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Response of Pasture Productivity and Soil Physical Properties to Compaction under Different Stocking Rates

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ABSTRACT

Aims: Understanding the interplay between cattle stocking rates, soil properties, and pasture productivity remains limited for tropical pastures, as most knowledge derives from temperate grasslands. This study investigated pasture productivity responses to soil compaction under moderate (MSR, 2.7 $AU.ha^{-1}.year^{-1}$) and heavy (HSR, 5 $AU.ha^{-1}.year^{-1}$) stocking rates in Malaysian tropical pasture.
Materials & Methods: A completely randomized design with paired grazed and ungrazed plots per treatment was employed. We assessed soil compaction via bulk density (BD), penetration resistance (PR), and infiltration rate, alongside pasture productivity (biomass, regrowth, and litter). Soil (0-15 cm depth) and plant (0.25 m^2 quadrats) were sampled at the end of four grazing periods in 2018.
Findings: Regrowth rate was 31% greater ($P < 0.05$) under MSR but unaffected ($P > 0.05$) by HSR. Litter was reduced by 51% (MSR) and 38% (HSR) compared to controls ($P < 0.05$). Mean PR increased by 10% (MSR) and 32% (HSR), while infiltration decreased by 74% under HSR. Pasture production was negatively correlated with BD (r = - 0.39 MSR, r = - 0.36 HSR) and PR (r = - 0.31 MSR, r = - 0.44 HSR). A positive relationship between soil moisture and HSR occurred only under HSR (r = 0.39, $P < 0.05$). No significant relationship was found between infiltration rate and either stocking rate.
Conclusion: Biomass production was closely related to soil physical variables in the heavy stocking, demonstrating compaction impacts are more pronounced at HSR. Maintaining a moderate stocking rate is recommended to sustain tropical pasture productivity and prevent soil degradation.

Keywords: Bulk Density; Grazing Intensity; Herbage Production; Infiltration Rate; Litter Production; Penetration Resistance; Regrowth Rate.

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Introduction

Humid tropical pastures and grasslands differ from those in temperate regions, which are defined by a dormant period produced by drought or freezing temperatures. This dormancy provides a period of rest where livestock are commonly removed from the grazing land in winter and fed preserved forage. Compacted soils can recover through physical processes, such as winter freeze-thaw cycles. This non-grazing period also provides adequate recovery time for forage plants to replenish root reserves [1]. Instead, humid tropical pastures have the natural potential to grow year-round, hence demanding year-round grazing management decisions. While soil compaction can recover through natural processes such as biological activity (e.g., earthworm burrowing and feeding, root penetration and decay) and wet-dry cycles, the absence of a dormant period means that overgrazing can persist continuously and soil degradation can accumulate without a distinct seasonal break for recovery [2]. These differences have direct implications for pasture management and production. Forage production can be consistently high, but it is always vulnerable to mismanagement. Although grazing is a significant activity in tropical pastures, knowledge of its effects is essential to understand its potential impacts and avoid detrimental effects; few studies have reported the effects of various stocking rates and grazing management strategies on pasture productivity and soil compaction [3]. Consequently, the impact of grazing management strategy on pasture productivity in the humid tropics does not follow the same processes as in temperate grasslands, from which most studies have been conducted [2]; hence, determining a sustainable stocking rate is a critical factor in tropical pastures.

Cattle can affect pasture productivity through three key activities, including treading (the physical pressure and soil disturbance caused by animal hooves), defoliation (the removal of plant shoots and leaves by grazing), and feces and urine excretion [4, 5]. However, the magnitude of the impact depends on several factors, such as stocking rate, animal type, grazing system, soil properties, and vegetation structure [4, 6, 7]. For instance, recent studies have demonstrated that varying grazing intensities directly alter soil physical properties and plant community composition [8], and these impacts are consistently mediated by local soil and climatic conditions [9]. Furthermore, the resulting soil compaction from excessive treading is a primary driver of reduced water infiltration and root growth, thereby limiting pasture productivity [10]. Cattle can increase soil compaction through excessive treading [11]. Soil compaction is defined as the compression of an unsaturated soil structure, resulting in a reduction in porosity. Soil compaction happens when the load of an animal imposed on unsaturated soil is greater than the load-bearing capacity of the soil. If imposed forces on soil due to animal treading exceed the soil's stability and strength, then compaction and changes in soil structure occur [12]. Cattle traffic and treading can change soil physical properties [11] by exerting significant force on the soil surface due to their large bodies and small hoof area. For example, an adult cow weighs ca. 350–600 kg and has a total hoof area of 60–90 cm^{-2}, exerting a static pressure of 200 kPa, or approximately 1.7 $kg.cm^{-2}$, in the hoof area [11]. Cattle traffic affects soil physical properties, including increased soil bulk density, decreased porosity, reduced soil aggregate size, and soil surface disturbance (e.g., chipping, churning, and breaking up of crusting) [13, 14]. For instance, the bulk density of continuously grazed plots was 1.22 $Mg.m^{-3}$ in the topsoil compared to 1.02 $Mg.m^{-3}$ in plots protected from grazing [13]. Cattle traffic can also influence the way water enters the soil (infiltration) and moves through the soil profile (percolation), thereby reducing infiltration rate and increasing potential runoff generation [6]. Illustrating this point, a study reported that cattle treading decreased the soil infiltration rate by 46% compared with undamaged areas [6].

Plant biomass plays a pivotal role in tropical pasture production and carbon storage capacity. Pasture condition and soil quality are interdependent, and pasture productivity is affected by the functioning of both soil and plant community [15]. The combined effects of soil compaction and grazing are commonly observed in a loss of pasture productivity [16]. In fact, excessive soil compaction and defoliation will likely reduce plant growth rate and pasture biomass production by limiting water and air movement in the soil [17]. Additionally, soil physical characteristics significantly affect vegetation. Rezaei *et al.* (2006) studied the relationships between soil properties and plant growth in the subhumid grassland of northern Iran [18]. They found that plant variables were more sensitive to soil physical properties than to soil chemical properties. Nemoto (1991) observed that pasture production in an ungrazed site was more than twice that of a grazed site in tropical pastures of Thailand [3]. These studies make convincing cases for the interaction between pasture productivity and soil compaction.

Stocking rate is a measure of grazing pressure at a given point in time and place. As stocking density increases, the frequency with which a grazing animal visits any given point in the pasture also increases, further altering soil structure. The relationship between soil alteration and stocking rate is therefore complex, being influenced by the differences in soil type, topography, climate, stocking rate, duration of experiments, and measured soil compaction indicators (e.g., bulk density, penetration resistance, porosity), and methods by which grazing intensities were simulated or produced [5, 9].

Despite the recognized importance of interactions between pasture production and soil properties, a significant knowledge gap persists regarding the quantitative relationships between stocking rates, soil physical properties, and pasture productivity in tropical pastures. The year-round growing conditions, distinct soil types (such as Oxisols), and different mechanisms of soil recovery in the tropics mean that findings from temperate systems cannot be directly applied. Consequently, there is a need for empirical data from the humid tropics to find sustainable stocking rates that optimize productivity without causing detrimental soil compaction. Therefore, we considered the pre-hypothesis that, in the humid tropics, different cattle stocking rates would affect soil physical characteristics and that pasture productivity would be related to these properties. Our objective was to quantify the effects of moderate (MSR, 2.7 animal $unit.ha^{-1}.year^{-1}$) and heavy (HSR, five animal $unit.ha^{-1}.year^{-1}$) stocking rates on selected soil physical properties (bulk density, penetration resistance, porosity, and infiltration rate) and to evaluate how these changes drive pasture productivity (biomass production, regrowth rate, and

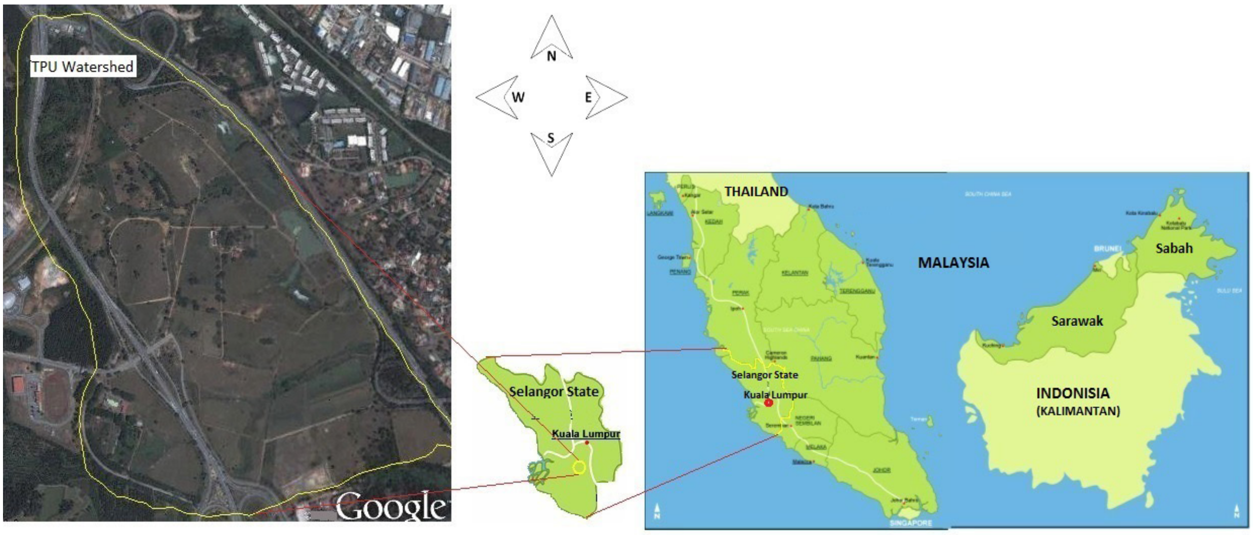

Figure 1) Location of the study site in Selangor State, south of Kuala Lumpur, Malaysia.

litter production) under each stocking rate. The selected stocking rates align with the management strategies for commercial improved and communal pastures in Malaysia, as advised by local agricultural extension services.

Materials & Methods

Site Description

This study was conducted at the Taman Pertanian Universiti (TPU) pastures in Selangor State, Malaysia, about 20 km south of Kuala Lumpur, in 2018. The site extends over a total area of 337 ha and lies between 101° 43' 38" and 101° 44' 03" E longitude and 2° 58' 53" and 2° 59' 57" N latitude (Figure 1). The area has a humid tropical climate, with a mean annual rainfall of 2,471 mm and a mean annual temperature of 24.5 °C (Figure 2). Mean elevation is about 80m above mean sea level. The topography ranges from level terrain to slightly sloping to gently rolling, with some steep hills. Slopes range from 5 to 100%, but most pastures have slopes below 30%, which are easily accessible to cattle under a free-grazing system. The soil was classified according to USDA Soil Taxonomy as a clayey, kaolinitic, isohyperthermic family of Typic Hapludox (Munchong series) within the Oxisol order [19]. This soil is characterized by a deep, well-drained profile and a clay content of > 35% (Table 1). The vegetation of the pastures was dominated by both introduced and native tropical grasses such as signal grass (*Brachiaria decumbens* Stapf.) (47%), guine grass (*Panicum maximum* Jacq.) (21%), carpet grass (*Axonopus compressus* (Sw.) Beauv.) (13%), and hillo grass (*Paspalum conjugatum* Berg.) (19%).

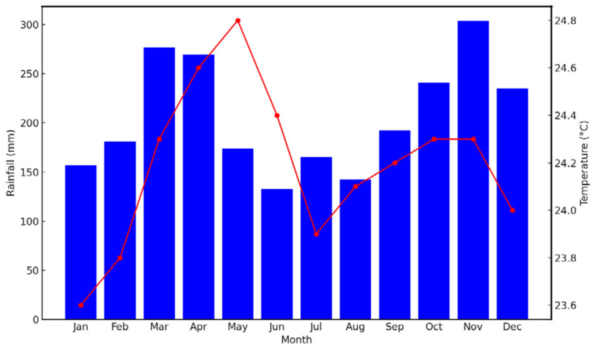

Figure 2) Climate diagram of study site in the south of Kuala Lumpur, Malaysia, showing monthly average temperature (red line) and rainfall (blue bars) for the period 1985-2015.

Experimental Design and Stocking Rates

The experiment was conducted as a

Table 1) General soil characteristics of the studied tropical pastures in the south of Kuala Lumpur, Malaysia.

Chemical Variables	Unit	Value	Physical Variables	Unit	Value Range
pH	-	4.53-4.68	Bulk density	$g.cm^{-3}$	1.27-1.35
EC	$\mu S.cm^{-1}$	50.20-69.54	Penetration Resistance	MPa	1.42-2.66
OC	%	1.80-1.86	Moisture Content	$g.g^{-1}$	25.21-36.80
AP	$Mg.kg^{-1}$	2.71-5.88	Porosity	%	48.58-51.38
TN	%	0.22-0.30	Infiltration Rate	$mm.h^{-1}$	17.10-68.10
^{+}K	$cmol.kg^{-1}$	0.037-0.049			
Ca^{+2}	$cmol.kg^{-1}$	0.50-2.13			
Mg^{+2}	$cmol.kg^{-1}$	0.16-0.28			

completely randomized design with three stocking treatments, i.e., i) moderate stocking rate (MSR, 2.7 animal $unit.ha^{-1}.year^{-1}$), ii) heavy stocking rate (HSR, five animal $unit.ha^{-1}.year^{-1}$), and iii) an ungrazed control (no stocking by cattle) over four years in 2018. The MSR treatment was applied to four replicate pastures (6.0, 6.6, 8.0, and 9.5 ha), and the HSR treatment was applied to four replicate pastures (each approximately 5.0 ha). An ungrazed protected site by a permanent exclosure (approximately 40 ha), contiguous to the grazed pastures on similar topography, soil, and vegetation, was separately established as a control for each stocking rate treatment. The selected stocking rates were based on the regional management practices. The moderate grazing (2.7 $AU.ha^{-1}.year^{-1}$) aligned with the stocking rate in commercial improved pastures in Malaysia, and heavy grazing (5 AU. ha-1.year-1) aligned with the stocking rate in communal improved pastures in Malaysia, as advised by local agricultural extension services.

In this study, the cattle were the Kedah-Kelantan breed, a native Malaysian breed known for its adaptation to the tropical climate. The cattle were about 5 years old. Mature animals of this breed typically weigh between 250 and 300 kg. This breed was used because it is representative of the local cattle commonly raised on pastures in Malaysia. An animal unit (AU) is defined as one mature cow weighing about 450 kg with or without a suckling calf. It is important to emphasize that the pastures studied were grazed exclusively by cattle.

The study site has been managed under a rotational grazing system since its establishment in 1977. The timing and duration of grazing periods were flexible, varying annually based on forage availability and the phenological stage of the dominant grasses. Grazing was initiated when the plants were near the end of their vegetative growth stage, just prior to flowering. Cattle were removed from the paddocks once the pasture height was grazed down to a stubble height of approximately 5 cm. Physical activities such as walking, standing, drinking, grazing, crossing streams, resting, and ruminating were performed by the cattle without any restrictions. Each grazing period typically lasted about two months, though the exact duration was adjusted according to seasonal rainfall and pasture conditions. The research team determined the phenological stage and stubble height of dominant grass plants using the ocular estimation method.

Sampling and Field Measurements

This study used a combination of systematic and randomized methods to conduct field measurements. The systematic sampling design was used to locate transect lines, while the random sampling design was used to establish the quadrats. Field measurements of soil and vegetation were conducted at the end of each grazing period, as shown in Figure 3. This timing was chosen to capture the cumulative and net effect of the entire grazing cycle on soil compaction and pasture productivity. It represents the maximum potential impact before pasture recovery begins. While this approach provides a robust measure of treatment effects, it may not capture the short-term dynamics of soil recovery, rainfall variation, and plant regrowth during grazing events. However, by replicating measurements over time and across different conditions within each period, we were able to distinguish the underlying grazing effects from short-term natural fluctuations.

Measurement of Pasture Productivity Attributes

Pasture vegetation sampling was made at the end of four grazing periods. At each sampling event, twenty equally-spaced transects (10 m in length) spaced 100 m apart were randomly established in each replicate, and a single

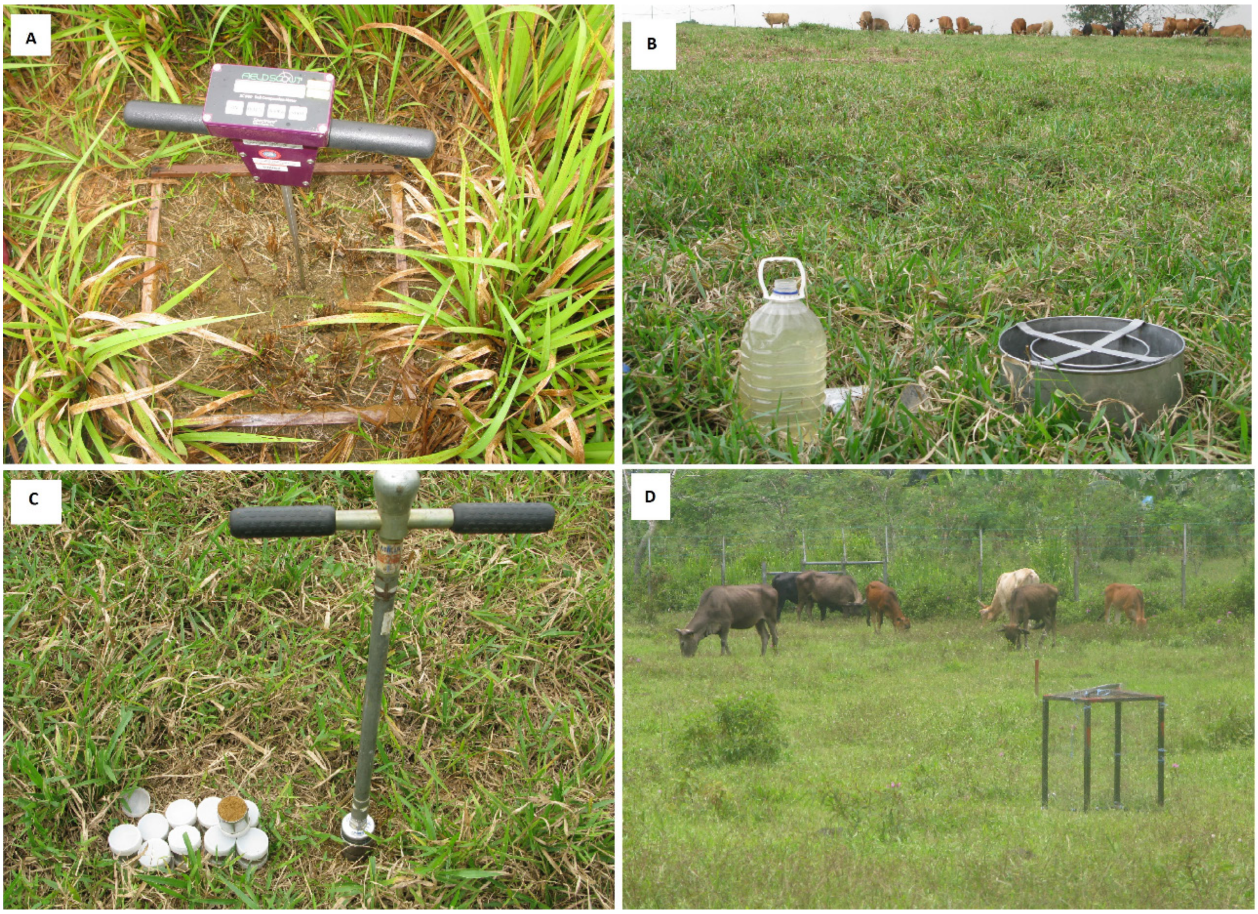

Figure 3) Field measurements, including penetration resistance (A), infiltration rate (B), bulk density (C), and a protection cage for measuring regrowth rate (D).

quadrate (0.25 m^2) was located randomly on each. To determine the regrowth rate, all quadrats were protected from grazing using portable cages secured to the ground with metal pins at the beginning of the grazing period (Figure 3). The harvesting-and-weighing method was used to measure the pasture regrowth rate and biomass [15]. A total of 80 vegetation measurements were recorded for each treatment.

At the beginning of each growth cycle, plant biomass was sampled in each quadrat by cutting to a 5 cm stubble height and hand-separating into live and dead fractions. The quantity of plant litter (g DM/m2) was also measured at the end of the grazing period. Only standing and fallen litter produced in the current growing season was collected as litter biomass. Each fraction was placed into a perforated paper bag and dried at 65 °C for 48 h (to constant weight). At the end of the growth cycle, the same quadrats were again harvested to the same height to determine regrowth, and the portable cage was moved to a new quadrat in preparation for sampling the next cycle. Pasture regrowth rate was expressed as the change in live biomass (DM) per unit time (g $DM.m^{-2}.d^{-1}$ [14]) and calculated using Eq. (1).

$$\text{Regrowth rate} = \frac{\text{Äy}_f}{\text{Ät}} \qquad \text{Eq. (1)}$$

where Δy_f is dry matter biomass (g $DM.m^2.d^{-1}$) after regrowth, and Δt is the number of days between harvests.

Measurement of Soil Physical Properties

Soil bulk density (BD), penetration resistance (PR), porosity (*f*), infiltration rate (*i*), and moisture content (*w*) were measured each time that vegetation was sampled. The soil samples were taken about 0.5 m from the vegetation sampling quadrats. Soils were sampled using a stainless steel hand-driven coring tool (5 cm diameter × 15 cm length). The soil cores were placed in sealed containers to prevent moisture loss and transported to the laboratory (Figure 3). The core sampling technique was used to measure bulk density [20, 21]. A total of 80 soil cores were collected for each treatment. The BD ($g.cm^{-3}$) was determined by dividing the dry soil mass by its volume. Gravimetric soil moisture content was determined by drying the soil in an oven at 105 °C for 24 h, then weighing it [22].

Soil penetration resistance (MPa) was measured with a hand-held Field Scout SC 900 digital soil cone penetrometer (Spectrum Technologies, Inc., Plainfield, IL, USA) (Figure 3). Five penetration resistance measurements were made to a depth of 15 cm at each vegetation quadrat and averaged. A total of 80 averaged penetration resistance measurements were recorded at each treatment. Soil porosity (%) was calculated using Eq. (2).

$$\text{Soil porosity (\%)} = \left[1 - \left(\frac{\text{Bulk density}}{\text{Particle density}}\right)\right] \qquad \text{Eq. (2)}$$

Particle density was considered equal to 2.65 $g.cm^{-3}$ [15] for soils of the studied pasture because of their similar composition of both sand and clay.

Water infiltration rate ($mm.h^{-1}$) into the soil was measured using a double-ring infiltrometer with inner and outer ring diameters of 30 and 60 cm, respectively (Figure 3). Vegetation, litter, and mulch cover were removed to expose the soil surface before measurements were made. Caution was taken to avoid disturbing the soil surface. The infiltrometer was pushed vertically into the ground to a depth of 5 cm using a plastic hammer. Then, clean water was poured between the outer and inner rings and then into the inner ring. The rate at which the water soaked into the soil was measured. Water level readings were recorded at 2, 5, 10, 18, 28, 38, and 48-minute intervals. The infiltrometer was left to run until a steady-state infiltration rate was achieved, usually after about 33-48 minutes. The last measured value was recorded as a steady-state infiltration rate. One infiltration measurement was recorded beside each vegetation sampling quadrat. A total of 80 water infiltration measurements were recorded for each treatment.

Statistical Analysis

Assumptions of normality of distribution and homogeneity of variance were checked using the Shapiro-Wilk test and Levene's test, respectively. The effects of different stocking rate treatments on soil physical variables were analyzed across soil depth intervals, which were treated as a repeated measure using the PROC MIXED ANOVA procedure of SAS 9.3. Stocking rate treatments with four replicates were considered fixed effects. Infiltration data were log-transformed to achieve normality prior to analysis using a multivariate analysis of variance (MANOVA) with GLM (general linear models) in SPSS 23.0. Variables including BD, PR, porosity, and moisture content were used as covariates in the analysis to control for the influence of baseline soil conditions and for a more precise assessment of the treatment effects on the pasture productivity response variables. Pasture productivity variables were analyzed using GLM, a multivariate analysis of variance, in SPSS 23.0. Plant litter biomass was log-transformed to approximate normality before analysis. While the final standard error, *F*-statistic, and *P*-value were presented based on transformed data, the reported means are from the original data. Treatment effects were declared significant at $P < 0.05$.

A correlation matrix was constructed using Pearson's correlation analysis to determine relationships between pasture productivity (dry matter biomass, regrowth rate, and litter biomass) and soil physical variables (bulk density, penetration resistance, porosity, moisture content, and infiltration rate). This matrix was used to quantify the pairwise linear relationships between pasture productivity and each soil physical property within each stocking-rate treatment. Linear regression was then applied to further model the most significant of these relationships with pasture productivity variables as the dependent variables and soil physical properties as the independent variables. Before analysis, the relationships between variables were assessed for linearity using scatter plots. The normality of residuals was also checked to ensure the assumptions of the tests were met.

Findings

Pasture Productivity Attributes

No significant differences ($P > 0.05$) in pasture biomass were observed between MSR and HSR with ungrazed treatments. The mean regrowth rate was 31% greater ($P < 0.05$) in the MSR treatment (3.23 g $DM.m^2.d^{-1}$) than the ungrazed control (2.47 g $DM.m^2.d^{-1}$), but it was not affected by HSR. Litter biomass was about 51% and 38% less ($P < 0.05$) in the MSR and HSR treatments, respectively, than in their paired ungrazed controls (Table 2).

Soil Physical Properties

Soil BD, PR, porosity, and infiltration rate were affected ($P < 0.05$) by HSR, but of these, only PR was affected ($P > 0.05$) by MSR. Penetration

Table 2) Changes in pasture productivity under moderate (MSR) and heavy (HSR) stocking rates by cattle in the south of Kuala Lumpur, Malaysia.

Pasture Productivity Attributes	Pastures under Moderate Stocking Rate				Pastures under Heavy Stocking Rate			
	Grazed Site	Ungrazed Site	†SE	F-Value	Grazed Site	Ungrazed Site	SE	F-Value
Pasture surface height (cm)	35.41[a]	34.84[a]	3.72	0.024	14.11[a]	16.50[a]	2.93	2.24
Dry matter biomass (g DM.m^2)	160.2[a]	132.4[a]	19.2	2.10	134.70[a]	129.88[a]	17.72	0.074
Regrowth rate (g DM.m^2.d^{-1})	3.23[a]	2.47[b]	0.316	5.81	2.58[a]	2.41[a]	0.327	0.025
Tiller density (Nr.m^2)	70.93[a]	34.56[b]	0.069	11.85	86.64[a]	57.79[b]	6.76	19.36
Litter biomass (g.m^2)	11.0[a]	22.6[b]	0.102	3.81	11.0[a]	17.8[b]	3.40	3.95

† Standard Error
Means in a row with different letters were significantly different at $P < 0.05$.

resistance of the surface layer (0–5 cm) was increased by 26.30 and 28.98% under heavy and moderate stocking rates, respectively. Gravimetric soil moisture content was similar ($P > 0.05$) between both MSR and HSR with ungrazed treatments (Figure 4 and Table 3). Soil BD, PR, and porosity in the HSR treatment were about 5.5% and 40% greater ($P < 0.05$), but 6.4% less ($P < 0.05$), respectively, than in the ungrazed treatment. These differences were also affected ($P < 0.05$) by soil depth (Figure 4 and Table 4). Soil BD and PR differences between HSR and the ungrazed control were greatest at the 10-15 cm soil depth. The infiltration rate was almost 4 times higher in the ungrazed control than in the HSR treatment (Table 3).

Interactions between treatment and soil depth showed that the impact of stocking rate on soil physical properties was not uniform across the soil profile. Under HSR treatment, the most compaction effects were observed in the subsurface layers. Soil BD was significantly higher in the HSR treatment compared to the ungrazed control at the 10-15 cm depth ($P < 0.05$). Similarly, soil PR under HSR was significantly greater than the control at both the 5-10 cm and 10-15 cm depths ($P < 0.05$). Porosity showed the inverse relationship. Porosity differences between the HSR and ungrazed control were mainly observed below 10 cm. Soil porosity was significantly lower ($P < 0.05$) in the HSR treatment than the control at the 0-5 cm (50.26% vs. 51.52%) and 10-15 cm (47.63% vs. 53.70%) depths. This pattern indicates that heavy grazing pressure primarily degraded the physical condition of the subsoils in the study area (Table 4).

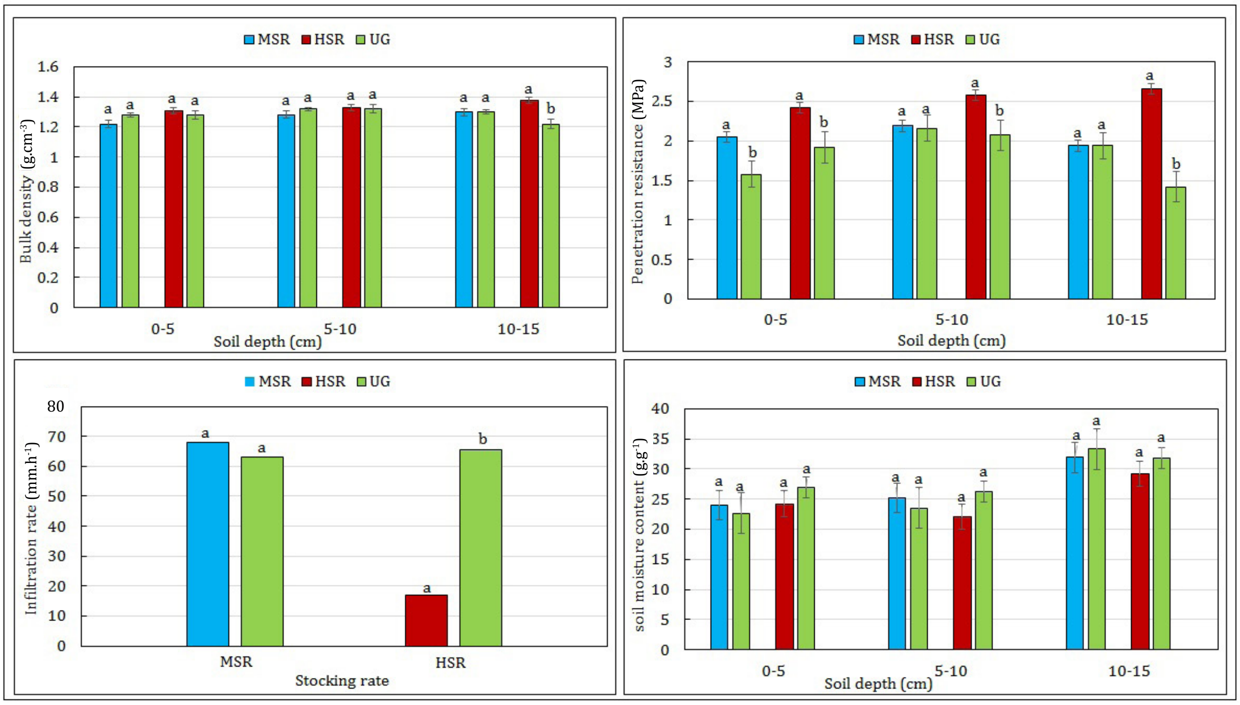

Figure 4) Effect of moderate (MSR) and heavy (HSR) stocking rates by cattle compared with no-grazing (UG) on soil physical properties at various soil depths in tropical pastures of the south of Kuala Lumpur, Malaysia.

Table 3) Soil physical properties response to moderate (MSR) and heavy (HSR) stocking rates by cattle in tropical pastures of the south of Kuala Lumpur, Malaysia.

Pasture Productivity Attributes	Pastures under Moderate Stocking Rate				Pastures under Heavy Stocking Rate			
	Grazed Site	Ungrazed Site	SE†	Grazed Site	Ungrazed Site	Ungrazed Site	Grazed Site	Ungrazed Site
Bulk Density ($g.cm^{-3}$)	1.27[a]	1.30[a]	0.020	2.70	1.35[a]	1.28[b]	0.027	6.52
Penetration Resistance (MPa)	2.06[a]	1.90[b]	0.10	4.00	2.52[a]	1.80[b]	0.17	12.15
Moisture Content ($g.g^{-1}$)	38.0[a]	36.8[a]	0.01	1.55	25.2[a]	28.3[a]	0.02	2.19
Porosity (%)	51.4[a]	50.6[a]	0.46	3.21	48.6[a]	51.91[b]	1.56	4.55
Infiltration Rate ($mm.h^{-1}$)	68.1[a]	63.1[a]	0.08	0.01	17.01[a]	65.54[b]	0.142	20.10

† Standard Error
Means in with different letters were significantly different at $P < 0.05$.

Relationship between Pasture Productivity and Soil Physical Properties

Pasture production (dry matter biomass) was negatively related to soil BD (r = - 0.39 for MSR and r = - 0.36 for HSR) and PR (r = - 0.31 for MSR and r = - 0.44 for HSR, but positively related to porosity (r = 0.39 for MSR and r = - 0.46 for HSR), at both treatments ($P < 0.05$). Pasture regrowth rate was negatively related to soil BD BD (r = - 0.38 for MSR and r = - 0.32

Table 4) Effect of stocking rate, soil depth, and their interactions on soil physical properties at tropical pastures of the south of Kuala Lumpur, Malaysia.

Soil Physical Properties	Stocking Treatment	Soil Depth (cm)	Pastures under Moderate Stocking Rate (MSR)		Treatment × Soil Depth		Pastures under Heavy Stocking Rate (HSR)		Treatment × Soil Depth	
			Mean	SE Difference	*F*-Value	*P*-Value	Mean	SE Difference	*F*-Value	*P*-Value
Bulk Density ($g.cm^{-3}$)	Grazed pasture	0–5	1.22^{a}	0.036	2.23	0.14	1.31^{a}	0.041	5.06	0.02
	Ungrazed pasture		1.28^{a}				1.28^{a}			
	Grazed pasture	5–10	1.28^{a}	0.025			1.33^{a}	0.052		
	Ungrazed pasture		1.32^{a}				1.32^{a}			
	Grazed pasture	10–15	1.30^{a}	0.010			1.38^{a}	0.42		
	Ungrazed pasture		1.30^{a}				1.22^{b}			
Penetration Resistance (MPa)	Grazed pasture	0–5	2.05^{a}	0.12	1.43	0.27	2.42^{a}	0.12	8.45	00
	Ungrazed pasture		1.58^{b}				1.92^{b}			
	Grazed pasture	5–10	2.19^{a}	0.13			2.58^{a}	0.13		
	Ungrazed pasture		2.16^{a}				2.07^{b}			
	Grazed pasture	10–15	1.94^{a}	0.20			2.66^{a}	0.20		
	Ungrazed pasture		1.97^{a}				1.42^{b}			
Moisture Content ($g.g^{-1}$)	Grazed pasture	0–5	24.01^{a}	0.013	0.60^{NS}	0.56	24.25^{a}	0.017	2.44	0.12
	Ungrazed pasture		22.69^{a}				26.88^{a}			
	Grazed pasture	5–10	25.19^{a}	0.009			22.13^{a}	0.021		
	Ungrazed pasture		23.52^{a}				26.29^{a}			
	Grazed pasture	10–15	64.92^{a}	0.010			29.25^{a}	0.025		
	Ungrazed pasture		64.19^{a}				31.75^{a}			
Porosity (%)	Grazed pasture	0–5	53.71^{a}	0.644	4.81*	0.04	50.26^{a}	1.78	9.56	0.007
	Ungrazed pasture		51.66^{b}				51.52^{b}			
	Grazed pasture	5–10	51.85^{a}	0.75			49.48^{a}	1.95		
	Ungrazed pasture		50.15^{b}				50.11^{a}			
	Grazed pasture	10–15	50.91^{a}	0.41			47.63^{a}	1.60		
	Ungrazed pasture		50.95^{a}				53.70^{b}			

Within each soil depth interval, means followed by different letters were significantly different at $P < 0.05$.

for HSR) and PR (r = - 0.31 for MSR and r = - 0.39 for HSR) ($P < 0.05$), but positively related to porosity (r = 0.38 for MSR and r = 0.32 for HSR), at both treatments ($P < 0.05$). These variables were affected by soil moisture content only at the HSR treatment (P < 0.05). Infiltration rate had no effect ($P > 0.05$) on these attributes at either stocking rate treatment. At the HSR site, litter biomass was related ($P < 0.05$) to soil BD (r = - 0.42) and PR (r = - 0.46), moisture content (r = 0.32), and infiltration rate (r = 0.32). It was negatively related (r = - 0.31, $P < 0.05$) only to soil BD in the MSR treatment (Table 5).

Table 5) Relationship (r) between pasture productivity variables and soil physical variables in tropical pastures of the south of Kuala Lumpur, Malaysia.

Pasture Productivity Variables	Soil Physical Variables	Pastures under Moderate Stocking Rate						Pastures under Heavy Stocking Rate					
		b	a	*r*	R^2	*F*-Value	*P*-Value	b	A	*r*	R^2	*F*-Value	*P*-Value
Dry Matter Biomass	Bulk Density	−277.9	502.93	−0.39	0.152	17.73	0.001**	−139.1	306.94	−0.36	0.128	4.60	0.037*
	Moisture Content	224.6	93.71	0.14	0.021	1.99	0.16NS	239.15	64.10	0.39	0.151	8.16	0.006**
	Porosity	7.4	−233.2	0.39	0.152	17.68	0.001**	4.22	−90.69	0.36	0.128	6.73	0.013*
	Penetration Resistance	−0.025	198.10	−0.31	0.096	9.98	0.002**	−0.044	221.57	−0.44	0.19	10.82	0.002**
	Infiltration rate	0.118	140.08	0.09	0.008	0.71	0.40NS	−0.183	131.36	0.15	0.023	1.09	0.30^{NS}
Regrowth Rate	Bulk Density	−1.118	2.129	−0.38	0.141	15.47	0.014**	−0.685	1.49	−0.32	0.103	5.15	0.048*
	Moisture Content	0.719	0.528	0.11	0.012	1.12	0.29^{NS}	1.202	0.294	0.42	0.174	9.68	0.003**
	Porosity	0.030	−0.829	0.38	0.141	15.37	0.002**	0.018	− 0.33	0.32	0.103	5.28	0.026*
	Penetration Resistance	−0.0001	0.916	− 0.31	0.097	10.10	0.004**	−0.0002	1.007	−0.39	0.155	8.47	0.006**
	Infiltration rate	0.001	0.645	0.15	0.022	2.11	0.15^{NS}	−0.001	0.634	0.17	0.03	1.40	0.24^{NS}
Litter Biomass	Bulk Density	−0.003	1.30	−0.31	0.10	10.27	0.002 **	−0.018	1.365	−0.42	0.180	10.06	0.003**
	Moisture Content	4.5×10^{-5}	0.240	0.02	2.2×10^{-4}	0.021	0.88^{NS}	0.010	0.222	0.32	0.102	5.21	0.027*
	Porosity	0.10	50.99	0.32	0.10	10.44	0.002 **	0.670	48.51	0.42	0.180	10.04	0.003**
	Penetration Resistance	−9.39	2157.70	−0.16	0.026	2.55	0.11^{NS}	− 84.90	2527.9	−0.46	0.209	12.18	0.001**
	Infiltration rate	0.149	63.06	0.04	0.002	0.175	0.67^{NS}	4.97	23.61	0.32	0.102	5.24	0.027*

* Correlation is significant at the 0.05 level. ** Correlation is significant at the 0.01 level. NS: non-significant.

Discussion

Stocking Rate and Pasture Productivity

Pasture productivity and soil physical properties were responsive to soil compaction under moderate and heavy cattle stocking rates on tropical pastures, supporting the pre-hypothesis of the study. The measured variables were responsive to stocking rate, thereby linking biomass production and permitting a detailed assessment of the role that stocking density can play in tropical pastures. Furthermore, a key consideration in interpreting the results is distinguishing the effects of soil compaction from other grazing-related factors (e.g., nutrient removal, changes in species composition, etc.). While these factors are inherently linked in a grazing system, our experimental design and analysis provide strong evidence that soil physical properties were a major driver of the observed patterns in the studied pastures. The use of ungrazed control plots for each treatment, on similar topography, soil, and vegetation types, allowed us to baseline measurements against a state without grazing or treading. Moreover, the statistically significant correlations between soil physical variables (BD, PR, porosity) and pasture productivity within each stocking treatment (Table 5) indicate a direct mechanistic link. If grazing alone were the primary driver, we would not expect to see such consistent relationships between plant growth and sub-surface soil conditions after accounting for the grazing treatment. The fact that pasture productivity was more closely tied to these soil physical variables under the heavy stocking rate, where compaction was most severe, further strengthens the inference that compaction itself was a critical limiting factor in the studied tropical pastures.

Grazing disturbance is an essential factor for maintaining the health and biodiversity of tropical pastures [7]. At least a part of that effect is due to litter production, which may accumulate to such an extent that it suppresses biomass production by preventing herbage regrowth, particularly in ungrazed pastures [23]. Grazing would also benefit regrowth by removing self-shading caused by accumulated plant litter, yet plants would retain a higher proportion of green leaf area.

The elimination of self-shading can play a critical role in stimulating short-term pasture regrowth by removing the light-blocking litter and mature canopy, and likely enhances photosynthetic efficiency in the remaining leaf area [24]. This is a key mechanism explaining the 31% greater regrowth rate we observed under the MSR treatment. However, this short-term boost in pasture growth must be balanced against the potential long-term costs of reduced root carbon reserves and the physical damage from repeated defoliation [24]. However, the effect of grazing on pasture productivity is transferred indirectly through soil properties. Productivity in tropical pastures, where water is not limiting, is primarily controlled by the soil environment and by canopy removal from grazing or cutting [25, 26, 15]. The lack of negative impacts of heavy stocking rate (HSR) on pasture regrowth rate and biomass production may be explained by competing processes. Although grazing removed a high proportion of leaf area, it also eliminated self-shading from accumulated litter and mature foliage, a factor that likely inhibited regrowth in the ungrazed control. It should be stressed that the reduction in litter biomass (51% under MSR and 38% under HSR) reveals a critical trade-off. While removing excess litter can stimulate regrowth in the short term, the long-term reduction in litter input into soil can threaten ecosystem health by depleting the soil organic matter (SOM) pool in pastures [27]. Over time, lower SOM diminishes soil fertility and aggregate stability, increasing susceptibility to compaction and undermining the productivity [28]. Thus, the short-term benefit of reduced self-shading must be carefully balanced against the long-term cost of degraded soil biogeochemical function.

Stocking Rate and Soil Physical Properties

Since soil moisture content did not vary between treatments at any sampling event, the difference in soil PR can be directly attributed to animal traffic and treading. Results showed that the maximum compaction effects under heavy stocking (HSR) often occurred in the subsurface layers (5-15 cm). The greater soil BD and PR in the subsurface than in the surface layer have also been reported by [29, 30]. In tropical soils of Colombia, Martinez and Zinck [30] observed that cattle treading had the most significant impact in the 5-10 cm layer. This lower BD in surface layers compared to subsurface layers, and the higher BD and PR in subsurface layers, can be explained by a shift in the dominant influencing factors, i.e., biological and physical processes. Biological processes, such as higher root concentrations, organic matter content, plant litter biomass, and micro-organism activity, can be partially offset in the surface layer (0-5 cm) [31]. In contrast, the subsurface layers (5-15 cm) are more influenced by physical processes. The pressure from animal treading and the lower abundance of roots and organic matter make these layers more susceptible to compaction and higher bulk density. Furthermore, consistent with [32], we found that even a moderate stocking rate (MSR) significantly increased soil PR in the upper 10 cm of soil (Table 4 and Figure 4). This increase in PR under MSR can be attributed to the combined effects of defoliation and cattle trampling, despite lower grazing pressure. In some cases, animal traffic chips or churns the soil, breaking up surface crusting without compacting it, particularly when it is dry [33]. In our study, soil moisture content was similar between stocking rate treatments in all sampling events.

The effect of increased BD and PR, combined with reduced porosity, was reflected in a reduced infiltration rate, particularly at the HSR site. These observations are similar to those of Castellano and Valone (2007) [34], Tian *et al.* (2007) [11], and Blanco Sepúlveda and Nieuwenhuyse [31]. Heathwaite *et al.* (1990) [35] and Mulholland and Fullen (1991) [29] reported that the steady-state infiltration rate was reduced by 80% and 98.5% on heavily grazed grassland compared with ungrazed grassland, respectively. A low infiltration rate was associated with high BD [17] and reduced land cover and standing grass cover [34].

At a high stocking rate (HSR), soil BD increased by 5.5%. While this increase is below the critical threshold for classifying the pasture as severely degraded, it is nonetheless ecologically significant. This significance is demonstrated by the negative relationships between both BD and PR with dry matter biomass and pasture regrowth (Table 5). The mechanism underlying this impact is that animal treading increases BD by reducing soil porosity, particularly macro-pores [26], which in turn restricts soil aeration and the level of air-filled pores critical for root function. This, in turn, reduces the amount of oxygen available to the root system [17]. The same study reported that denitrification may occur in soils with reduced air-filled porosity, thereby affecting pasture production. It has also been indicated that plant production was more sensitive to soil physical characteristics than chemical properties in subhumid grasslands [18, 36].

Relationship between Pasture Productivity and Soil Physical Properties

The significant positive relationship between biomass production and available soil moisture at the HSR site (*r* = 0.39, Table 5) indicates a shift in the limiting factors of plant growth. Once grazing pressure and soil compaction exceed their thresholds, pasture plants become more dependent on available soil water. This limitation likely arises from the interplay between high daily temperatures and the constrained water-holding capacity of the compacted soil. The situation is exacerbated under a heavy stocking rate. In HSR pastures, the significantly lower pasture surface height (14.1 cm vs. 16.5 cm in ungrazed control; Table 2) probably exposed more soil surface to direct solar radiation. This increased heat flux elevates topsoil temperature and dramatically accelerates evaporation rates. Consequently, despite the high annual rainfall, the plant-available water in the root zone is rapidly depleted, leading to water stress and exacerbating the negative impact of compaction on pasture productivity [13, 14, 37]. Therefore, even in a humid tropical climate, production in heavily stocked pastures becomes sensitive to slight variations in soil moisture, signaling a loss of resilience and a transition towards a more vulnerable state [38].

The significant negative correlation between soil PR and regrowth rate (Table 5) confirms that compaction is a severe stressor in grazed pastures. However, the finding that pasture regrowth rate was not significantly reduced under the high stocking rate, despite a substantial 32% increase in soil PR, can be explained by several compensatory mechanisms. The heavy defoliation in HSR pasture likely removed self-shading from mature foliage and litter, improving light availability for new tillers and compensating for the root growth limitations imposed by soil compaction [24]. Furthermore, tropical forage grasses can exhibit compensatory growth following defoliation, allocating resources to shoot regrowth even under suboptimal soil conditions [39]. Moreover, pasture grasses such as *Brachiaria decumbens* and *Panicum maximum* may exhibit some physiological resilience to soil strength. Such species can mitigate compaction stress through mechanisms like osmotic adjustment and the production of root exudates that improve rhizosphere conditions [40].

The dramatic 74% reduction in steady-state infiltration rate under HSR treatment was not significantly correlated with pasture productivity. This suggests that infiltration rate was not the direct limiting factor for plant growth in the studied pastures. Its effect was likely indirect, mediated by the same soil structural degradation that causes increases in soil BD and PR. However, the hydrological implications of reduced infiltration could be severe and extend beyond pasture productivity. A 74% reduction in infiltration rate can drastically increase surface runoff, soil erosion, even on gentle slopes, and represents a critical loss of ecosystem services over time [41].

Conclusion

This study provides empirical evidence on the relationship between stocking rates, soil physical properties, and pasture productivity in the humid tropics, a region where such data are scarce. Knowledge of the relationships among stocking rates, soil physical properties, and pasture productivity in tropical pasture systems is important for land managers and farmers. This study concludes that pasture production was more closely related to soil physical variables at a high stocking rate. It provides strong evidence that this management practice can push the pasture towards a more fragile state, where productivity becomes highly sensitive and vulnerable to additional physical soil degradation. Heavy stocking degrades the soil environment to the point where productivity becomes critically dependent on the soil's physical condition. Continued heavy grazing in the long term exacerbates soil compaction and increases the risk of decline in pasture productivity and long-term degradation.

The findings of this study indicate that the heavy stocking rate (five AU. $ha^{-1}.year^{-1}$) is unsustainable. In contrast, the moderate stocking rate (2.7 A. $ha^{-1}.year^{-1}$) appears to be a more sustainable grazing strategy in the studied tropical pastures. Under moderate stocking, the pastures appear resilient, with productivity buffered against variations in soil conditions. Consequently, a stocking rate of 2.7 AU. $ha^{-1}.year^{-1}$ or lower is suggested as optimal for the sustainable management of these tropical pastures. This threshold can effectively balance short-term economic productivity with the long-term ecological sustainability of the pastures.

This study had some limitations that should be considered when interpreting the results. Sampling was conducted at the end of grazing periods to capture the cumulative effects of grazing, which may not reflect the short-term dynamics of soil recovery and plant regrowth throughout grazing cycles. While experimental design and correlation analysis provided strong evidence for the role of soil compaction, the effects of grazing are complex, and the impact of treading and compaction cannot be entirely separated from other simultaneous effects, such as defoliation and nutrient redistribution. Using a single control exclosure as a reference for grazed replicates in each treatment is a limitation compared to replicated control sites. Future research would benefit from continuous monitoring throughout grazing cycles and from using more replicated control exclosures to further isolate causal mechanisms. Despite these limitations, the consistent and significant patterns observed over four years provide robust support for our conclusions regarding the impact of stocking rates on soil-plant interactions in tropical pastures.

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