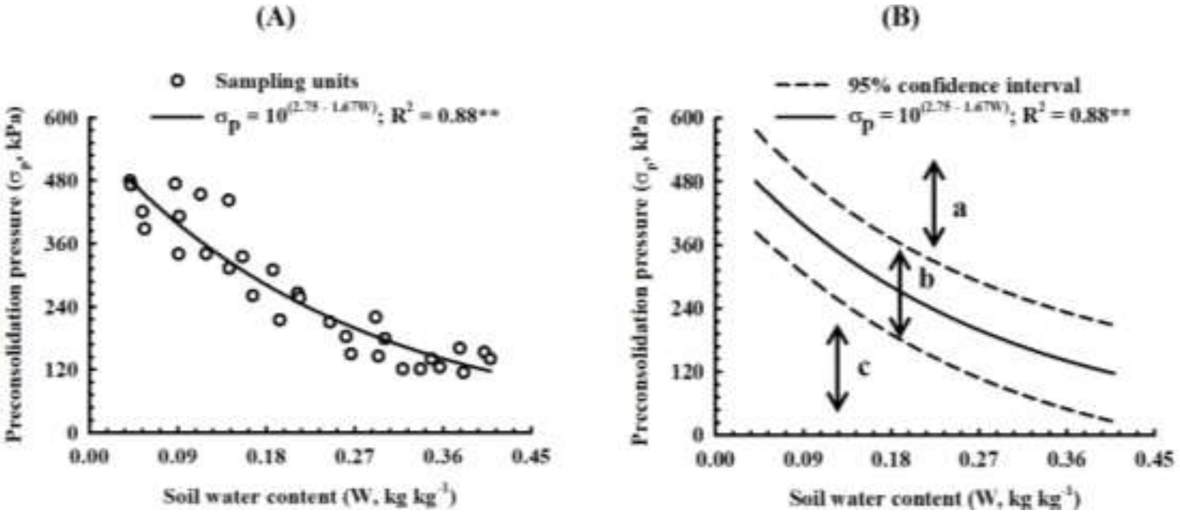

Figure 2. (A) Bearing capacity model [pre-consolidation pressure (σ_p) as a function of soil water content (W)] for Latossolo Vermelho Distrófico típico at a depth of 0-0.05 m and; (B) criteria used to analyze the effect of animal trampling in crop-livestock integration systems: "a": region in which there was additional soil compaction; "b": region in which the soil did not undergo additional compaction and; "c": region in which there was biological soil loosening by forage plants.

Figure 3 shows the dispersion of pre-consolidation pressure values obtained after each grazing cycle in each study area. The classification of pre-consolidation pressure values, in percentage, of the samples collected immediately after grazing, according to each region of the confidence interval, are presented in Table 3. These data showed that additional compaction (14.59%) was highest in the first grazing cycle compared to that in the other grazing cycles (Figure 3a). Similar results were found by Flores et al. (2007) and, although small, the impact of trampling was more representative in the first cycle of grazing than in the others, with no increase in soil compaction from the second cycle of grazing.

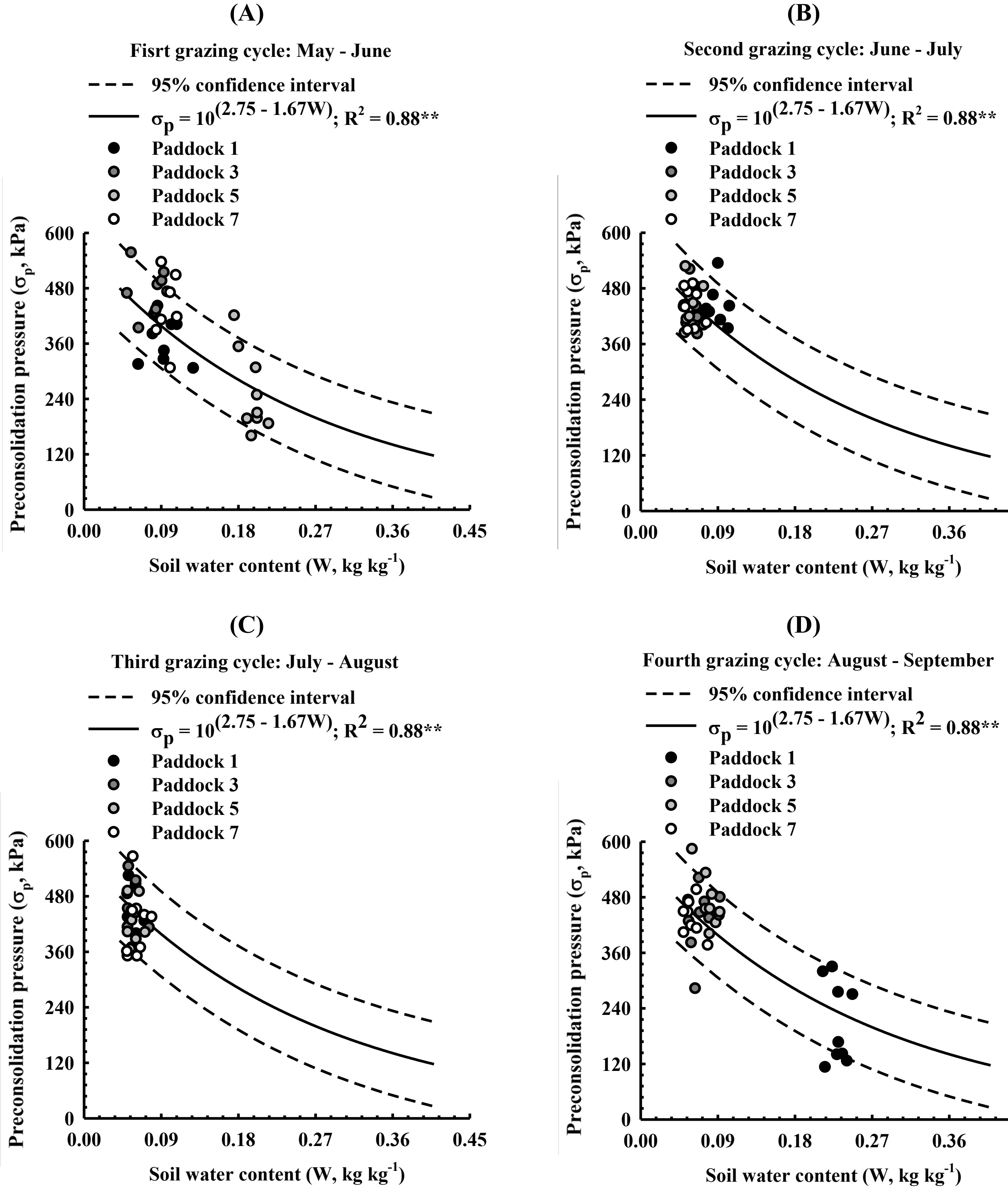

Figure 3. Soil load bearing capacity model for additional compaction [pre-consolidation pressure (σ_p) as a function of soil water content (W)] and pressure values (σ) obtained after bovine grazing on a Latossolo Vermelho Distrófico típico in Rio Verde, state of Goiás, Brazil, under crop-livestock integration system.

In the second and third grazing cycle, (Figures 3b and 3c), there was less variation of σp in relation to the first and fourth grazing cycle. This effect resulted from small oscillations in the water content in the soil during this grazing period, which occurred between June and August (Table 2), because of the low rainfall rates in the period. The two rains that occurred during the grazing phase preceded the first grazing of paddock 5 and last grazing of paddock 1 (Figures 1 and 3). Only 3% of samples from the second and third grazing cycles exceeded the upper limit of the confidence interval (Table 3), characterizing additional soil compaction. In contrast, the soil structure of 97% and 91% of samples remained unchanged. Severiano et al. (2011) analyzed the compressive behavior of soil and observed that at low humidity, the soil resists deformation, which is negligible under these conditions; these results impact the management of the soil structure and thus sustainability (Braga et al., 2015; P. C. F. Carvalho et al., 2018).

Table 3
Classification of the samples, in percentage, according to each region presented in Figure 5, after animal grazing in the different cycles, in a Latossolo Vermelho Distrófico típico

Percentage of soil samples with σ in the region	Compaction (%)				
	1st cycle	2nd cycle	3rd cycle	4th cycle	Total
a – With additional compaction	12	3	3	5	6
b – No structural change	85	97	91	89	90
c – With biological soil decompaction	3	0	6	6	4
Total samples	36	36	36	36	144

Our results highlight the low impact of livestock on soil structure in this ICL modality, where animal grazing occurs in the off-season, although there is a risk of soil compaction when grazing extends into the rainy season. According to Jordon (2021), the hoof pressures applied by steers at an age equivalent to those in the present study can vary from 200 to 280 kPa [reaching 350–400 kPa in adult animals (Serrano et al., 2023)]. This value doubles when the animals are in motion. As shown in Figure 3, the distribution of pre-consolidation pressure values after grazing are compatible with the CI (therefore, it is considered that no pressures higher than the load-bearing capacity of the soil were applied), but the values had already reached the upper limit of the range. The physical water content was expected to be higher than 0.20 kg kg^{-1} when the soil is compacted by cattle trampling.

In the fourth grazing cycle (Figure 3d), additional compaction reached 5% of the samples evaluated, which was very low (even with the increase in the soil water content resulting from accumulated rainfall in August). This result shows that when well-managed and respecting the stocking rate, as observed in this study (Table 1), even with increased soil water content, soil compaction (Sone et al., 2020). This is because when the forage supply is appropriate for the number of animals, there is less grazing time and fewer animal steps per area (P. C. F. Carvalho et al., 2018). Notably, the average occupancy in the period during which the animals remained in the pasture was 2.4 AU ha^{-1}, a stocking rate at least two-fold higher than that found for Brazilian livestock (Muniz et al., 2022) and with several benefits to the soybean crop when applied in succession (M. B. C. Dias et al., 2020; Muniz et al., 2021). It is therefore a technically feasible, economically profitable, and environmentally sustainable production system (M. B. C. Dias et al., 2021).

Throughout the livestock cycle, variation of σp is observed between repetitions in the same paddock both above and below the limits of the confidence interval, demonstrating that both additional compaction and biological soil loosening by the forage plant may occur simultaneously (Figure 3; Table 3). These results may be attributed to the variability in trampling as a result of animal behavior associated with locations, such as at the entry and exit of the paddock and resting of animals, as suggested by Flores et al. (2007). Less frequent grazing may have contributed to the development of forage, resulting in biological soil decompaction. In contrast, the cultivated forage plant B. ruziziensis has a lower productive potential (M. B. C. Dias et al., 2021) and limited decompaction capacity compared with those of other grasses in the genus (Silva et al., 2019). In contrast, B. ruziziensis is the most commonly used grass in Brazil in integrated systems of agricultural and livestock production because of its efficiency in desiccation and mulch formation in no-till farming systems. The adoption of other forage species, besides enabling a greater animal carrying capacity (Muniz et al., 2022) would also contribute to a more effective structural improvement of the soil, with gains even in water availability to the crop in succession (Silva et al., 2019).

Throughout the livestock phase of the integrated system, only 6% of total samples analyzed were in region “a,” characterizing additional compaction (Table 3). Increased compaction can reduce the physical quality of soil (Severiano et al., 2011). In this context, studies of the σcr are necessary to understand whether the observed compaction, even in small amounts, is limited to the edaphic functions of soil.

Figure 4a presents the load bearing capacity model for additional compaction (σp) and for critical compaction (σcr) obtained by equation 1, of the Latossolo under study. The critical pressure overestimates the load bearing capacity of soils by incorporating bulk density at critical levels (values presented in Table 1, responsible for reducing macroporosity to 10 m3 m-3) in modeling the compressive behavior of the soil (Severiano et al., 2010a). Figure 4b represents the load bearing capacity model for critical pressure with a 95% confidence interval. In this modeling, it is assumed the possibility of occurrence of soil compaction, without, however, restrictions related to plant production and groundwater recharge (Severiano et al., 2011).

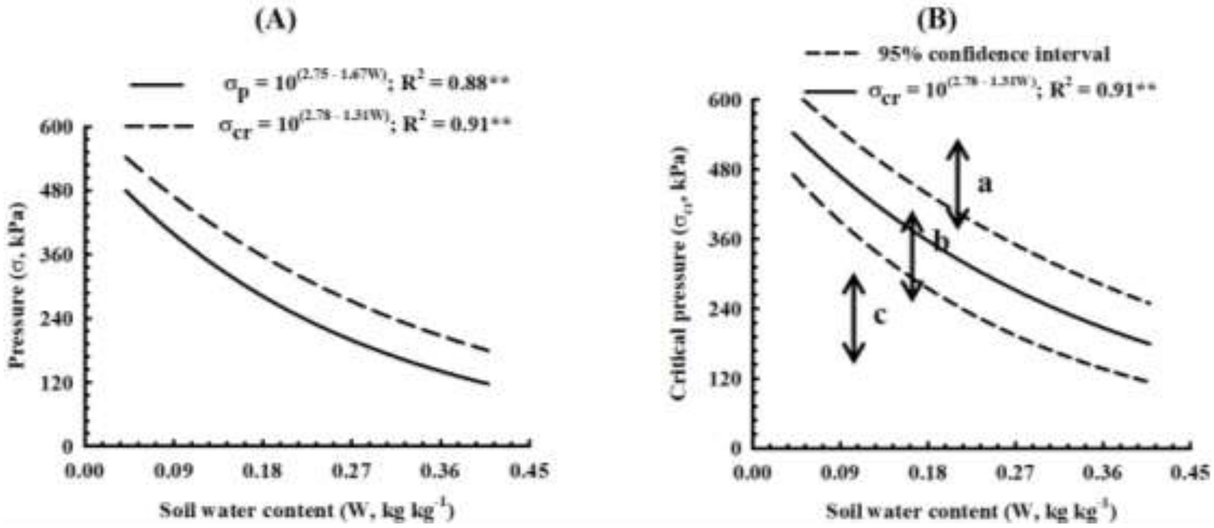

Figure 4. (A) Bearing capacity models [pressure (σ) as a function of soil water content (W)] for additional (σ_p) and critical (σ_{cr}) compaction of Latossolo Vermelho Distrófico típico of Rio Verde, state of Goias, Brazil; and (B) criteria used to analyze the effect of animal trampling in agriculture-livestock integration systems "a": Region limiting soil edaphic functions, "b": no critical compaction and "c": no compaction.

We adopted the criteria defined by Severiano et al. (2010a) to interpret the three regions of the load-bearing capacity model of the soil for σcr. The dispersion of pressure values obtained when the animals left each pasture and grazing cycle was evaluated (Figure 3). The classification of samples in each region for the soil compaction criteria is presented in Table 4.

It is observed that, although additional compaction occurs due to animal trampling in the crop-livestock integration system (Figure 3), this does not imply soil structural degradation (Figure 5), because it does not reduce macroporosity to critical values that lead to the impairment of soil edaphic functions, corroborating R. P. Carvalho et al. (2015) and Bonetti et al. (2023). It also reiterates that the water content at the time of grazing was low throughout the period, resulting in the higher load bearing capacity of the soil (Flores et al., 2007; Severiano et al., 2011; M. S. Dias et al., 2019).

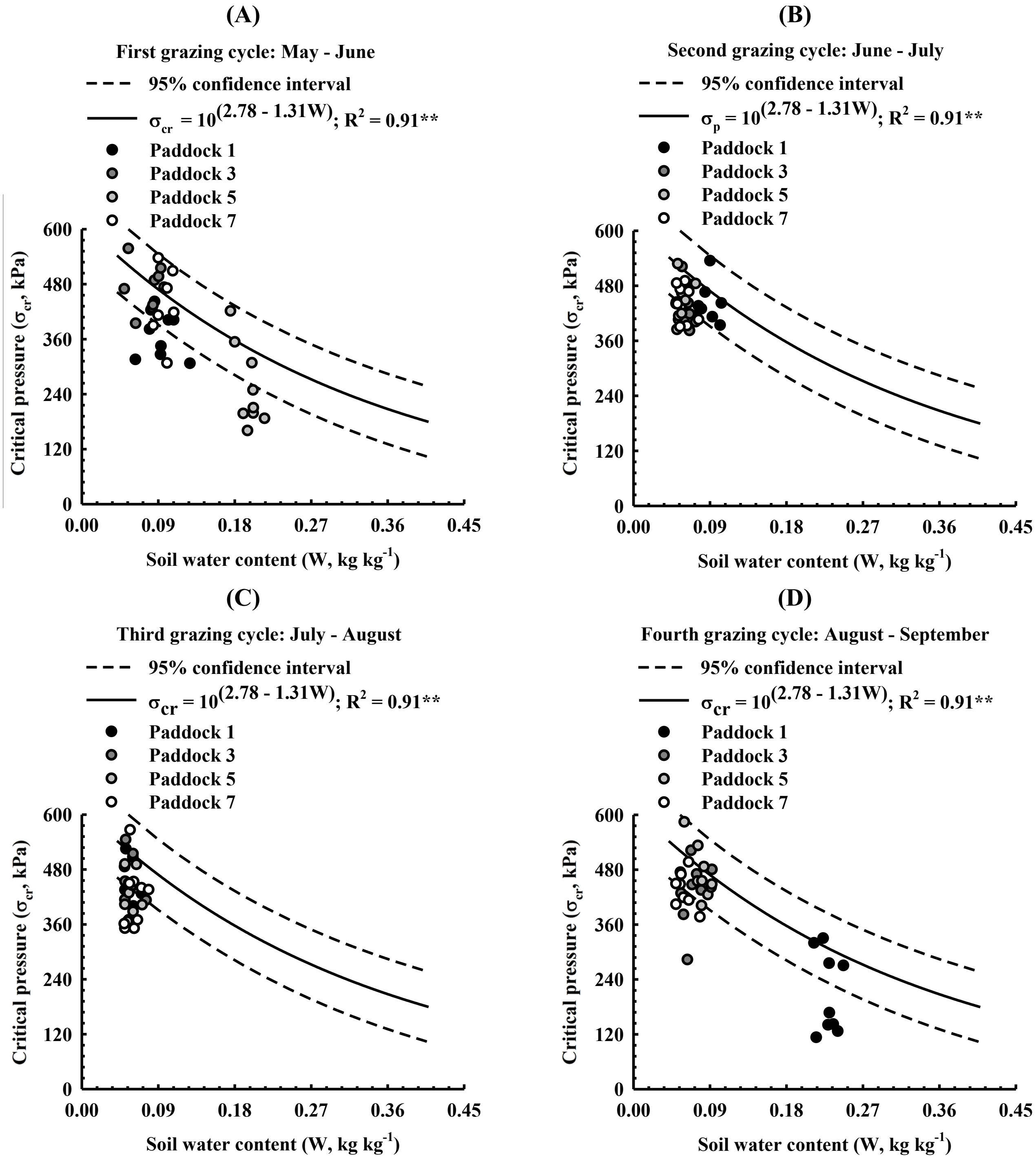

Figure 5. Soil bearing capacity model for detrimental compaction [critical pressure (σcr) as a function of soil water content (W)] and pressure values (σ) obtained after bovine grazing on a Latossolo Vermelho Distrófico típico in Rio Verde, state of Goias, Brazil, under crop-livestock integration system.

For the criterion of harmful compaction, it is observed the absence of pressure values in the region limiting the edaphic functions of the soil (Table 4) and demonstrating the agro-environmental sustainability of the livestock phase with grazing carried out in the off-season of grain farming, and not being this factor responsible for the spread of soil compaction. In the agricultural phase, in turn, the period when the rainy season is concentrated, intense machinery traffic occurs for agricultural operations, also coinciding with the time of greater susceptibility of soils to compaction (Severiano et al., 2013; Braga et al., 2015; P. C. F. Carvalho et al., 2018). Thus, the definition of management strategies associated with the load-bearing capacity of the soil can become the basis of sustainable tropical agriculture, assisting in decision-making around land use.

Table 4
Classification of the samples, in percentage, according to each region presented in Figure 5, after animal grazing in the different cycles, in a Latossolo Vermelho Distrófico típico

Percentage of soil samples with σ in the region	Compaction (%)				
	1st cycle	2nd cycle	3rd cycle	4th cycle	Total
a – Limiting to edaphic functions	0	0	0	0	0
b – No critical compaction	60	60	54	67	60
c – No compaction	40	40	46	33	40
Total samples	36	36	36	36	144

Thus, the evaluation of animal-soil interaction in crop-livestock integration systems by means of compressibility allows modeling and understanding the processes of additional and critical compaction, proving to be a careful and effective analysis in quantifying the impact of animal trampling on soil structure.

Conclusions

The results showed that only the first cycle of grazing presented additional compaction and in only 14.59% of the samples. There was no critical compaction in the evaluated area.

The animal trampling in conditions studied is not responsible for the dissemination of structural soil degradation in crop-livestock integration systems and may even contribute to the physical improvement resulting from the biological soil loosening.

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