

Article

Pasture Management and Mineral Fertilization on Soil Properties, Plant Nutrition, and Biomass Production of *Urochloa decumbens* in Tropical Lixisols

Tiago de Carvalho Pessoa¹, Tancredo Augusto Feitosa de Souza^{1,2,*}, Vânia da Silva Fraga¹, João Henrique Melo¹, Flavio Pereira de Oliveira¹, Gislaïne dos Santos Nascimento¹, Ramon Freire da Silva¹, Thiago Jardelino Dias¹ and Milton Cesar Costa Campos¹

¹ Postgraduate Program in Soil Science, Agrarian Science Centre, Department of Soils and Rural Engineering, Federal University of Paraíba, Areia 58397-000, PB, Brazil; tiago.pessoa@hotmail.com (T.d.C.P.); vsfragas@gmail.com (V.d.S.F.); joao.henrique@gmail.com (J.H.M.); flavio.oliveira@academico.ufpb.br (F.P.d.O.); gislaynesantos30@hotmail.com (G.d.S.N.); ramonsilvagro@gmail.com (R.F.d.S.); thiagojardelinodias@gmail.com (T.J.D.); mcesarsolos@gmail.com (M.C.C.C.)

² Centre for Functional Ecology, Department of Life Sciences, University of Coimbra, 3000-456 Coimbra, Portugal

* Correspondence: tancredo_agro@hotmail.com

Abstract

Pasture management and mineral fertilization are key factors influencing soil fertility and pasture yield. However, their effects on the soil properties of Lixisols in the Brazilian semi-arid region, and their subsequent impact on *Urochloa decumbens* biomass production, remain unclear. We compared soil properties between short- and long-term pastures and evaluated how fertilization affects the growth of *U. decumbens*. The grass was cultivated in pots with soil subjected to four treatments: nitrogen (N), phosphorus (P), combined NP fertilization, and an unfertilized control. We assessed shoot dry biomass, plant responsiveness to fertilization, plant N and P concentrations, and the fertilization effect on nutrient uptake. Long-term managed pasture exhibited higher levels of K⁺, soil pH, available P, and total organic carbon, whereas short-term degraded pasture had higher total nitrogen, Mg²⁺, H⁺, Al³⁺, and cation exchange capacity. NP fertilization significantly enhanced *U. decumbens* growth in both pasture conditions, resulting in greater shoot dry biomass, higher responsiveness to fertilization, and improved N and P uptake compared with the control. In addition, N and P fertilization applied individually promoted the accumulation of their respective nutrients in plant tissues, with N fertilization resulting in the highest plant N content and P fertilization resulting in the highest plant P content. Our findings suggest that (i) short-term degraded pasture management altered soil nutrient status, which may be associated with changes in nutrient cycling and soil chemical properties, and (ii) adequate fertilization in short-term degraded pastures can enhance *U. decumbens* biomass production.



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1. Introduction

Grassland degradation is a major environmental and agricultural concern in tropical regions, where declining soil fertility can constrain plant productivity, reduce pasture

quality, and increase pressure on native ecosystems. In northeastern Brazil, these challenges are particularly relevant because pasture systems are frequently characterized by uncontrolled grazing, limited soil-fertility management, and the widespread cultivation or occurrence of exotic plant species [1]. Among these species, *Urochloa decumbens* is an important forage grass used extensively in Brazilian pasture systems. Its widespread use is associated with its capacity to establish and produce forage under relatively low-fertility and seasonally dry conditions, which makes it particularly relevant for semi-arid and degraded pasture systems. However, its productivity and nutritional performance can decline when soil degradation and nutrient limitations become pronounced, and poorly managed pastures dominated by exotic grasses may also contribute to pressure on native vegetation [1]. Thus, *U. decumbens* represents both an important forage resource and a useful model for evaluating how changes in soil conditions and nutrient availability affect pasture productivity. Understanding how pasture management affects soil fertility and, consequently, the productivity of *U. decumbens* is therefore essential for assessing degradation processes and developing strategies for sustainable pasture management in the Brazilian semi-arid region.

Pasture management can substantially modify soil properties and plant productivity. Appropriate grazing management and fertilization have been shown to improve soil physical and chemical properties and to promote plant growth, pasture yield, and plant macronutrient concentrations [2,3]. Conversely, insufficient management may contribute to soil degradation and the expansion of grassland systems into adjacent natural ecosystems. In the Brazilian semi-arid region, pasture expansion is associated with deforestation, declining soil fertility, and reduced productivity in degraded or abandoned areas [4,5]. Changes in soil properties, including soil pH and phosphorus (P) availability, may occur as degradation progresses and can further constrain plant production and ecosystem recovery [6–8]. However, existing studies have largely emphasized overall differences in soil fertility or pasture condition, whereas less attention has been given to how soil properties vary spatially along slope positions within pasture landscapes and how this spatial variation translates into differences in plant nutrient limitation and fertilization response [3,5,7]. In particular, soils occupying different positions along a slope may experience contrasting patterns of erosion, deposition, soil translocation, and exposure of subsoil material, potentially generating spatially heterogeneous soil conditions even within the same pasture system. These processes highlight the need to understand the interactions between land management, soil fertility, spatial heterogeneity, and plant productivity across heterogeneous landscapes [8].

Soil fertility is strongly influenced by the availability of essential nutrients, particularly nitrogen (N) and P. Mineral fertilization with N and P can increase productivity in grassland ecosystems, and positive responses to these nutrients have been reported for exotic grasses in semi-desert grasslands of North America and semi-arid grasslands of Africa and Brazil [9–11]. Nevertheless, these studies do not necessarily lead to the same prediction for soils subjected to different degrees of pasture degradation. A high concentration of a nutrient in soil does not necessarily indicate that the nutrient is available to plants at a rate sufficient to sustain maximum growth, because nutrient availability is also influenced by soil chemical properties, nutrient interactions, and plant demand [10]. Conversely, a low concentration may reflect nutrient depletion associated with degradation. Consequently, the magnitude of the plant response to fertilization cannot be inferred solely from the concentration of nutrients measured in the soil. The magnitude and direction of plant responses to nutrient addition may therefore depend on initial soil fertility, nutrient stoichiometry, soil properties, and landscape position. N and P availability can act as important constraints on plant growth and productivity, but nutrient limitation is not necessarily

uniform across grassland ecosystems [12]. The specific gap addressed here is whether differences in soil condition associated with pasture management and slope position are accompanied by differences in the response of *U. decumbens* to N and P supplied individually or in combination. This distinction is important because N or P fertilization may increase the concentration of the corresponding nutrient in plant tissues without necessarily producing the same magnitude of response in total biomass production.

These uncertainties are particularly relevant in the Brazilian semi-arid region, where spatial variation in soil properties and degradation processes may interact with pasture management to determine plant productivity. The landscape degradation hypothesis predicts that soil translocation and exposure of less fertile subsoil along slopes can generate spatial patterns of declining soil quality [4,13]. Under this framework, slope position is not simply a spatial descriptor but a potential driver of differences in soil fertility and plant performance. In contrast, the external nutrient sources hypothesis proposes that plant productivity may remain nutrient limited despite relatively high nutrient concentrations in soil when nutrient availability to plants is constrained by other biogeochemical or physiological processes [9,14]. This perspective provides a complementary explanation for situations in which soil nutrient concentrations alone do not predict plant productivity or fertilization response. Similarly, nutrient-stewardship approaches suggest that balanced nutrient management, rather than the addition of a single nutrient, may be required to optimize plant production under degraded conditions [15]. Taken together, these three perspectives provide a connected framework for the present study: landscape processes may generate spatial differences in soil properties along slopes; these soil conditions may influence the extent to which nutrients limit plant growth [10]; and the resulting nutrient limitation may determine whether N, P, or combined N–P fertilization produces the strongest plant response [12,13]. Thus, the three perspectives are complementary rather than independent: landscape degradation provides a mechanism for generating heterogeneous soil conditions, the external nutrient sources hypothesis provides a framework for interpreting plant responses that are not directly predicted by soil nutrient concentrations, and nutrient stewardship provides a framework for evaluating whether balanced N–P fertilization can overcome multiple nutrient constraints. These perspectives lead to contrasting predictions regarding whether degraded soils should exhibit stronger responses to N, P, or combined N–P fertilization.

The present study was designed to connect field-scale variation in soil properties with experimentally measured plant responses to nutrient addition. The field component was used to characterize soil chemical and physical conditions under different pasture-management histories and along different slope positions, thereby testing whether pasture management was associated with spatial heterogeneity in soil conditions. The subsequent controlled microcosm experiment used soils representing these contrasting conditions to evaluate whether differences in soil status were reflected in the response of *U. decumbens* to N and P fertilization. This experimental approach allowed us to distinguish changes in soil nutrient status from actual plant nutrient limitation and to determine whether the addition of N, P, or both nutrients resulted in different plant responses.

Against this background, this study investigated the effects of pasture management on soil chemical and physical properties in Lixisols of the Brazilian semi-arid region and evaluated how soil fertility influences the productivity of *U. decumbens*. Specifically, we addressed three questions: (1) Does short-term pasture management alter soil chemical and physical properties and their spatial distribution across different slope positions? We hypothesized that degradation would be associated with unfavorable changes in soil properties resulting from soil translocation and subsoil exposure across the landscape, as predicted by the landscape degradation hypothesis [4,13]. (2) Does N and P fertilization,

applied individually or in combination, increase biomass production and plant nutrient accumulation of *U. decumbens* under contrasting soil conditions? Based on the external nutrient sources hypothesis [9,14], we hypothesized that mineral fertilization would increase plant biomass and nutrient accumulation even when soil nutrient concentrations were relatively high, because soil nutrient concentration does not necessarily represent effective nutrient availability to plants. (3) Does the magnitude and nature of the *U. decumbens* response to N and P fertilization differ between soils obtained from pastures with contrasting management histories and levels of degradation? We hypothesized that combined N–P fertilization would produce the greatest increase in biomass and overall plant responsiveness to fertilization, whereas N and P applied individually would primarily increase the accumulation of their respective nutrients in plant tissues. This prediction links the fertilization experiment directly to the nutrient-stewardship perspective [15] by testing whether balanced N–P supply provides a stronger growth response than either nutrient applied alone, while recognizing that individual nutrients may nevertheless produce distinct effects on plant nutrient concentrations.

To address these questions, we combined field characterization of soil chemical and physical properties in grassland areas subjected to short-term degraded pasture and long-term pasture management across different slope positions with a controlled glasshouse microcosm experiment. The field component allowed us to evaluate whether pasture management was associated with spatial variation in soil fertility and physical condition along the slope, whereas the microcosm experiment enabled us to isolate the effects of N and P fertilization on *U. decumbens* biomass production and nutrient concentrations under soils representing these contrasting field conditions. By linking spatially structured soil characterization with a controlled nutrient-addition experiment, the study directly connects landscape-scale degradation processes with plant-level nutrient responses. Together, these findings provide insights into the links among pasture management, soil degradation, spatial soil heterogeneity, nutrient limitation, and forage productivity and contribute to the development of more effective strategies for maintaining soil fertility and pasture production in semi-arid environments.

2. Materials and Methods

2.1. Characterization of the Field Experiment

Field sampling was conducted in two adjacent sites within the Vaca Brava hydrographic basin, Remígio, Paraíba, Brazil (Site 1: 06°57'55.9" S, 35°46'14.4" W; and Site 2: 06°57'37.7" S, 35°45'46.7" W). According to the Köppen–Geiger classification, the region has an “As” climate type, characterized by a tropical wet and dry climate with a pronounced dry season, an average annual precipitation of 1500 mm, and a mean temperature of 21 °C [16]. The soil type in both sites was classified as Lixisols [17]. Both study sites are dominated by *Urochloa decumbens* (Stapf.) R.D. Webster, a widely used exotic grass for pasture formation in the Brazilian semi-arid region [18].

The study sites were part of a long-term field experiment established in 2002. At each site, two areas (A1 and A2) representing contrasting pasture management and degradation conditions were evaluated. Area 1 (A1), designated as the long-term managed pasture (LMP), had been maintained under controlled grazing and pest management, including the control of weeds and termites. In contrast, Area 2 (A2), designated as the short-term degraded pasture (SDP), had been monitored since 2018, before the commencement of the present study in January 2020. The SDP classification was based on the two-year period (2018–2020) during which the area exhibited uncontrolled grazing, an absence of pest management, and a substantial presence of termites and invasive plant species, particularly *Sporobolus indicus*. Thus, the two-year period refers to the documented duration of the

degraded management conditions before the beginning of the present study, rather than the duration of the long-term field experiment. Neither area had received lime or fertilizer. To characterize soil chemical and physical properties across the landscape, three topographic positions (shoulder, backslope, and footslope) were selected within each area [19]. Soil data were collected from January 2020 to January 2024.

2.2. Experimental Design of the Field Experiment

In each of the two study areas (SDP and LMP), we established three slope positions (shoulder, backslope, and footslope) and ten 10 m² plots at each slope position, following Fortin and Dale [20]. Within each plot, twenty soil subsamples were randomly collected from a depth of 15 cm using a 1 × 1 m sampling grid. The 20 subsamples from each plot were then combined and thoroughly homogenized to obtain one composite soil sample representing each plot. This composite sample was subsequently divided into two portions: a smaller portion was used for soil physicochemical characterization, whereas the remaining, larger portion was used for the fertilization bioassay. For physicochemical characterization, the composite soil from each plot was analyzed independently, thereby preserving the plot as the experimental unit. For the fertilization bioassay, the larger portion of the homogenized composite soil from each plot was transferred to a 6-kg plastic pot and used as the soil substrate for the corresponding plot-level treatment. Thus, the soil used in both the physicochemical analyses and the pot experiment originated from the same composite sample, with the plot retained as the independent experimental unit.

2.3. Soil Physical and Chemical Characterization

To characterize the soil physicochemically at each plot, we analyzed soil texture, clay flocculation, bulk density, pH, available phosphorus, exchangeable cations (K⁺, Na⁺, Ca²⁺, Mg²⁺, Al³⁺), active hydrogen (H⁺), cation exchange capacity (CEC), sodium saturation, total organic carbon, and total nitrogen at plot level. Soil texture was determined by particle size analysis of dispersed soil [21]. Clay flocculation was assessed according to the method described by Black [22], using NaCl to promote clay flocculation, and the degree of flocculation was determined by comparing the clay content measured under flocculated and fully dispersed conditions. Bulk density was measured based on soil weight per unit volume in a metallic cylinder [22]. Soil pH was determined in a 1:2.5 (soil:water) suspension [22]. Available phosphorus was extracted with Mehlich-1 solution and determined by colorimetry [23]. Exchangeable cations (K⁺, Na⁺, Ca²⁺, Mg²⁺) were extracted and analyzed using atomic absorption spectrophotometry for Ca²⁺ and Mg²⁺, and a flame photometer for K⁺ and Na⁺ [21]. Exchangeable Al³⁺ was determined using potassium chloride extraction [24]. CEC was calculated as the sum of K⁺, Na⁺, Ca²⁺, Mg²⁺, H⁺, and Al³⁺ [22], and sodium saturation (%) was determined as (Na⁺/CEC) × 100 [25]. Total organic carbon was estimated following Okalebo et al. [26]. Total nitrogen was quantified using Kjeldahl digestion with sulfuric acid and potassium sulfate [22].

2.4. Controlled Fertilization Bioassay

The experimental design of the controlled fertilization bioassay followed a completely randomized 4 × 3 × 2 factorial structures, accounting for four fertilization treatments (unfertilized, P addition, N addition, and combined P + N addition), three slope positions (shoulder, backslope, and footslope), and two pasture management systems (SDP and LMP). Pots were repositioned periodically throughout the experiment to minimize positional effects within the glasshouse. Four fertilization treatments were evaluated: unfertilized control; P addition (25 kg P₂O₅ ha⁻¹); N addition (50 kg N ha⁻¹); and combined P and N addition (25 kg P₂O₅ ha⁻¹ + 50 kg N ha⁻¹). Fertilization rates were established according to Cavalcanti et al. [27] and converted to the corresponding amount of fertilizer applied to

each 6-kg soil pot. The P treatment received [76.9 mg P_2O_5 pot⁻¹, equivalent to ~150 mg $NaH_2PO_4 \cdot H_2O$ pot⁻¹], whereas the N treatment received [153.8 mg N pot⁻¹, equivalent to ~726 mg $(NH_4)_2SO_4$ pot⁻¹]. The combined treatment received both fertilizer sources at the corresponding amounts. Thus, fertilizer application was based on the soil quantity and pot dimensions used in the bioassay. Each fertilization treatment had 10 independent replicates.

The experiment was conducted under controlled glasshouse conditions, with average temperatures of approximately 28 °C during the day and 20 °C at night. *Urochloa decumbens* seeds were surface-sterilized with 10% sodium hypochlorite for 10 min and subsequently rinsed thoroughly with deionized water. Seeds were germinated in sterilized trays containing sand that had been autoclaved at 121 °C for 20 min on two consecutive days. Seed germination and seedling emergence occurred in the trays. Seven days after emergence, seedlings measuring 4–6 cm in height were selected, and 20 healthy, uniformly developed seedlings were individually transplanted into plastic pots containing 6 kg of field-collected soil. Thus, the seedlings had already germinated and emerged before transplantation and were not expected to germinate after being transferred to the pots. Following transplantation, the plants were maintained under controlled glasshouse conditions and irrigated with sterilized water as needed for seven months.

The experiment was conducted in a glasshouse-controlled condition under average temperatures of 28 °C (day) and 20 °C (night). *Urochloa decumbens* seeds were sterilized in 10% sodium hypochlorite for 10 min, then rinsed thoroughly with deionized water. Seeds were germinated in sterilized trays filled with sand (autoclaved at 121 °C for 20 min on two consecutive days). Seven days after emergence, 20 seedlings (4–6 cm in height) were selected and individually transplanted into plastic pots containing 6 kg of field-collected soil. Plants were watered with sterilized water as needed during 7 months after planting.

2.5. Assessment of Plant Response to Fertilization and Nutrient Concentrations in *Urochloa decumbens*

U. decumbens plants were harvested 7 months after planting. Shoots were cut 5 cm above the soil surface to simulate herbivory. To estimate shoot dry biomass, the harvested shoots were oven-dried at 72 °C for 48 h. Plant responsiveness to fertilization (PRF) was calculated using the dry biomass values from the fertilized treatments and the control, applying the following formula: $PRF = [(B_{fertilized} - B_{control}) / B_{fertilized}] \times 100$, where $B_{fertilized}$ is the dry biomass of plants in the fertilized treatments, and $B_{control}$ is the dry biomass in the control treatment [28]. A known mass of the dry material was digested in a 10:1:4 mixture of $HNO_3:H_2SO_4:HCl$ (60%) and then analyzed for plant N concentration using the Kjeldahl method [23], and plant P concentration was determined using the vanadate-molybdate colorimetric method [29]. We also calculated the fertilization effect on plant N (FEN) and P (FEP) concentrations using the following formulas: $FE = (N \text{ or } P_{fertilized} - N \text{ or } P_{control}) / (N \text{ or } P_{fertilized} + N \text{ or } P_{control})$, where $N \text{ or } P_{fertilized}$ represents plant N and P concentrations in fertilized treatments, and $N \text{ or } P_{control}$ refers to plant N and P concentrations in the control treatment [28]. The fertilization effect can range from −1 to +1, with positive values indicating beneficial effects of fertilization on plant N and P concentrations and negative values indicating detrimental effects [28].

2.6. Statistical Analysis

The Kolmogorov–Smirnov test was used to assess the normality of the soil physicochemical variables. Before conducting the principal component analysis (PCA), the physicochemical dataset was organized at the plot level, with each plot represented by a single observation and each measured soil property represented by a variable. The PCA input matrix was therefore constructed from the plot-level values of the measured soil physicochemical properties. The variables were standardized to zero mean and unit

variance prior to PCA to place properties measured on different scales and with different units on a comparable basis. PCA was then performed on the standardized data using the correlation matrix to identify the major dimensions of variation and to evaluate similarities among soil samples based on their physicochemical properties. Principal components were retained according to their eigenvalues and cumulative proportion of explained variance, and variable loadings were examined to identify the soil properties contributing most strongly to each component. A Student's *t*-test for independent samples was used to evaluate differences between long-term managed pasture and short-term degraded pasture for each soil physicochemical property measured in the field. The plot was considered the experimental unit for field comparisons. For the fertilization bioassay, each individual pot containing 6 kg of homogenized soil collected from a given plot was considered the experimental unit.

One-way ANOVA was used to assess the effect of fertilization treatments on plant dry biomass, and plant N and P concentrations in *U. decumbens* from the fertilization bioassay. Data sets were $\log_{10}(x)$ transformed for all variables [30], but results are presented in their original scale of measurement (mean $\pm$ standard deviation). In the control treatment, plant response to fertilization (PRF) and fertilization effect (EF) were zero, so these were excluded from statistical analyses. When appropriate, Tukey's HSD post hoc comparisons were conducted. All statistical analyses were performed using SAS 9.1.3 Portable, while ecological indices and PCA analyses were conducted with MVSP 3.1 [31].

3. Results

3.1. Effects of Pasture Management on Soil Physicochemical Properties in Lixisols from Brazilian Northeast

Significant differences between the field samples from long-term managed pasture and short-term degraded pasture were found for soil physical properties across all studied slope positions (Table 1). Sand ($p < 0.01$), soil clay flocculation (SCF, $p < 0.01$), and soil bulk density (SBD, $p < 0.01$) were significantly higher in the soil samples from long-term managed pasture, while silt ($p < 0.01$) and clay ($p < 0.01$) were significantly higher in the soil samples from short-term degraded pasture. In the footslope position, both short-term and long-term pasture samples showed particularly high sand ($p < 0.05$), SCF ($p < 0.01$), and SBD ($p < 0.05$) values (Table 1).

For all studied conditions, significant differences in soil pH, available P, soil exchangeable cations, cation exchange capacity (C.E.C.), sodium saturation (S.S.), total organic carbon (T.O.C.), and total nitrogen (TN) were observed between the soil samples from long-term managed pasture and short-term degraded pasture (Table 2). The soil pH ($p < 0.01$), available P ($p < 0.01$), K^+ ($p < 0.05$), Na^+ ($p < 0.05$), and S.S. ($p < 0.05$) were significantly higher in the long-term managed pasture compared to the short-term degraded pasture soils. In the soil samples from long-term managed pasture, significant differences were found across slope positions for available P, soil exchangeable cations, C.E.C., sodium saturation, T.O.C., and TN, except for soil pH, where no differences were observed between slope positions. The highest values of available P ($1.80 \pm 0.01 \text{ mg kg}^{-1}$), Na^+ ($0.09 \pm 0.02 \text{ cmol}_c \text{ kg}^{-1}$), and sodium saturation ($1.95 \pm 0.04\%$) were found in the footslope, while the shoulder samples showed the highest Ca^{2+} ($1.53 \pm 0.11 \text{ cmol}_c \text{ kg}^{-1}$) and T.O.C. ($22.8 \pm 0.4 \text{ g kg}^{-1}$), and the backslope samples exhibited the highest K^+ ($0.24 \pm 0.01 \text{ cmol}_c \text{ kg}^{-1}$), Mg^{2+} ($1.13 \pm 0.02 \text{ cmol}_c \text{ kg}^{-1}$), $H^+ + Al^{3+}$ ($5.50 \pm 0.22 \text{ cmol}_c \text{ kg}^{-1}$), C.E.C. ($7.11 \pm 0.04 \text{ cmol}_c \text{ kg}^{-1}$), and TN ($1.61 \pm 0.05 \text{ g kg}^{-1}$). In contrast, for the short-term degraded pasture, Ca^{2+} ($p < 0.01$), Mg^{2+} ($p < 0.01$), $H^+ + Al^{3+}$ ($p < 0.01$), C.E.C. ($p < 0.01$), T.O.C. ($p < 0.05$), and TN ($p < 0.01$) were significantly higher compared to the long-term managed pasture. In the short-term degraded pasture, significant differences between slope positions were found for all studied soil chemical properties. The highest values

of soil pH (5.50 ± 0.03), available P ($1.10 \pm 0.03 \text{ mg kg}^{-1}$), and K^+ ($0.23 \pm 0.02 \text{ cmolc kg}^{-1}$) were found in the footslope, while the backslope samples exhibited the highest Na^+ ($0.10 \pm 0.01 \text{ cmolc kg}^{-1}$) and sodium saturation ($1.27 \pm 0.02\%$), and the shoulder samples showed the highest Ca^{2+} ($2.16 \pm 0.14 \text{ cmolc kg}^{-1}$), Mg^{2+} ($1.70 \pm 0.11 \text{ cmolc kg}^{-1}$), $\text{H}^+ + \text{Al}^{3+}$ ($5.50 \pm 0.22 \text{ cmolc kg}^{-1}$), C.E.C. ($9.55 \pm 1.09 \text{ cmolc kg}^{-1}$), T.O.C. ($23.2 \pm 0.3 \text{ g kg}^{-1}$), and TN ($1.93 \pm 0.02 \text{ g kg}^{-1}$) (Table 2).

Table 1. Soil physical properties as influenced by soil pasture management (mean $\pm$ SD).

Slope Position	Area	Sand	Silt	Clay	SCF	SBD
		g kg^{-1}			g cm^{-3}	
Shoulder	LMP ^a	798 ± 2.53	74 ± 4.61	128 ± 4.00	802 ± 1.06	1.30 ± 0.02
	SDP	629 ± 1.67	122 ± 1.72	249 ± 2.73	725 ± 3.45	1.20 ± 0.09
	<i>t</i> -test	8.13 *	12.03 **	19.80 **	7.19 *	8.55 **
Backslope	LMP	763 ± 3.86	74 ± 5.77	163 ± 8.12	844 ± 2.37	1.24 ± 0.12
	SDP	733 ± 9.45	116 ± 1.12	151 ± 6.44	662 ± 7.87	1.29 ± 0.01
	<i>t</i> -test	8.00 *	11.01 **	8.53 **	13.66 **	7.99 *
Footslope	LMP	837 ± 5.26	68 ± 1.56	95 ± 7.54	864 ± 1.92	1.43 ± 0.11
	SDP	817 ± 6.12	77 ± 3.32	106 ± 1.83	724 ± 12.02	1.33 ± 0.02
	<i>t</i> -test	8.35 *	8.94 **	9.26 **	11.98 **	8.01 *
	LMP vs. SDP ¹	12.34 **	11.63 **	16.32 **	12.65 **	13.78 **

^a LMP is the long-term managed pasture; SDP is the short-term degraded pasture. Neither area has received liming or fertilization during the field experiment. SCF: soil clay flocculation; SBD: soil bulk density. Asterisks indicate statistically significant differences between the studied areas in the physical soil properties (unpaired *t*-test, * for $p < 0.05$ and ** for $p \leq 0.01$), ¹ Independent sample *t*-test comparing LMP $\times$ SDP soil groups.

Table 2. Soil chemical properties as influenced by soil pasture management (mean $\pm$ SD).

Soil Property	Shoulder		<i>t</i> -Test	Backslope		<i>t</i> -Test	Footslope		<i>t</i> -Test	LMP vs. SDP ²
	LMP ^a	SDP		LMP	SDP		LMP	SDP		
Soil pH (H ₂ O)	5.60 ± 0.04	5.30 ± 0.03	11.90 **	5.50 ± 0.01	5.40 ± 0.02	8.33 *	5.60 ± 0.02	5.50 ± 0.03	8.21 *	10.20 **
Available P (mg kg ⁻¹)	1.30 ± 0.09	0.80 ± 0.02	15.13 **	1.00 ± 0.02	0.40 ± 0.05	10.01 **	1.80 ± 0.01	1.10 ± 0.03	9.98 **	11.32 **
K^+ (cmolc kg ⁻¹)	0.22 ± 0.02	0.14 ± 0.03	8.18 *	0.24 ± 0.01	0.17 ± 0.02	8.17 *	0.21 ± 0.01	0.23 ± 0.02	6.99 ns	8.25 *
Na^+ (cmolc kg ⁻¹)	0.08 ± 0.01	0.05 ± 0.01	8.30 *	0.08 ± 0.02	0.10 ± 0.01	7.01 ns	0.09 ± 0.02	0.06 ± 0.01	8.27 *	8.21 *
Ca^{2+} (cmolc kg ⁻¹)	1.53 ± 0.11	2.16 ± 0.14	14.23 **	1.26 ± 0.02	1.90 ± 0.04	8.98 **	1.16 ± 0.02	1.38 ± 0.03	7.12 ns	9.38 **
Mg^{2+} (cmolc kg ⁻¹)	1.12 ± 0.02	1.70 ± 0.11	9.38 **	1.13 ± 0.02	1.35 ± 0.01	8.12 *	0.95 ± 0.01	1.06 ± 0.02	7.21 ns	9.01 **
$\text{H}^+ + \text{Al}^{3+}$ (cmolc kg ⁻¹)	3.70 ± 0.31	5.50 ± 0.22	16.55 **	4.40 ± 0.06	4.30 ± 0.05	1.12 ns	2.20 ± 0.05	3.70 ± 0.03	9.53 **	8.03 *
CEC ¹ (cmolc kg ⁻¹)	6.65 ± 0.53	9.55 ± 1.09	15.83 **	7.11 ± 0.04	7.82 ± 0.02	8.26 *	4.61 ± 0.10	6.43 ± 0.02	10.23 **	9.87 **
S.S. (%)	1.21 ± 0.10	0.52 ± 0.05	16.21 **	1.12 ± 0.01	1.27 ± 0.02	2.12 ns	1.95 ± 0.04	0.93 ± 0.03	9.26 **	8.21 *

Table 2. Cont.

Soil Property	Shoulder		<i>t</i> -Test	Backslope		<i>t</i> -Test	Footslope		<i>t</i> -Test	LMP vs. SDP ²
	LMP ^a	SDP		LMP	SDP		LMP	SDP		
T.O.C. (g kg ⁻¹)	22.8 ± 0.4	23.2 ± 0.3	6.05 ns	22.5 ± 0.2	19.2 ± 0.1	11.12 **	21.1 ± 0.1	16.2 ± 0.2	12.45 **	12.33 **
TN (g kg ⁻¹)	1.52 ± 0.01	1.93 ± 0.02	8.91 **	1.61 ± 0.05	1.74 ± 0.01	8.33 *	1.41 ± 0.03	1.24 ± 0.02	8.21 *	11.31 **

^a LMP is the long-term managed pasture; SDP is the short-term degraded pasture. Neither area has received liming or fertilization. ¹ C.E.C.: cation exchange capacity (cmolc kg⁻¹); S.S. (%): sodium saturation. Asterisks indicate statistically significant differences between the studied areas in the soil properties (unpaired *t*-test, * for $p < 0.05$ and ** for $p \leq 0.01$), “ns” for non-statistical significant differences; ² Independent sample *t*-test comparing LMP × SDP soil groups.

The principal component analysis (PCA) revealed a distinct cluster for the long-term managed pasture, while a clear separation based on slope positions was observed for the short-term degraded pasture (Figure 1). PCA further indicated that long-term managed pastures, across all studied slope positions, were strongly correlated with higher levels of exchangeable K, soil pH, available P, soil clay flocculation, and total organic carbon (TOC). In contrast, short-term degraded pasture from the footslope position showed a correlation with higher total nitrogen (TN), exchangeable Mg, H⁺ + Al³⁺, clay content, and cation exchange capacity (C.E.C.) (Figure 1). Sodium saturation, soil bulk density, available P, total organic carbon, cation exchange capacity, clay, silt, and exchangeable Ca and K were the primary factors distinguishing the long-term managed pasture and short-term degraded pasture. The two principal components explained 83.46% of the variation observed in the samples (Figure 1).

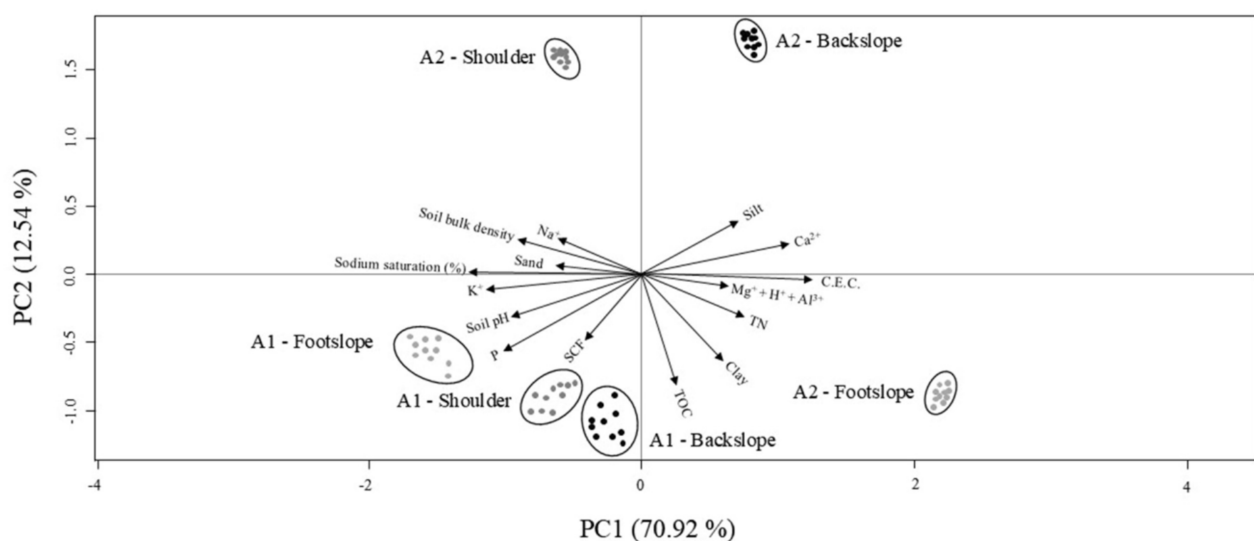


Figure 1. PCA score plot of soil properties for the studied sites. A1 refers to LMP, A2 refers to SDP. The points represent samples from each plot by pasture management and slope positions. SCF soil clay flocculation, C.E.C. cation exchange capacity, TOC total organic carbon, and TN total nitrogen.

3.2. Impact of Nitrogen and Phosphorus Fertilization on Plant Response and Nutrient Concentrations in *Urochloa decumbens*: A Controlled Experiment Bioassay

Mineral fertilization (i.e., N, P, and NP interactions) significantly influenced shoot dry biomass across all treatments ($F = 12.78$, $p < 0.0001$). In the shoulder position of the short-term pasture, no differences were observed between the control, N, and P fertilization treatments in terms of shoot dry biomass, whereas NP fertilization had a significantly positive effect. For the other treatments, both N and P fertilization positively affected shoot

dry biomass, with the highest values observed under NP fertilization (Figure 2a). Plant responsiveness to fertilization varied significantly across pasture type, mineral fertilization, and slope position treatments ($F = 15.21, p < 0.0001$). In both the long-term degraded pasture and short-term managed pastures, NP fertilization resulted in higher plant responsiveness compared to N and P fertilization treatments ($p < 0.05$). However, in the long-term degraded pasture, P fertilization had a negative effect on plant responsiveness ($p < 0.05$; Figure 2b).

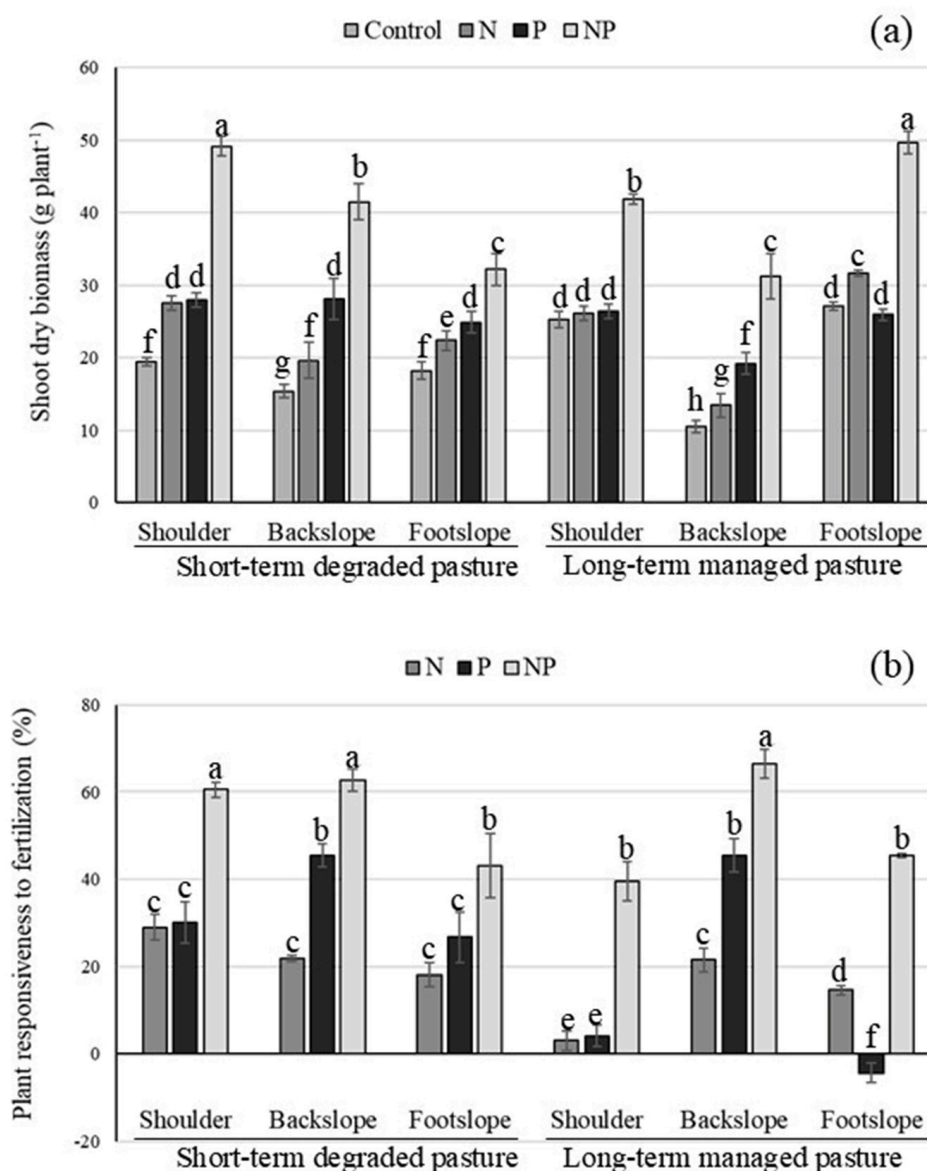


Figure 2. (a) Shoot dry biomass (g plant⁻¹). (b) Plant responsiveness to fertilization (%) for *Urochloa decumbens* growing in soil fertilized with NP (mineral N and P fertilization); N (N fertilization); P (P fertilization); and control (unfertilized). Values are mean and standard deviation of the mean. Different letters indicate significant differences after Tukey's HSD post hoc test ($p < 0.05$) between mineral fertilization treatments for each studied treatment.

Significant differences in plant P content were observed between mineral fertilization treatments for both long-term managed pasture and short-term degraded pastures ($F = 10.22, p < 0.0001$). No significant differences in plant P content were found between the control and mineral fertilization treatments. Analysis of the fertilization effect on plant P concentration, considering pasture management and slope position, revealed that both long- and short-term pastures experienced significant positive effects ($F = 15.21, p < 0.0001$).

when grown with P fertilization, while negative effects were observed when grown with N fertilization (Figure 3a,b).

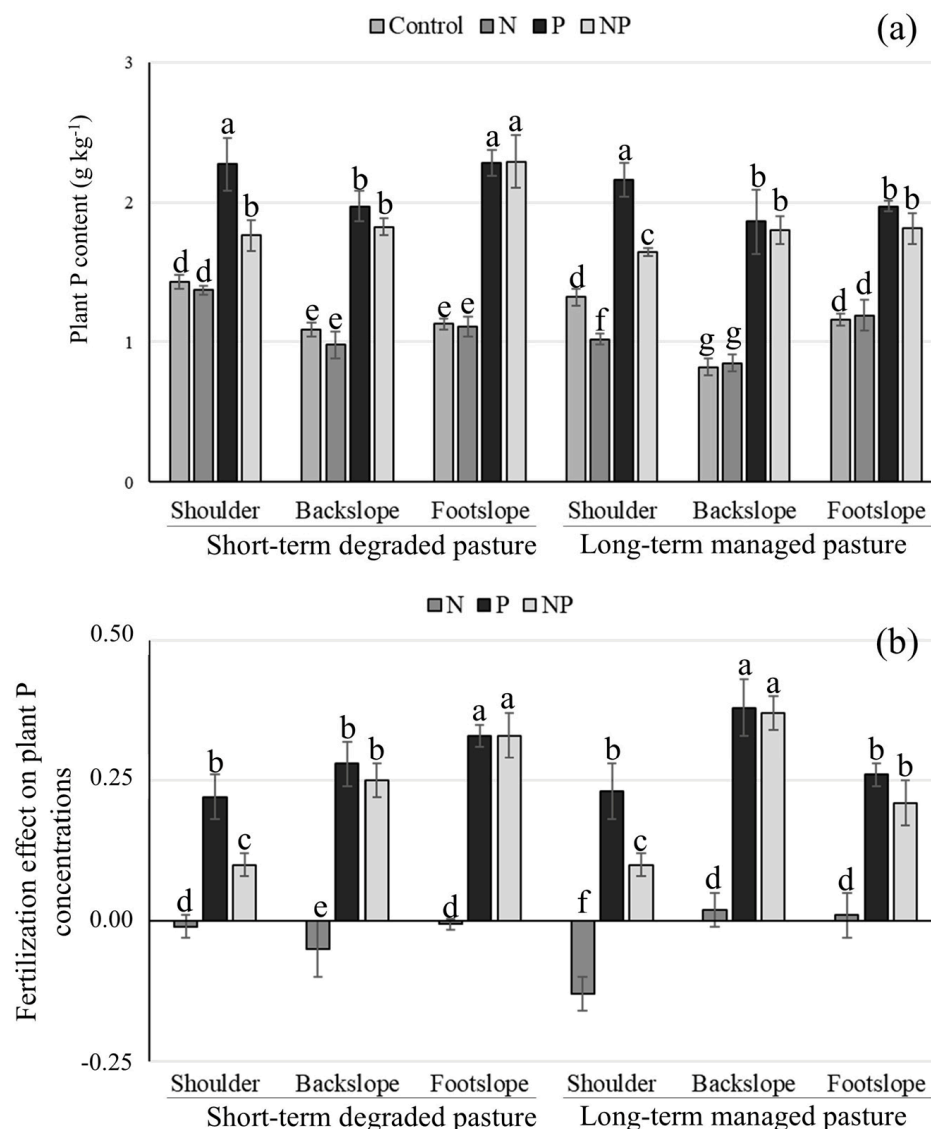


Figure 3. (a) Plant P content (g kg⁻¹). (b) Fertilization effect on plant P concentration for *Urochloa decumbens* growing in soil fertilized with NP (mineral N and P fertilization); N (N fertilization); P (P fertilization); and control (unfertilized). Values are mean and standard deviation of the mean. Different letters indicate significant differences after Tukey's HSD post hoc test ($p < 0.05$) between mineral fertilization treatments for each studied treatment.

Significant differences were observed in plant nitrogen content ($F = 13.44$, $p < 0.0001$) and the fertilization effect on plant N concentrations ($F = 16.02$, $p < 0.0001$) between long- and short-term pastures (Figure 4a,b). In long-term pastures, plant nitrogen content was significantly reduced under non-fertilization (control) and mineral fertilization treatments (e.g., N and NP fertilization). In contrast, N fertilization significantly increased plant nitrogen content (Figure 4a). The fertilization effect on plant N concentrations was significantly reduced under both mineral P and NP fertilization treatments, while N fertilization significantly enhanced the fertilization effect on plant N concentrations (Figure 4b).

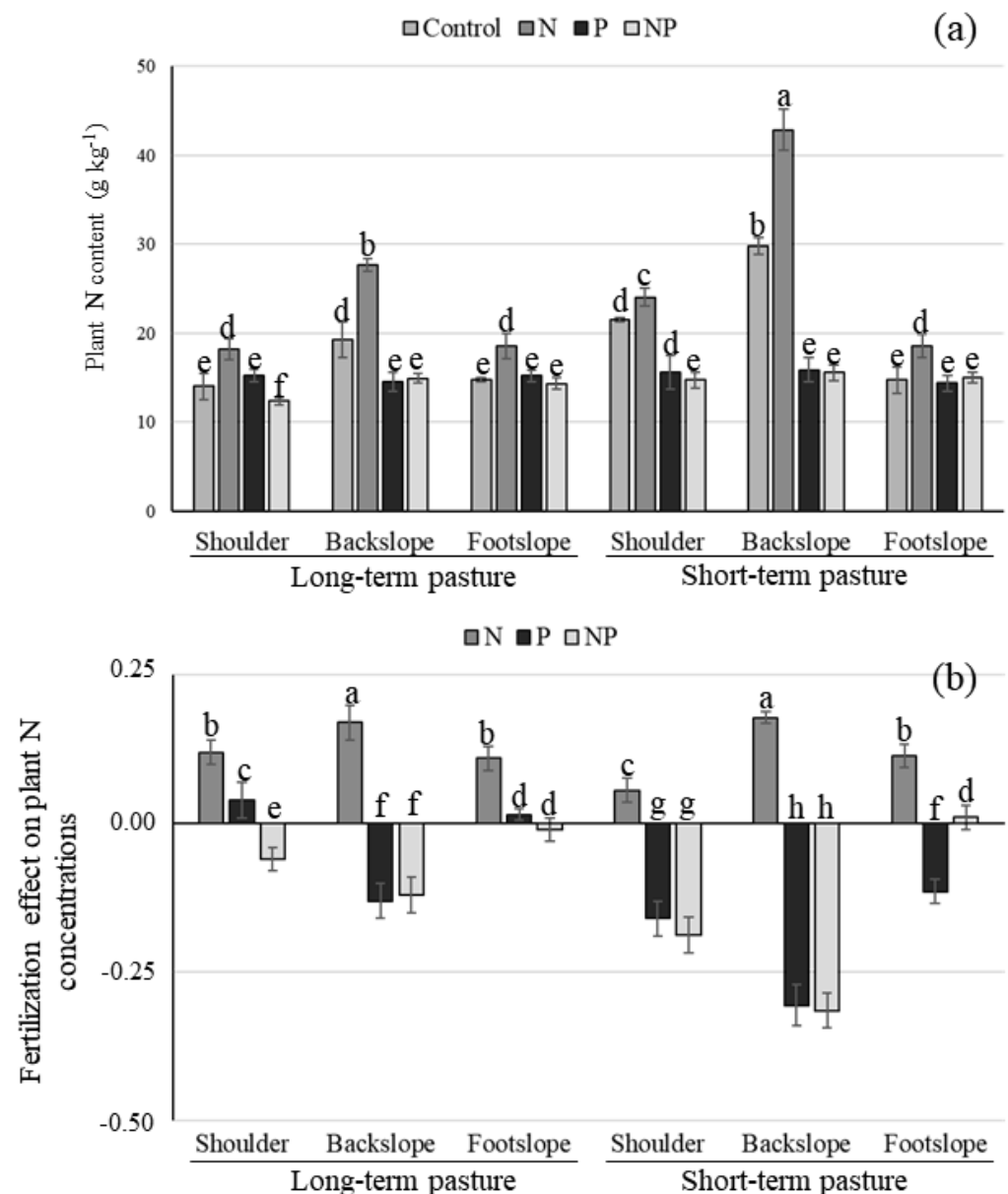


Figure 4. (a) Plant N content (g kg⁻¹). (b) Fertilization effect on plant N concentrations (%) for *Urochloa decumbens* growing in soil fertilized with NP (mineral N and P fertilization); N (N fertilization); P (P fertilization); and control (unfertilized). Values are mean and standard deviation of the mean. Different letters indicate significant differences after Tukey's HSD post hoc test ($p < 0.05$) between mineral fertilization treatments for each studied treatment.

4. Discussion

4.1. Effects of Pasture Management on Soil Physicochemical Properties in Lixisols from the Brazilian Northeast

The differences observed between the long-term managed pasture (LMP) and short-term degraded pasture (SDP) indicate that contrasting management histories were associated with changes in multiple soil physical and chemical attributes [32]. Similar effects of land-use and management changes on soil texture, bulk density, pH, organic carbon, and nutrient availability have been reported in other soil systems [33–35]. In addition, changes in soil aggregation and surface-soil properties under pasture management have been documented, highlighting the sensitivity of soil physical structure to management history [36]. Thus, the differences between LMP and SDP should be interpreted as a multidimensional

response involving several interacting soil attributes rather than as changes in a single indicator of degradation.

The higher sand content, bulk density, and clay flocculation observed under LMP, together with the higher clay and silt contents detected under SDP, demonstrate differences in the physical characteristics of the soils under the two management histories [33]. However, these results should not be interpreted as direct evidence of sediment loss or erosion, because sediment transport was not quantified in the present study. Likewise, higher bulk density does not necessarily indicate greater degradation in isolation, since this property is influenced by particle-size distribution, organic matter content, aggregation, and management conditions [34]. Previous studies have similarly emphasized the importance of considering multiple physical properties when evaluating changes in soil structure and compaction [35,36]. Therefore, the observed differences indicate contrasting soil physical conditions but do not allow the specific processes responsible for these differences to be directly established.

The higher soil pH and greater availability of P and exchangeable K observed in LMP suggest more favorable conditions for nutrient availability under this management history. Nutrient cycling is an important component of pasture functioning, with N, P, and K dynamics being closely associated with plant production and nutrient redistribution within pasture systems [37]. Nevertheless, because no fertilizer or amendment was applied during the period evaluated in the present study, the observed differences cannot be directly attributed to recent fertilizer inputs [38]. Instead, they indicate differences in the accumulated soil fertility status associated with the contrasting management histories [39]. These results are consistent with evidence that pasture management and nutrient inputs can modify soil fertility and nutrient cycling [37,40].

The greater total organic carbon and total nitrogen contents observed in SDP should also be interpreted cautiously [33,35,38]. Although these differences indicate contrasting soil nutrient pools, they do not demonstrate greater carbon stabilization, reduced decomposition, or enhanced microbial activity because these processes were not directly measured. Soil organic carbon responses to pasture management can vary according to pasture species, pasture age, and environmental conditions, and increases in soil carbon stocks have also been reported under managed pasture intensification [34,35,41]. Therefore, the higher carbon and nitrogen contents observed in SDP should be considered differences in measured soil pools rather than direct evidence of a particular carbon or nitrogen cycling mechanism.

The fertilization bioassay provided additional evidence that nutrient availability differed between the management histories. The growth response of *Urochloa decumbens* was more pronounced under combined N and P addition, particularly in soil from SDP, indicating that simultaneous availability of these nutrients can substantially affect plant performance. Previous studies have demonstrated that N and P availability can influence grass nutrient stoichiometry, forage production, and soil quality in managed grassland systems [39,40], while broader assessments of pasture nutrient cycling have also emphasized the importance of N and P in regulating plant productivity [37]. The stronger response to combined N and P addition in SDP may therefore indicate a greater limitation of plant growth by nutrient availability under this management history. However, this interpretation should not be taken to mean that SDP was uniformly nutrient depleted, because total soil nutrient pools and plant-available nutrient fractions represent different aspects of soil fertility.

The response of *U. decumbens* to fertilization is also consistent with previous observations that fertilization management can modify structural and anatomical characteristics of *Urochloa* plants [41–43]. In the present study, however, the bioassay was used primarily to evaluate plant responses to nutrient additions rather than to identify the physiological

mechanisms underlying these responses. Thus, the results support the interpretation that nutrient availability contributed to differences in plant performance between soils from LMP and SDP, while the specific physiological pathways responsible for these responses remain beyond the scope of the present study.

Overall, the results indicate that pasture degradation was associated with a multidimensional alteration of soil physical and chemical properties and with a different plant response to nutrient supplementation. The observed differences in clay and silt contents are compatible with possible differences in particle redistribution or retention, but sediment loss was not measured and therefore cannot be inferred directly [33]. Similarly, nutrient leaching was not quantified, and the present data do not permit its magnitude or contribution to the observed differences to be established. These processes should therefore be regarded as potential explanations requiring direct investigation rather than as demonstrated mechanisms. Future studies combining measurements of sediment transport, nutrient leaching, soil nutrient availability, and temporal changes in soil properties would help clarify the processes responsible for the divergence between managed and degraded pasture systems.

4.2. Impact of Nitrogen and Phosphorus Fertilization on Plant Response and Nutrient Concentrations in *Urochloa decumbens*: A Controlled Bioassay

The results demonstrate that pasture management history and slope position jointly influenced soil properties and the response of *Urochloa decumbens* to nutrient addition, supporting the landscape degradation hypothesis [8,13]. However, the most relevant finding was not simply the greater biomass response to fertilization in degraded pasture but the contrasting relationship between soil nutrient pools and plant nutrient status. In particular, the occurrence of relatively high total soil nitrogen alongside reduced plant N concentration indicates that total soil N did not necessarily translate into an adequate N supply to plants. Total soil N comprises organic and inorganic forms with different degrees of availability and therefore represents a nutrient pool rather than a direct measure of plant-available N [8,33,40]. Consequently, the observed N limitation may reflect restricted N availability or synchronization between N release and plant demand rather than a simple depletion of total soil N [41,42]. This distinction is important when interpreting soil fertility in degraded pasture systems.

The response of *U. decumbens* to fertilization varied among slope positions and nutrient combinations. At the shoulder position of the short-term pasture, N or P applied individually did not significantly increase shoot dry biomass, whereas combined NP fertilization produced a significant increase [40]. At other slope positions, N and P additions increased biomass, with the greatest response generally occurring under NP fertilization. This pattern indicates that plant growth was not controlled by a single nutrient across the landscape [43]. Instead, the stronger response to combined N and P suggests that simultaneous limitations can occur and that supplying only one nutrient may be insufficient to overcome the constraints imposed by the prevailing soil conditions [44]. Similar responses to N and P availability have been reported in managed grasslands, where nutrient additions can modify plant production and nutrient stoichiometry [38–40].

The greater response to NP fertilization in the short-term degraded pasture is particularly relevant because it indicates that nutrient limitation was more readily expressed when plants were exposed to degraded soil conditions [45]. The lower plant N concentration observed under several fertilization treatments, together with the positive response to N addition when N was supplied alone [46], suggests that the capacity of the soil to provide N to plants was an important constraint. Importantly, however, this pattern should not be interpreted as evidence that total soil N was depleted. Rather, the contrast between soil total N and plant N indicates that the size of the total N pool and its availability to plants

were not equivalent. Differences in N mineralization, immobilization, nutrient retention, or synchronization between nutrient release and plant demand could potentially contribute to this discrepancy, but these processes were not directly measured in the present study. Thus, they should be considered plausible explanations rather than demonstrated mechanisms.

The plant P response further emphasizes the importance of nutrient interactions. Significant differences in plant P concentration among fertilization treatments indicate that P availability contributed to plant nutritional status and biomass production [45]. However, the contrasting responses to N and P additions indicate that nutrient supply cannot be evaluated independently for each element. Changes in the availability of one nutrient may alter plant demand for, or acquisition of, another, particularly when nutrient ratios are unbalanced [39,47]. The greater biomass response to NP than to either nutrient alone therefore provides stronger evidence for combined nutrient limitation than for an isolated N or P deficiency. This interpretation is also consistent with studies showing that balanced N and P supply can improve forage production and soil quality in managed grasslands [40].

The differences among slope positions should likewise be interpreted cautiously. The absence of a biomass response to N or P alone at the shoulder position of the short-term pasture may be compatible with differences in soil redistribution and nutrient availability along the slope [42,43], but the present study did not directly quantify soil translocation, erosion, or nutrient fluxes. Therefore, erosion and nutrient redistribution cannot be established as the causes of the observed spatial pattern. The results instead demonstrate that slope position modified the soil–plant response to fertilization and that local soil conditions can influence the effectiveness of nutrient inputs [48].

From a management perspective, these findings indicate that fertilizer recommendations based exclusively on total soil nutrient concentrations may not adequately reflect plant nutrient requirements. Nutrient management should consider nutrient availability, plant response, slope position, and the balance between N and P rather than focusing on the addition of a single nutrient. In degraded pasture, combined and appropriately balanced nutrient inputs may be more effective for recovering plant productivity than isolated applications, particularly where simultaneous nutrient limitations occur [37,40]. At the same time, fertilizer management should be based on soil testing and site-specific requirements to avoid unnecessary nutrient inputs and potential nutrient losses. Maintaining adequate pasture cover and reducing management practices that accelerate soil degradation are also important complementary measures for sustaining soil fertility and plant productivity.

Several limitations should be considered when interpreting these results. The experiment evaluated plant responses in a controlled fertilization bioassay and therefore does not directly reproduce the full range of processes operating under field conditions. In addition, nutrient leaching, erosion, sediment transport, N mineralization, microbial immobilization, and temporal changes in plant-available N and P were not directly measured. The study therefore cannot establish whether these processes caused the observed differences in plant nutrient status or biomass. Future field-based studies incorporating measurements of mineral N, available P, nutrient fluxes, erosion or sediment redistribution, and temporal changes in soil and plant nutrient pools would help identify the processes responsible for the contrasting responses observed among management histories and slope positions.

5. Conclusions

This study demonstrates that contrasting pasture management histories were associated with significant differences in the physicochemical properties of Lixisols across slope positions in the Brazilian Northeast. Long-term managed pasture (A1) was characterized by higher soil pH, available phosphorus, and exchangeable potassium, indicating a more favorable soil fertility status for plant production with respect to these properties. In

contrast, short-term unmanaged/degraded pasture (A2) exhibited higher clay and silt contents, as well as greater total organic carbon and total nitrogen. These differences indicate contrasting soil nutrient pools and physical conditions but do not, by themselves, demonstrate specific processes such as erosion, nutrient leaching, or altered nutrient cycling. The fertilization bioassay further demonstrated that *Urochloa decumbens* responded most strongly to combined N and P addition, particularly in A2, indicating that plant productivity may be constrained by multiple nutrient limitations rather than by a single nutrient alone. These responses, however, should be interpreted within the context of the controlled pot-experiment conditions and should not be directly extrapolated to field conditions. The contrast between relatively high soil total N and reduced plant N under some treatments also highlights that total soil nutrient pools do not necessarily reflect nutrient availability to plants. Under field conditions, plant responses to fertilization may differ because of spatial variability in soil properties, root exploration, water availability, microbial interactions, and nutrient dynamics. Consequently, the bioassay identifies potential nutrient limitations but does not establish their magnitude or persistence under field conditions or predict long-term forage productivity. These findings emphasize the importance of evaluating soil fertility using both soil properties and plant responses when assessing degraded pasture systems. The results support the adoption of site-specific and balanced nutrient management, particularly with respect to N and P supply, as a potential strategy for improving plant growth, although field validation is required before these findings can be translated into specific fertilizer recommendations. Field experiments conducted under realistic grazing and pasture-management conditions, with repeated measurements of plant productivity and nutrient availability, are needed to determine whether the observed fertilization responses persist under field conditions and to establish their agronomic relevance. The results also support the consideration of management practices that maintain soil cover and reduce further degradation. However, direct measurements of nutrient availability, nutrient fluxes, erosion, sediment redistribution, and leaching are needed to identify the processes responsible for the observed differences among management histories and slope positions. Such approaches would improve the development of sustainable pasture-management strategies for maintaining soil fertility and forage productivity in tropical environments.

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Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

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