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Reginaldo Barboza Da Silva

reginaldo.barboza@unesp.br

Sao Paulo State University Julio de Mesquita Filho: Universidade Estadual Paulista Julio de Mesquita Filho

Rodrigo Batista Pinto

Francisca Alcivania de Melo Silva

Rafael Duarte L'Abbate

Pedro Henrique de Oliveira Vilela

Guilherme Souza Florêncio

Heitor Marcel da Silva Ribeiro

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Buffalo Grazing Effects on the Physical–Mechanical Quality and Load-Bearing Capacity of Hydromorphic Riparian Soils in the Brazilian Atlantic Forest

Reginaldo Barboza da Silvab^{c*}, Rodrigo Batista Pinto^a, Francisca Alcivania de Melo Silva^b, Rafael Duarte L'Abbate^b, Pedro Henrique de Oliveira Vilela^b, Guilherme Souza Florêncio^b, Heitor Marcel da Silva Ribeiro^b

^aSão Paulo State University (UNESP), School of Agricultural and Veterinary Sciences, Jaboticabal, Via de Acesso Prof. Paulo Donato Castellane s/n, Jaboticabal, SP 14884-900, Brazil

^bSão Paulo State University (UNESP), School of Agricultural Sciences, Registro, Department of Agronomy and Natural Resources, Registro, São Paulo, Brazil

^cInstitute for Advance Studies of the Sea (IEAMAR), São Paulo State University, UNESP, São Vicente, SP, Brazil

***Corresponding Author:** reginaldo.barboza@unesp.br

Email: rodrigo.pinto@unesp.br; alcivania.silva@unesp.br; duarte.labbate@unesp.br; pedro.vilela@unesp.br; g.florencio@unesp.br; heitor.marcel@unesp.br

Abstract

Background and Aims: Buffalo production is an economically relevant alternative in Brazilian livestock systems, particularly in São Paulo State. However, intensifying this activity in hydromorphic soils of Atlantic Forest floodplains may accelerate compaction and structural degradation. This study evaluated the impact of semi-extensive grazing (SEG), intensive grazing for 20 years (IG20), and intensive grazing for 1 year (IG1), compared with native vegetation (NV), on soil erodibility, laboratory penetration resistance (LPR), load-bearing capacity (LBC), and compressibility in hydromorphic soils.

Methods: Soil samples were collected from four land-use systems at 0.0–0.2 and 0.2–0.4 m depths. Soil erodibility was determined using the K factor of the Universal Soil Loss Equation. LPR was evaluated under two soil water contents, while LBC and compressibility were assessed through uniaxial compression tests under five moisture conditions. Data were analyzed by analysis of variance and Scott-Knott test ($p < 0.05$), and precompression stress was evaluated by regression as a function of soil moisture.

Results: Soil erodibility varied among systems and depths, with IG20 showing the highest values and being the only treatment classified as highly erodible in the subsurface layer. LPR increased under drier conditions, whereas LBC decreased with increasing soil moisture. NV showed the highest LBC, while IG20 exhibited greater sensitivity to moisture changes and increased structural vulnerability.

Conclusion: Soil moisture strongly controls the mechanical behavior of hydromorphic soils, while grazing management influences their susceptibility to compaction and erosion. Combining physical-mechanical indicators with erodibility assessments can support sustainable management of floodplain environments.

Keywords: Soil physical-mechanical quality, Animal trampling, Soil compaction, Hydromorphic soils, Wetland soils

Introduction

Agricultural production faces increasing challenges related to sustainability and efficiency. In this context, buffalo farming (*Bubalus bubalis*) has emerged as a promising alternative, mainly due to the species' high adaptability to diverse environmental conditions (Marques et al., 2020). Currently, the state of São Paulo hosts the third largest buffalo herd in Brazil, with approximately 122,766 animals (IBGE, 2023). In the Ribeira Valley region, livestock production has expanded rapidly, favored by suitable soil and climatic conditions (Magalhães et al., 2023).

However, intensive animal trampling under these conditions can lead to significant soil degradation. Studies have shown that trampling reduces water infiltration (Castellano & Valone, 2007; Pulido et al., 2018) and increases surface runoff and erosion (Gizicki et al., 2018). These changes in soil physical properties can compromise nutrient storage and distribution, directly affecting pasture productivity (Allington & Valone, 2014; Pulido et al., 2018).

Animal traffic under high soil moisture conditions, particularly when soils are near saturation (Dias Junior & Pierce, 1996; Novais & Smyth, 1999; Imhoff et al., 2001; Silva et al., 2002; Chamen et al., 2003), is considered one of the main drivers of soil structural degradation, leading to reduced productive potential. This process is closely associated with soil compaction (Hu et al., 2021) and excessive compressibility, particularly during the rainy season, when soil pores are near saturation and the soil becomes more susceptible to structural damage (Silva et al., 2022).

Animal trampling under high-moisture conditions promotes soil compaction, resulting in increased bulk density and penetration resistance, as well as reduced porosity (Shaheb, Venkatesh & Shearer, 2021). These changes restrict root growth and nutrient uptake (Das et al., 2023), decrease soil water storage capacity (Ngo-Cong et al., 2021), and impair soil aeration and gas exchange (Umaru et al., 2021).

In this context, the evaluation of soil load-bearing capacity (LBC), defined as the soil's resistance to stresses imposed by animal and machinery traffic (Chamen et al., 2003; de Souza et al., 2024), is essential for understanding how different land uses affect soil

structure (de Moraes et al., 2019; de Souza et al., 2024). The LBC is based on the precompression stress, which represents the threshold between elastic and plastic deformation. Stresses below this limit cause reversible deformation, whereas stresses exceeding it result in permanent structural damage, indicating a higher susceptibility to compaction (Horn et al., 1995; Horn & Fleige, 2003; Silva et al., 2009).

Thus, assessing soil load-bearing capacity is a key tool for determining whether soils are being subjected to stresses close to or exceeding their structural resistance, allowing the prediction of degradation risks associated with land use and management practices (de Souza et al., 2024). In pasture systems, LBC indicators have been widely applied to support decisions regarding stocking rate and grazing timing, particularly under varying soil moisture conditions, contributing to the mitigation of compaction and physical degradation risks (Pinto et al., 2025; Janssen et al., 2023). Furthermore, knowledge of stress history and soil mechanical behavior enables anticipation of cumulative compaction effects, helping to preserve soil structure and promote long-term sustainability of production systems (Silva et al., 2003).

Buffalo production involves large-bodied animals, with reported body masses typically ranging from approximately 300 to over 1,000 kg, with average values between 400 and 800 kg depending on the population studied (Paján-Jiménez et al., 2023). Soil contact pressure depends on animal mass and hoof contact area, and measurements in cattle indicate static pressures of 160–190 kPa, with dynamic peaks reaching approximately 300 kPa during movement. These pressure levels are sufficient to increase soil bulk density, raise penetration resistance, and reduce macroporosity (Hamza & Anderson, 2005; Pinto et al., 2025). Experimental and review studies consistently demonstrate that animal trampling primarily affects surface soil properties—such as bulk density, penetration resistance, porosity, and hydraulic conductivity—and that these effects are intensified under high soil moisture conditions. Therefore, combining animal mass and contact pressure data with measurements of soil bulk density, penetration resistance, saturated hydraulic conductivity, aggregate stability, and precompression stress is essential for quantifying impacts and establishing sustainable management thresholds (Pietola et al., 2005).

Given the high mechanical stresses potentially imposed on soil by buffalo trampling and their strong interaction with soil water conditions typical of hydromorphic environments, this study aimed to assess the effects of different buffalo grazing systems

on the structural degradation of hydromorphic soils in southern São Paulo State, Brazil. The assessment was based on the determination of soil compressibility parameters - preconsolidation pressure (σ_p) and compression index (m) - and on the analysis of their influence on soil load-bearing capacity (LBC), as indicators of the soil mechanical response to grazing-induced stress.

The following hypotheses were tested: (i) buffalo trampling induces significant changes in the structural organization of hydromorphic soils, leading to a reduction in load-bearing capacity when compared with native vegetation; and (ii) load-bearing capacity models are sensitive to grazing-induced structural changes, allowing the discrimination of the impact magnitude associated with different grazing intensities and management systems on soil susceptibility to compaction.

Materials and methods

Study Area and Site Characterization

The study was conducted at Estaleiro Farm (24°34'16.1" S, 47°40'51.2" W; approximately 6 m a.s.l.), located in the municipality of Registro, São Paulo State, Brazil (Fig. 1a). The property covers an area of approximately 1,500 ha and maintains a buffalo herd of about 700 animals. The predominant soils in the study area are classified as Dystric Gleysols (Fig. 1b), characterized by poor to imperfect drainage and a predominance of flat relief conditions (WRB/FAO, 2014; dos Santos et al., 2018).

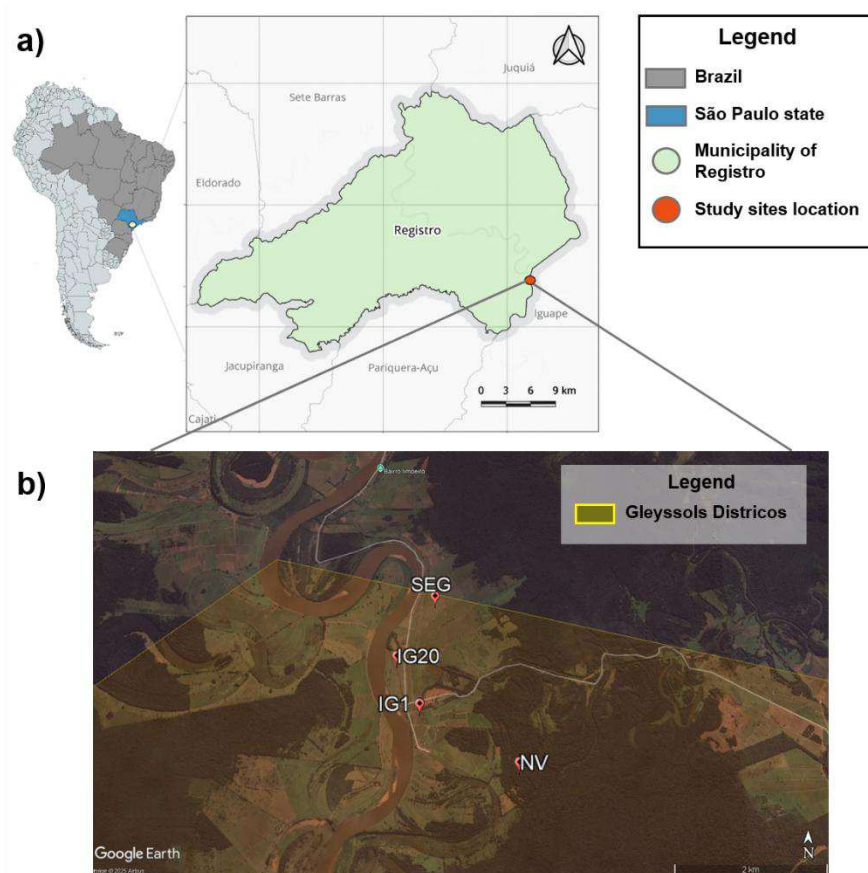


Fig. 1. (a) Location of the study area in the municipality of Registro, São Paulo State, Brazil. (b) Spatial distribution of the evaluated land-use systems (NV, native vegetation; SEG, semi-extensive grazing; IG20, intensive grazing for 20 years; and IG1, intensive grazing for 1 year) within an area classified as Dystric Gleysol.

The regional climate is classified as humid subtropical (Cfa) according to Köppen's classification (Alvares et al., 2013), with a mean annual precipitation of 1,450 mm and an average air temperature of 21.5 °C (Fig. 2).

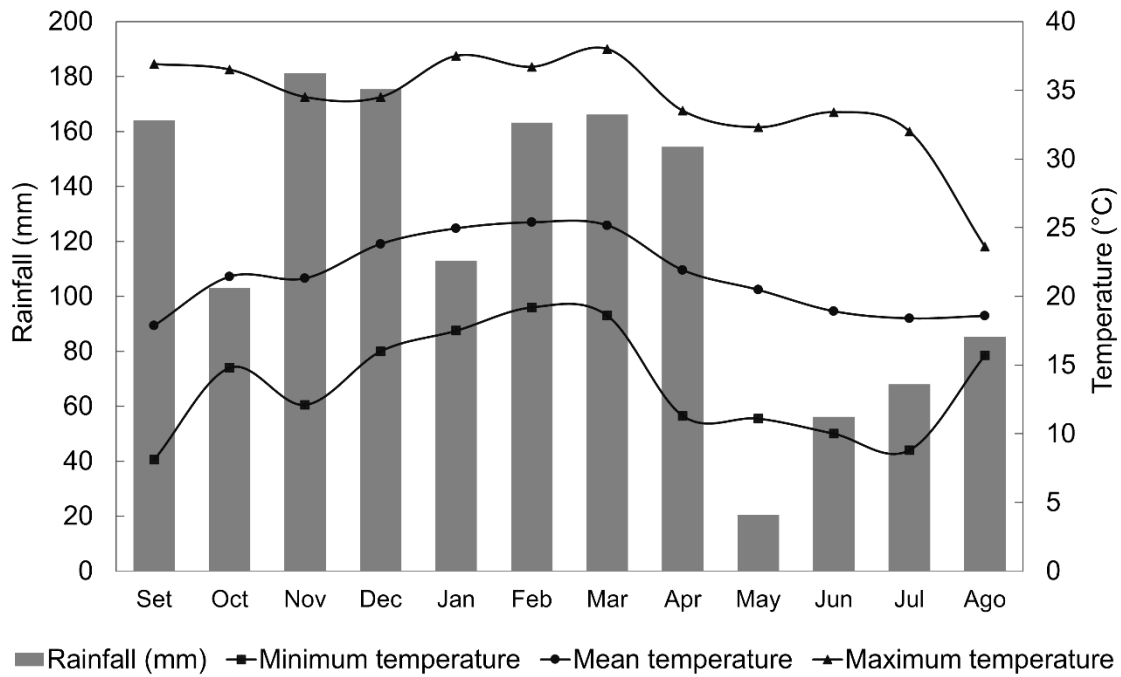


Fig. 2. Meteorological information from Registro (SP) referring to the year 2023, based on information provided by INMET (National Institute of Meteorology, Brazil, <https://portal.inmet.gov.br/>).

Treatments and sample collection

The evaluated land-use systems were selected to represent the range of management practices commonly adopted in the region, differing in both grazing intensity and time since conversion from native vegetation. The following systems were considered: (i) a remnant fragment of Atlantic Forest, used as a reference area due to the absence of grazing history (NV); (ii) an area managed under a semi-extensive grazing system for approximately 30 years (SEG); (iii) an area subjected to intensive grazing for about 20 years (IG20); and (iv) an area recently converted to intensive grazing, with approximately one year of use (IG1).

Soil physical and hydraulic properties were evaluated at depths of 0.0–0.20 m and 0.20–0.40 m. Table 1 summarizes the general characteristics and land-use history of each area, while Table 2 presents the main physical and chemical soil properties associated with each management scenario.

Soil sampling

In each land-use system, three sampling locations were selected, where soil samples were collected in triplicate from the surface (0.0-0.20 m) and subsurface (0.20-0.40 m) layers. In each plot, a trench approximately 1.0 x 0.7 x 0.4 m (length x width x depth) was excavated to allow soil sampling (Fig. 3).

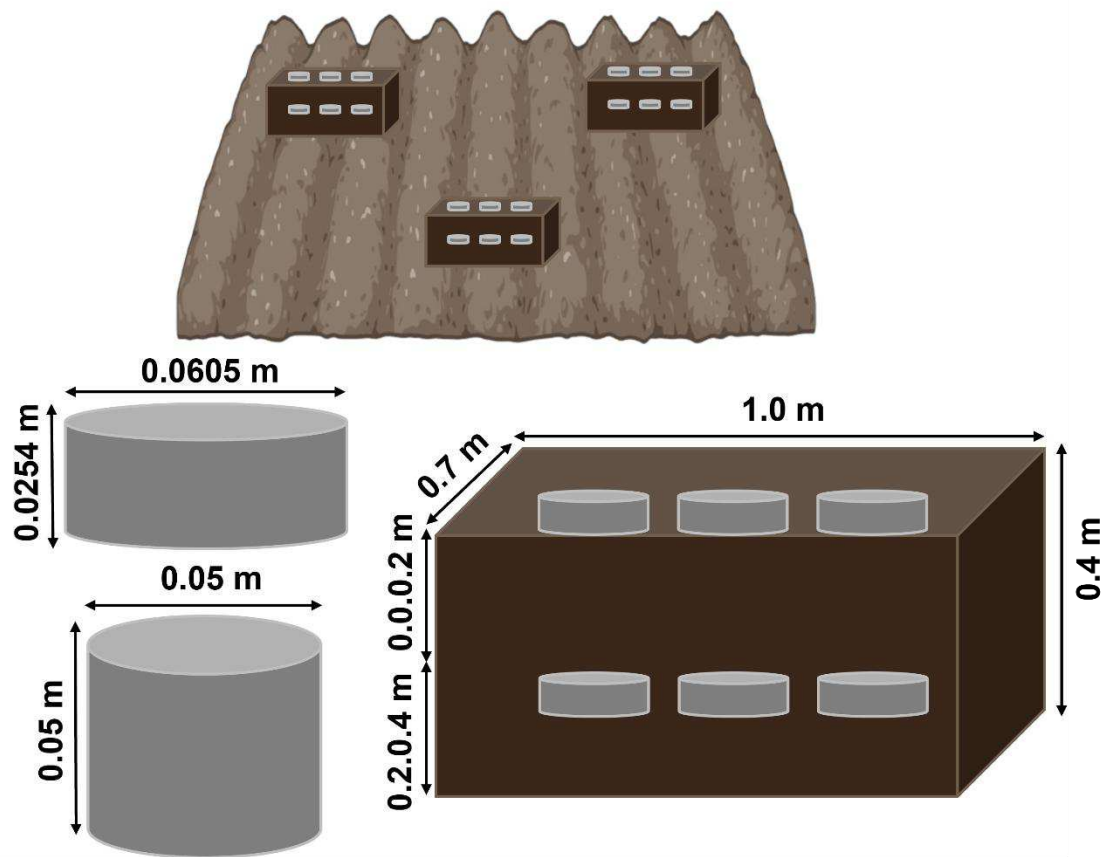


Fig. 3. Volumetric rings used for collecting soil monoliths and excavated trenches for sampling, with their dimensions indicated.

The sampling strategy varied according to the type of analysis performed. For laboratory tests and determination of soil penetration resistance under two moisture conditions, undisturbed soil cores were collected using volumetric rings with 0.05 m diameter and 0.05 m height. For the compressibility tests, undisturbed samples were obtained using rings with 0.0605 m diameter and 0.0254 m height. A Huland-type soil sampler was adapted to allow extraction of the cylinders with minimal disturbance, ensuring sample integrity.

In the field, the undisturbed samples were carefully wrapped with plastic film and transported to the laboratory. The soil erodibility (K) were determined using disturbed

soil samples (air-dried fine earth - ADFE), collected with a Dutch auger and/or shovel at each defined soil depth.

Structural Stability, Erodibility, and Soil Mechanical Analyses

Soil erodibility (K factor of the Universal Soil Loss Equation - USLE) was used as an indicator of soil susceptibility to erosion and was determined using the equation proposed by Wischmeier et al. (1971):

$$K = \frac{[2.1 \times 10^{-4} (12 - MO) M^{1.14} + 3.25(E - 2) + 2.5 (Pe - 3)]}{100} \times 0.1317 \quad (1)$$

Where: MO: is the organic matter content; M: represents the soil texture (% silt + % very fine sand) (100 - % clay); E: soil structure class; Pe: permeability coefficient.

Soil Penetration Resistance

Undisturbed soil cores were equilibrated to two gravimetric water contents: θ_1 (0.58 kg kg⁻¹) and θ_2 (0.30 kg kg⁻¹), and subsequently subjected to laboratory soil penetration resistance (LPR) tests using a bench electronic penetrometer. A total of 72 undisturbed soil cores were collected across the four land-use systems and two soil layers. For each soil core, penetration resistance was measured at three different positions, and the mean value was used for statistical analyses. The equipment used was a MA 933 penetrometer (Marconi, São Paulo, Brazil). The test consisted of inserting a conical needle (4 mm diameter, 30° apex angle) vertically into the soil at a constant penetration rate of 0.04 mm s⁻¹.

Load-Bearing Capacity and Soil Compressibility

Soil load-bearing capacity (LBC) was estimated based on precompression stress (σ_p) as a function of five soil water contents. The compressibility parameters, including σ_p and the compression index (m), were obtained from soil compression curves generated through uniaxial compression tests.

The experimental procedure comprised four steps: (i) collection of undisturbed soil cores; (ii) adjustment of soil moisture and execution of uniaxial compression tests; (iii) estimation of σ_p and m; and (iv) model fitting and determination of LBC.

Methodological details and theoretical assumptions follow those described by Taylor (1948), Dias Junior (1994), Silva (2003), Silva et al. (2007), and Silva et al. (2009).

For compressibility testing, samples were initially saturated by capillarity using distilled water and, after approximately 48 h, transferred to a pressure plate apparatus. This procedure allowed the establishment of five soil moisture levels, representing conditions from unsaturated to near-saturated states.

Following recommendations by Dias Junior (1994), Kondo (1998), and Silva (2002), each soil core was tested at five moisture levels. For each moisture condition, four replicates were used ($n = 4$). Considering four land-use systems and two soil depths, a total of 160 uniaxial compression tests were performed. Each compression model was therefore based on 20 soil samples.

Uniaxial Compression Testing and Model Adjustment

Uniaxial compression tests were conducted using an automated consolidometer with human-machine interface (model CNTA-IHM/BR-001/07), developed by Silva et al. (2015). Applied vertical stresses were 25, 50, 100, 200, 400, 800, and 1600 kPa, following the procedure proposed by Taylor (1948), which limits deformation to a maximum of 90% at each load level. The system allowed automatic control of loading time, applied pressure, and maximum deformation (Silva et al., 2007).

Compression data were processed using CA LINKER software (Silva & Masquetto, 2007), generating soil compression curves expressed as bulk density versus the logarithm of applied stress. Precompression stress (σ_p) was determined based on the M1 and M3 methods proposed by Dias Junior and Pierce (1996), which recommend evaluating samples equilibrated at matric potentials below and above 100 kPa, respectively.

The compression index (m) was calculated as the slope of the virgin compression line (Bradford & Gupta, 2002). Higher values of m indicate greater soil susceptibility to compaction.

Finally, soil load-bearing capacity models were obtained by fitting σ_p as a function of volumetric water content (θ) using the equation: $\sigma_p = 10^{(a + b\theta)}$ as proposed by Dias Junior (1994). Homogeneity tests of the fitted equations for each soil layer were performed according to Snedecor and Cochran (1989).

Determination of contact pressure

The static hoof contact pressure (CP) exerted by the animals on the soil surface was calculated as the ratio between the average body weight of the animals (F) and the hoof–soil contact area (AC), using the equation adapted from Souza et al. (2015):

$$CP = \frac{F}{AC} \quad (2)$$

where CP is the contact pressure (kgf cm⁻²), F is the applied force (kgf), and AC is the hoof contact area with the soil surface (cm²).

The force applied by buffalo trampling was determined based on the average body mass of the animals (n = 150 females), which was 550 kgf. Two scenarios of hoof-soil contact were considered (Fig. 4a-b): (i) maximum contact pressure, corresponding to the actual contact area observed immediately after hoof impact; and (ii) mean contact pressure, corresponding to an average contact area representative of typical animal movement. In the first scenario, a contact pressure of 204 kPa was obtained for a contact area of 66 cm² (Fig. 4a). In the second scenario, the estimated contact pressure was 124.85 kPa for a contact area of 108 cm² (Fig. 4b).

The hoof contact area was obtained from footprints impressed on the soil and quantified using ImageJ software (National Institutes of Health – NIH, Maryland, USA). Three photographs were taken perpendicular to the soil surface, using an object of known dimensions as a reference to establish scale (Fig. 4c). In ImageJ, a reference line was drawn over the known distance to calibrate the image, after which the hoof imprint was manually outlined using the freehand selection tool to calculate the contact area.

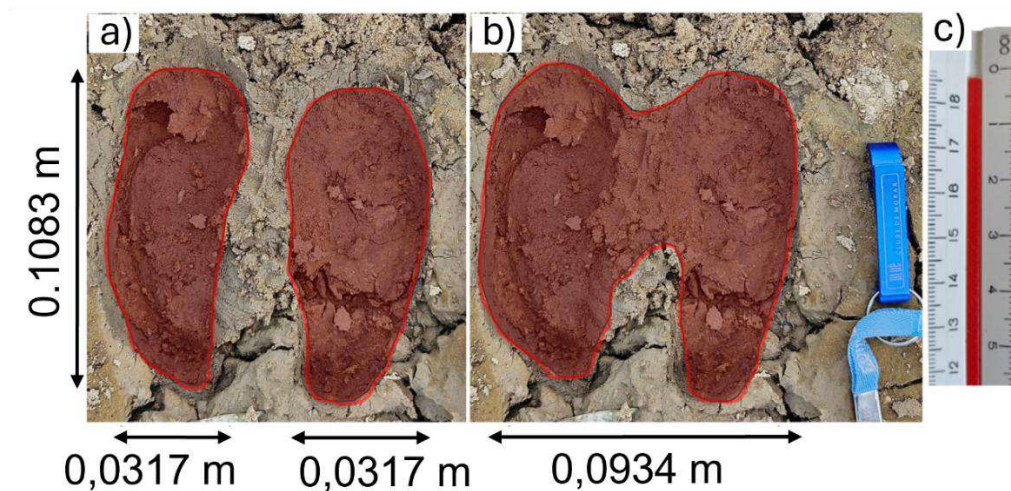


Fig. 4. Buffalo footprint on the ground for calculating average contact area. (a) average footprint with a contact area of 66 cm²; (b) average footprint with an area of 108 cm²; (c) measurement of the reference object.

Statistical analysis of the data

Data were initially subjected to verification of statistical assumptions, with normality assessed using the Shapiro-Wilk test ($p \leq 0.05$). Once the assumptions of normality and homogeneity of variances were met, analysis of variance (ANOVA) was performed to evaluate the effects of land-use systems and soil layers. When the F-test indicated significant effects ($p < 0.05$), means were grouped using the Scott-Knott test at the same significance level.

Uniaxial compression data were analyzed by regression, with exponential models of precompression stress as a function of soil moisture being linearized to allow comparison and grouping of statistically similar models. Based on the fitted models, soil load-bearing capacity was estimated for different soil consistency conditions.

All statistical analyses were performed using R software (version 4.3.2; R Core Team, 2023). Graphical representations were generated using SigmaPlot for Windows, version 11 (demo).

Results

Soil Erodibility

Soil erodibility (K factor), estimated using the equation proposed by Wischmeier and Smith (1978), varied significantly among land-use systems and soil depths (Fig. 5). In the surface layer (0.0-0.2 m), the NV and SEG scenarios exhibited erodibility values classified as low and moderate, respectively, whereas IG20 and IG1 were classified as moderate. In this layer, K values ranged from 0.010 to 0.020 t ha h ha⁻¹ MJ⁻¹ mm⁻¹.

In the subsurface layer (0.2–0.4 m), erodibility values ranged from 0.018 to 0.051 t ha h ha⁻¹ MJ⁻¹ mm⁻¹. The IG20 scenario showed the highest erodibility values, classified as high, and differed significantly from the other land-use systems, which remained within the moderate class.

When comparing soil layers within each land-use system, a significant difference was observed for IG20, in which the 0.2-0.4 m layer showed higher erodibility than the surface layer ($p < 0.05$). A similar pattern was observed for NV and IG1, although with

lower magnitude. In contrast, no significant differences between layers were observed in the SEG system.

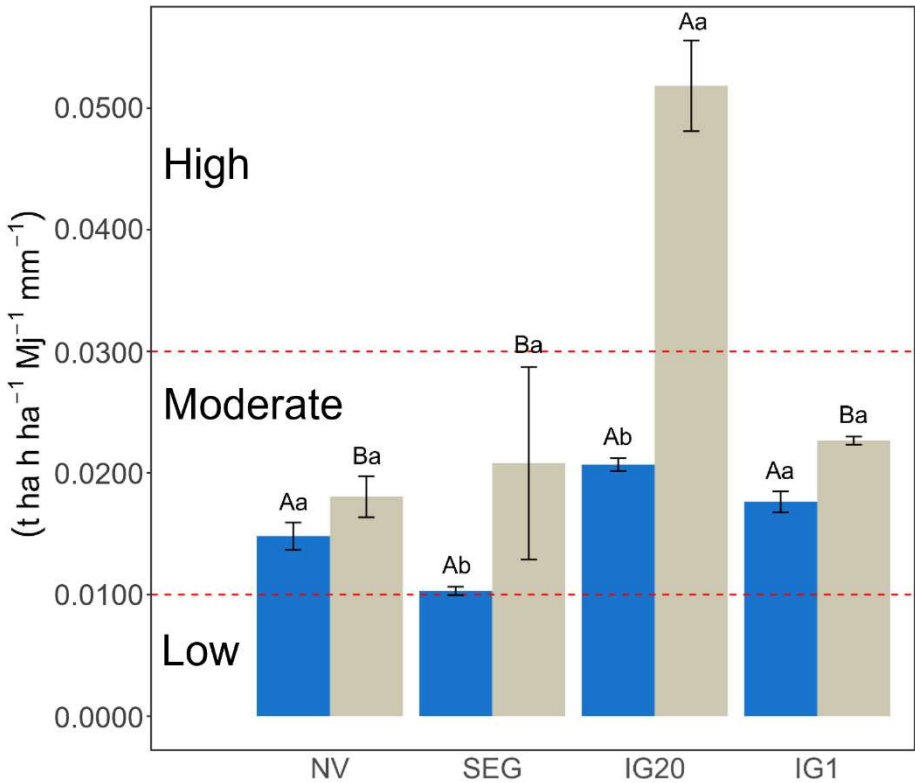


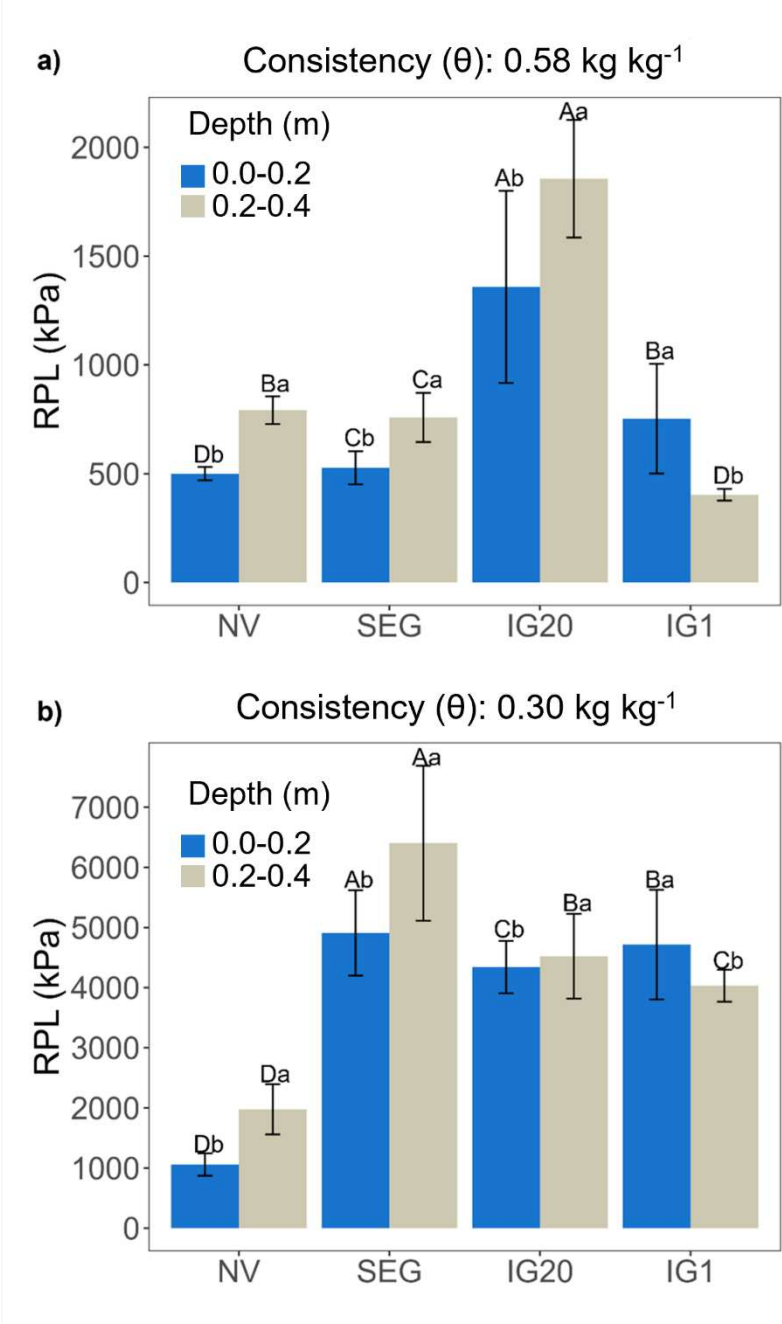
Fig. 5. Soil erodibility estimate (K factor of the universal soil loss equation - USLE) for scenarios under NV, SEG, IG20 and IG1 in the 0.0-0.2 and 0.2-0.4 m layers. Dashed red lines represent the erodibility classes (<0.010 = Low; 0.010-0.030 = Moderate; >0.030 = High) suggested by Foster (1981). Lowercase letters compare ($p < 0.05$) soil layers. Uppercase letters compare ($p < 0.05$) land uses. Error bars represent the standard error of the mean ($n=3$).

Soil resistance to penetration measured in the laboratory (RPL)

Laboratory soil penetration resistance (RPL) varied according to soil moisture and depth (Fig. 6). At a water content of 0.58 kg kg⁻¹ (Fig. 6a), most land-use systems exhibited higher RPL values in the subsurface layer compared with the surface layer, except for NV, which showed greater resistance in the surface layer. Under this moisture condition, the highest RPL value was recorded in IG1 (1,856 kPa) in the surface layer, whereas the lowest value occurred in NV at the same depth.

At a lower soil moisture (30 kg kg⁻¹; Fig. 6b), RPL values remained generally higher in the subsurface layer, except in IG20, which exhibited greater resistance in the

surface layer. The highest RPL value (6,403.17 kPa) was observed in the SEG system at 0.0-0.2 m, while the lowest value (1,058.79 kPa) again occurred in NV.



300

301 **Fig. 6.** Soil resistance to penetration measured in the laboratory (RPL), for the different
302 scenarios, in the 0.0-0.2 m and 0.2-0.4 m layers as a function of consistencies: 0.58 kg
303 kg⁻¹ (a) and 0.38 kg kg⁻¹ (n=496).

304 Overall, RPL showed a clear dependence on soil moisture. At lower moisture
305 content (0.30 kg kg⁻¹), most systems exhibited greater resistance, particularly in the
306 subsurface layer, except for IG1. Under higher moisture conditions (0.58 kg kg⁻¹), soil

resistance decreased, with IG1 showing the highest and NV the lowest resistance in the surface layer. In the subsurface layer, IG20 exhibited the greatest resistance, whereas NV showed the lowest values.

The marked increase in RPL under lower soil moisture conditions reflects the strong influence of water content on soil mechanical behavior. As soil water decreases, capillary forces and particle cohesion increase, resulting in greater resistance to penetration. The consistently lower RPL values observed under native vegetation indicate better structural conditions and lower soil compaction, whereas the higher values found in grazed systems suggest that animal trampling contributed to soil densification. Under the drier condition (0.30 kg kg^{-1}), several treatments exhibited RPL values above 2,000 kPa, a threshold commonly associated with restrictions to root growth, indicating potential limitations for plant development in compacted areas.

Soil Load-Bearing Capacity

To evaluate structural changes induced by animal trampling, soil load-bearing capacity models were compared using the homogeneity test (Snedecor & Cochran, 1989). As shown in Table 3, no significant differences were observed between the NV and IG20 models in the subsurface layer, indicating similar load-bearing capacities under these conditions.

The load-bearing capacity models, expressed by precompression stress (σ_p), showed a consistent negative relationship with soil moisture in all land-use systems and depths (Fig. 7), with high coefficients of determination ($R^2 = 0.88\text{-}0.94$). In general, the subsurface layer exhibited higher σ_p values than the surface layer, indicating greater structural resistance and lower susceptibility to compaction.

Significant differences between soil layers were observed within all land-use systems ($p \leq 0.05$), demonstrating that management effects are more pronounced in the surface layer. This behavior was especially evident in grazed systems, where increasing soil moisture resulted in a marked reduction in load-bearing capacity.

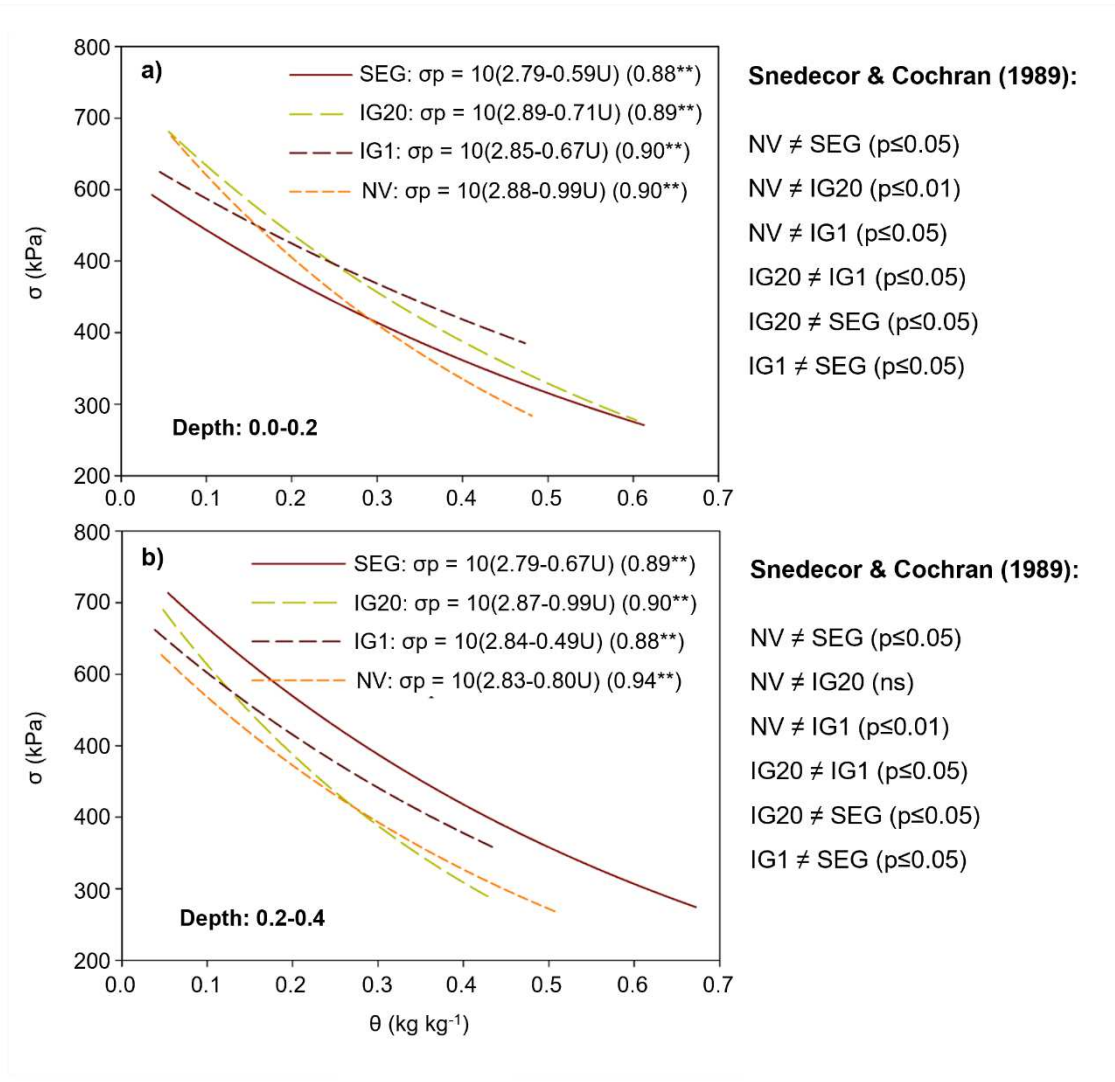
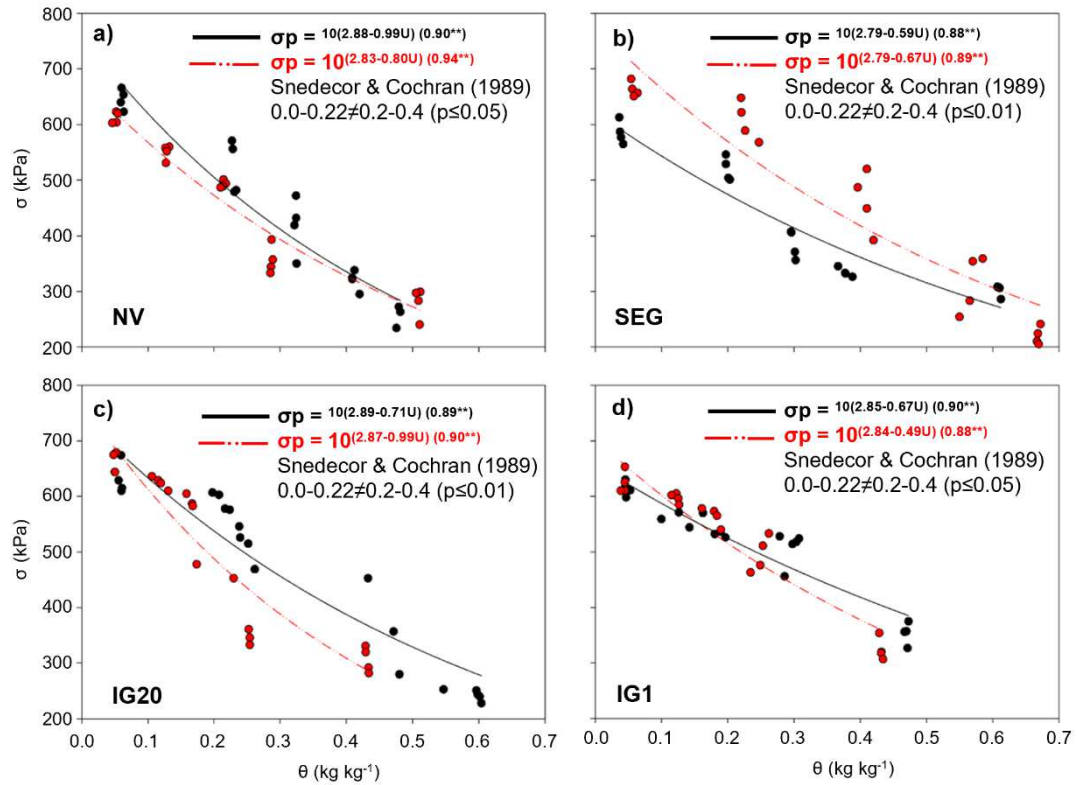


Fig. 7. Soil load-bearing capacity models, expressed as precompression stress (σ_p) as a function of soil water content (θ), for the surface (0.0–0.20 m) and subsurface (0.20–0.40 m) layers within each land-use system: (a) native vegetation (NV), (b) semi-extensive grazing (SEG), (c) intensive grazing for 20 years (IG20), and (d) intensive grazing for 1 year (IG1). Different curves represent the fitted load-bearing capacity models for each soil layer. Higher σ_p values indicate greater resistance to applied mechanical loads and lower susceptibility to compaction.

Similarly, when analyzed by land use (Fig. 8), σ_p decreased with increasing soil moisture in all systems. Native vegetation consistently exhibited the highest σ_p values across the moisture range, while grazed systems (SEG, IG20, and IG1) showed progressive reductions in load-bearing capacity, particularly under wetter conditions. In all cases, the surface layer exhibited lower σ_p values than the subsurface layer, confirming greater vulnerability to trampling-induced compaction.



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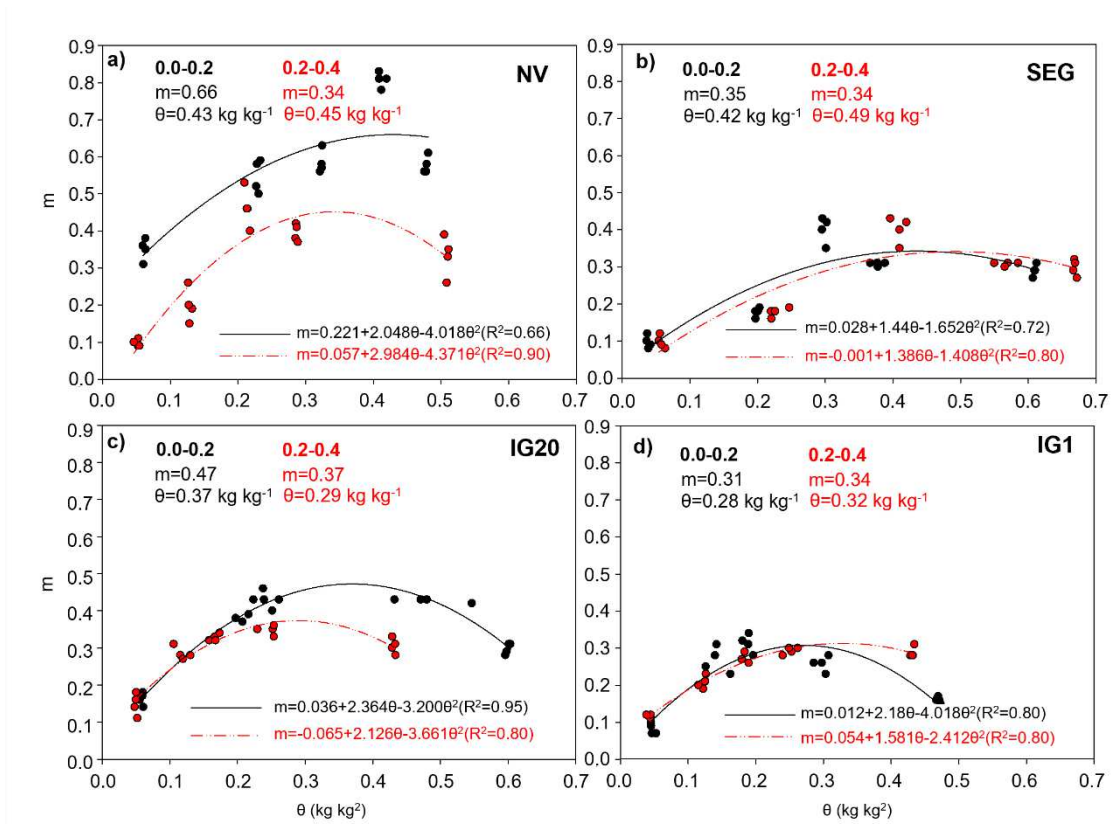
349 **Fig. 8.** Soil load-bearing capacity models, expressed as precompression stress (σ_p) as a
 350 function of soil water content (θ), for the evaluated land-use systems: (a) native vegetation
 351 (NV), (b) semi-extensive grazing (SEG), (c) intensive grazing for 20 years (IG20), and
 352 (d) intensive grazing for 1 year (IG1). Black symbols and fitted curves represent the
 353 surface layer (0.0–0.20 m), whereas red symbols and fitted curves represent the
 354 subsurface layer (0.20–0.40 m). Higher σ_p values indicate greater soil load-bearing
 355 capacity and lower susceptibility to compaction.

356 Soil Compressibility

357 The compression index (m) varied as a function of land use, soil depth, and water
 358 content, with quadratic relationships observed between m and soil moisture ($R^2 = 0.66$ –
 359 0.95 ; Fig. 9). In all systems, higher m values were generally observed in the surface layer
 360 (0.0–0.2 m), indicating greater susceptibility to compression as soil moisture increased.

361 Native vegetation exhibited the highest m values, whereas the semi-extensive
 362 grazing system showed lower compressibility in both layers. The IG20 system showed
 363 pronounced sensitivity of the compression index to increasing soil moisture, highlighting
 364 its greater structural vulnerability. Overall, the results indicate that trampling combined

with elevated soil moisture substantially increases soil compressibility, particularly in the surface layer.



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Fig. 9. Compression index (m) as a function of soil water content (θ) for the evaluated land-use systems: (a) native vegetation (NV), (b) semi-extensive grazing (SEG), (c) intensive grazing for 20 years (IG20), and (d) intensive grazing for 1 year (IG1). Black symbols and fitted curves represent the surface layer (0.0–0.20 m), whereas red symbols and fitted curves represent the subsurface layer (0.20–0.40 m). Higher values of the compression index indicate greater soil susceptibility to deformation and compaction under applied loads.

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Discussion

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Soil erodibility is controlled by a combination of physical and chemical properties, including texture, organic matter content, aggregate stability, and permeability (Phinzi & Ngetar, 2019). The erodibility equation proposed by Wischmeier and Smith (1978) remains widely used for evaluating soil susceptibility to erosion and serves as a key tool in soil conservation studies. Recent research, including that of Lima et al. (2021) and Rehman et al. (2022), has demonstrated that inappropriate land-use practices substantially

increase soil erosion rates. Likewise, Cui et al. (2023) reported that soils with low organic matter content and high compaction exhibit greater erodibility, reinforcing the importance of conservation-oriented management strategies. Understanding these relationships is essential for guiding land-use policies aimed at reducing soil loss and enhancing ecosystem resilience.

In the present study, the IG20 scenario in the subsurface layer was classified as having high erodibility, whereas the remaining scenarios showed moderate erodibility, according to the classification proposed by Foster (1981). The greater susceptibility observed in IG20 can be attributed to its lower clay content, which plays a key role in soil aggregation and structural stability. Clay particles contribute to aggregate formation and cohesion, thereby increasing resistance to erosive forces (Bronick & Lal, 2005; Seben, Corá & Lal, 2016). Additionally, the reduced organic carbon content observed in this scenario likely intensified its vulnerability, as organic matter is essential for aggregate stabilization and soil structural resilience.

Soil penetration resistance was strongly influenced by soil moisture. When moisture content decreased from 0.58 to 0.30 kg kg⁻¹, a pronounced increase in penetration resistance was observed, highlighting the sensitivity of soil mechanical behavior to water availability. Similar patterns were reported by Arruda et al. (2021), who observed resistance values exceeding 2,000 kPa under dry conditions in Amazonian soils. In the present study, however, maximum values reached 6,403 kPa under grazing conditions, exceeding those reported by Soares et al. (2021) for pasture areas converted from native vegetation. These results emphasize the critical role of soil moisture in controlling mechanical resistance, while also indicating that management practices may intensify compaction effects.

The contrasting behavior observed between the two moisture conditions is explained by the role of water in soil mechanical resistance. At higher water contents, water acts as a lubricant between soil particles, reducing friction and facilitating probe penetration. As the soil dries, particle cohesion and friction increase, resulting in substantially higher penetration resistance. This explains the markedly higher RPL values observed at 0.30 kg kg⁻¹ compared with 0.58 kg kg⁻¹ across all land-use systems.

Although grazing management may have contributed to differences among land-use systems, the results indicate that soil moisture was the dominant factor controlling

penetration resistance. The substantial increase in RPL observed when water content decreased from 0.58 to 0.30 kg kg⁻¹ was considerably greater than the differences observed among management systems. Nevertheless, grazed areas generally exhibited higher resistance values than native vegetation, suggesting that animal trampling may have intensified soil densification, particularly under drier conditions. Livestock trampling is widely recognized as a major driver of soil compaction, leading to reduced porosity and impaired water infiltration (Furquim et al., 2020; Júnior et al., 2023).

In hydromorphic soils, periodic water saturation reduces soil strength and load-bearing capacity, making these environments particularly susceptible to structural degradation caused by mechanical stresses. Consequently, the effects of animal trampling may be more pronounced than in well-drained soils, accelerating degradation processes under both natural and anthropogenic pressures (Osorio-Acosta & Menezes, 2022).

As highlighted by Souza et al. (2021), disentangling the effects of soil moisture and management practices on penetration resistance is complex, as both factors interact strongly. Although the present study evaluated two contrasting moisture conditions, this range does not encompass the full variability encountered under field conditions. Therefore, further research incorporating a broader range of moisture levels is necessary, particularly in climatically variable regions such as the study area (Galvani, Lima & Alves, 2012). Future investigations should also consider additional land-use systems, such as banana monoculture, which is common in the region, to better elucidate the interactions between soil moisture, mechanical resistance, and land management.

Analysis of soil load-bearing capacity (LBC) curves revealed an inverse relationship between precompression stress (σ_p) and soil moisture, indicating greater resistance to applied loads under drier conditions. This behavior is consistent with findings reported by Gontijo et al. (2011) and Silveira et al. (2022), who observed increased σ_p values as soil moisture decreased.

Comparisons among land-use systems showed that IG20 and SEG exhibited higher load-bearing capacity in the surface and subsurface layers, respectively. This increased resistance may be attributed to prolonged exposure to mechanical stresses, which can induce structural rearrangement and soil densification over time. Similar conclusions were reported by Vasques et al. (2019), who found that long-term pasture use can increase soil load-bearing capacity compared with native vegetation.

Nevertheless, caution is warranted. Soares et al. (2021) demonstrated that soils under pasture, particularly in the Amazon biome, may become increasingly susceptible to compaction when applied stresses exceed their load-bearing capacity. Their findings also indicated that native forest soils tend to exhibit higher σ_p values in the surface layer under certain moisture conditions, reflecting greater structural resilience. These observations align with the present results, which showed higher resistance in native vegetation soils up to specific moisture thresholds.

Overall, the results demonstrate that grazing intensity and soil moisture jointly control the mechanical behavior of hydromorphic soils. Intensive grazing systems showed greater susceptibility to erosion and structural degradation, whereas native vegetation maintained superior physical quality and structural resilience. These findings highlight the importance of avoiding animal traffic under high-moisture conditions and of adopting grazing strategies that minimize mechanical stress on hydromorphic soils.

Conclusions

Buffalo grazing significantly affected the physical–mechanical quality of hydromorphic soils in riparian environments of the Atlantic Forest. Intensive grazing increased soil susceptibility to structural degradation, as evidenced by changes in precompression stress (σ_p), compression index (m), and soil load-bearing capacity (LBC), particularly under high soil moisture conditions.

Native vegetation maintained greater structural stability and lower susceptibility to degradation, whereas semi-extensive grazing promoted intermediate responses. Soil erodibility also increased with grazing intensity, with the IG20 system presenting the highest erodibility values, especially in the subsurface layer, indicating greater vulnerability to erosion following long-term intensive use.

The combined evaluation of soil mechanical properties and erodibility demonstrated that hydromorphic soils are highly sensitive to buffalo trampling, particularly when soil moisture is elevated. From a practical perspective, grazing management in these environments should avoid animal traffic under near-saturated soil conditions and adopt strategies that reduce trampling intensity, such as appropriate stocking rates and rotational grazing. These measures can help maintain soil structural quality and preserve the ecological functions of riparian ecosystems.

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Table 1: Description, grazing management, stocking rate, and land-use history of the areas evaluated in the experiment. Grazing intensity was characterized based on stocking rate (animal units per hectare, AU ha⁻¹), grazing frequency, and pasture management history, distinguishing semi-extensive grazing (SEG) from intensive grazing systems established for 20 years (IG20) and 1 year (IG1). NV = native vegetation; SEG = semi-extensive grazing; IG20 = 20-year intensive grazing; IG1 = 1-year intensive grazing; AU = animal unit.

Land use	Grazing duration (years)	Number of animals	⁽¹⁾ AU (ha ⁻¹)	Grazing frequency	Grass	Area (ha)	Distance to the river (m)	Description and background of the area
NV	N/A	N/A	N/A	N/A	N/A	4.68	1438.59	Preserved area belonging to a remnant of the Atlantic Forest, with no history of agricultural use.
SEG	30	300 buffaloes	21	Summer: 21 days in the paddock and return after 30 days. Winter: 7 days in the paddock with return after 21 days.	Tangola grass (hybrid of <i>Brachiaria mutica</i> and Angola grass) and Tanner grass (<i>Brachiaria arrecta</i>).	17.78	426.71	Semi-extensive grazing system, without recent pasture renewal.
IG20	20	140 Dairy buffalo cows	24	Summer: 5 days in the paddock and return after 15 days. Winter: 5 days in the paddock and return after 30 days.	Tangola grass (hybrid of <i>Brachiaria mutica</i> and Angola grass) and Tanner grass (<i>Brachiaria arrecta</i>).	8.95	227.71	Intensive grazing. The pasture was renewed about 4 years ago, with the incorporation of the same type of grass.
IG1	1	140 Dairy buffalo cows	24	Summer: 2 days in the paddock and return after 15 days. Winter: 1 day in the paddock and return after 25 days.	Papuã (<i>Brachiaria plantaginea</i>).	4.21	250.96	Intensive system, established in an area previously used for corn cultivation.

NV: native vegetation; SEG: semi-extensive grazing; IG20: 20-year intensive grazing; IG1: 1-year intensive grazing. ⁽¹⁾AU: animal unit.

Table 2: Means $\pm$ standard error of physical and chemical soil properties under the interactive effects between land use and soil layers. Uppercase letters compare significant differences between land uses, while lowercase letters indicate significant differences between soil layers, according to the Scott-Knott test ($p < 0.05$).

Land use	NV		SEG		IG20		IG1	
Depth (m)	0.0-0.2	0.2-0.4	0.0-0.2	0.2-0.4	0.0-0.2	0.2-0.4	0.0-0.2	0.2-0.4
pH (CaCl ₂)	4.6 $\pm$ 0.23	4.8 $\pm$ 0.11	4.0 $\pm$ 0.10	4.1 $\pm$ 0.10	4.2 $\pm$ 0.05	4.5 $\pm$ 0.11	4.7 $\pm$ 0.15	4.5 $\pm$ 0.05
P (mg kg ⁻¹)	22.4 $\pm$ 16.97	14.5 $\pm$ 9.36	9.4 $\pm$ 2.74	7.2 $\pm$ 1.11	18.9 $\pm$ 10.14	6.94 $\pm$ 0.41	10.3 $\pm$ 3.02	5.3 $\pm$ 1.15
Ca (cmolc kg ⁻¹)	2.2 $\pm$ 1.23	2.1 $\pm$ 0.34	0.6 $\pm$ 0.01	0.8 $\pm$ 0.03	1.5 $\pm$ 0.91	1.0 $\pm$ 0.12	1.8 $\pm$ 1.36	0.7 $\pm$ 0.15
K (cmolc kg ⁻¹)	0.11 $\pm$ 0.04	0.06 $\pm$ 0.01	0.18 $\pm$ 0.10	0.07 $\pm$ 0.02	0.34 $\pm$ 0.05	0.23 $\pm$ 0.12	0.09 $\pm$ 0.05	0.06 $\pm$ 0.01
H+Al (cmolc kg ⁻¹)	4.6 $\pm$ 1.98	3.3 $\pm$ 0.48	8.8 $\pm$ 1.19	7.7 $\pm$ 0.99	6.1 $\pm$ 1.30	3.5 $\pm$ 0.42	3.3 $\pm$ 0.21	3.4 $\pm$ 0.50
CEC (cmolc kg ⁻¹)	7.9 $\pm$ 3.62	6.6 $\pm$ 0.84	9.8 $\pm$ 1.15	8.8 $\pm$ 0.90	8.5 $\pm$ 2.24	5.2 $\pm$ 0.31	6.0 $\pm$ 1.72	4.7 $\pm$ 0.39
SB (cmolc kg ⁻¹)	3.3 $\pm$ 1.63	3.2 $\pm$ 0.34	0.9 $\pm$ 0.03	1.1 $\pm$ 0.09	2.4 $\pm$ 1.12	1.6 $\pm$ 0.32	2.6 $\pm$ 1.8	1.2 $\pm$ 0.19
V (%)	41.3 $\pm$ 1.52	50.0 $\pm$ 1.00	10.0 $\pm$ 1.00	12.3 $\pm$ 2.08	27.3 $\pm$ 7.37	32.3 $\pm$ 6.80	43.0 $\pm$ 22.51	27.0 $\pm$ 5.29
BD (Mg m ⁻³)	1.52 $\pm$ 0.02Da	1.57 $\pm$ 0.02Db	1.55 $\pm$ 0.04Aa	1.63 $\pm$ 0.03Ab	1.51 $\pm$ 0.02Ba	1.58 $\pm$ 0.02Bb	1.48 $\pm$ 0.02Ca	1.55 $\pm$ 0.02Cb
SOM (g kg ⁻¹)	48.33 $\pm$ 0.88Aa	43.33 $\pm$ 0.66Ab	25.00 $\pm$ 0.57Ca	21.00 $\pm$ 0.57Cb	31.33 $\pm$ 0.88Ba	22.33 $\pm$ 0.33Bb	25.66 $\pm$ 0.66Ca	20.33 $\pm$ 0.33Cb
TOC (%)	2.18 $\pm$ 0.00Ba	0.84 $\pm$ 0.00Bb	2.08 $\pm$ 0.00Aa	1.61 $\pm$ 0.00Ab	1.97 $\pm$ 0.01Ca	0.44 $\pm$ 0.00Db	1.67 $\pm$ 0.00Da	0.54 $\pm$ 0.00Cb

PD (%)	2.58±0.02Aa	2.64±0.02Aa	2.59±0.04Aa	2.55±0.02Aa	2.57±0.02Aa	2.58±0.02Aa	2.64±0.05Aa	2.61±0.04Aa
CDW (%)	9.66±3.91Ba	11.00±0.57Ba	22.83±4.33Aa	19.33±2.6Aa	14.33±1.33Ba	12.50±6.33Ba	27.33±1.16Aa	20.33±0.92Aa
FI (%)	80.84±6.90Aa	72.82±3.54Aa	36.43±2.92Ca	34.10±10.99Ca	77.95±2.46Aa	69.66±3.38Aa	60.81±1.95Ba	54.17±1.66Ba
Clay (%)	42.8±0.28	43.6±2.08	44.6±0.76	46.0±0.50	44.3±0.76	44.5±1.80	46.6±10.7	45.5±4.2
Silt (%)	37.3±0.95	37.6±0.70	42.3±0.59	42.4±1.11	38.7±1.21	38.1±2.07	37.7±5.95	36.6±6.25
Sand (%)	19.8±0.94	18.7±1.56	12.9±0.16	11.5±0.78	16.9±1.60	17.3±0.55	15.6±2.59	17.8±2.73
Soil textural class	Clay		Clay		Clay		Clay	

CEC: cation exchange capacity; SB: sum of bases; V: base saturation; BD: bulk density; TOC: total organic carbon; PD: particle density; CDW: clay dispersed in water; FI: flocculation index.

Table 3: Comparison of carrying capacity models for native vegetation (NV), semi-extensive grazing (SEG), 20-year intensive grazing (IG20) and 1-year intensive grazing (IG1), in soil depth ranges of 0.0-0.2 m and 0.2–0.4 m (Snedecor and Cochran (1986)).

Depth (m)	Land use	F	F-test	
			Regression intercept (a)	lope coefficient (b)
0.0-0.2	NV vs SEG	H	*	ns
	NV vs IG20	H	ns	**
	NV vs IG1	NH	*	*
	IG20 vs IG1	NH	ns	*
	IG20 vs SEG	H	ns	*
	IG1 vs SEG	H	*	ns
0.2-0.4	NV vs SEG	H	*	ns
	NV vs IG20	H	ns	ns
	NV, IG20 vs SEG	H	ns	*
	NV vs IG1	H	*	ns
	IG20 vs IG1	NH	ns	**
	IG20 vs SEG	H	*	ns
	IG1 vs SEG	H	*	ns

F: tests the homogeneity of variances; (1) George W. Snedecor and William G. Cochran (1986); (2) $\sigma_p = 10(a+b\theta)$; NH: non-homogeneous; H: homogeneous; *significant at the 1% probability level; **significant at the 5% probability level; ns: not significant. F: tests the homogeneity of variances; (1) George W. Snedecor and William G. Cochran (1986); (2) $\sigma_p = 10(a+b\theta)$; NH: non-homogeneous; H: homogeneous; *significant at the 1% probability level; **significant at the 5% probability level; ns: not significant.