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Productive response of grasses and legumes to different levels of phosphorus fertilization

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ABSTRACT: Phosphorus deficiency in tropical soils restricts forage production, requiring appropriate fertilisation to improve the yield of grasses and legumes. The objective of the study was to evaluate the productive response of two forage grasses (*Brachiaria decumbens* and *Brachiaria dictyoneura*) and three legumes (*Desmodium ovalifolium, Stylosanthes guianensis* cv. "Pucallpa", and *Pueraria phaseoloides* - "Kudzu") to different levels of phosphorus fertilisation and its combination with calcium, sulphur, and potassium. A randomised complete block design with three replications was used at the "La Esperanza" Experimental Station, Puerto Bermúdez, Peru. Ten fertilisation treatments were established, ranging from no fertilisation to combined applications of 60 kg ha^{-1} of P_2O_5, 750 kg ha^{-1} of Ca, 20 kg ha^{-1} of S, and 40 kg ha^{-1} of K_2O. The results showed significant differences in dry matter production between species and treatments ($p < 0.05$). Among grasses, *Brachiaria decumbens* achieved its highest yield with treatment 10 (2953 kg ha^{-1}), while among legumes, *Stylosanthes guianensis* excelled with 2682 kg ha^{-1} under treatment 8. These findings highlight the importance of balanced fertilisation in forage productivity, providing key information for optimising agronomic management in low-fertility tropical soils.
Keywords: forage grasses; forage legumes; forage productivity; tropical soils.

Resposta produtiva de gramíneas e leguminosas a diferentes níveis de fertilização com fósforo

Resumo: A deficiência de fósforo em solos tropicais restringe a produção de forragem, exigindo fertilização adequada para melhorar o rendimento de gramíneas e leguminosas. O objetivo do estudo foi avaliar a resposta produtiva de duas gramíneas forrageiras (*Brachiaria decumbens e Brachiaria dictyoneura*) e três leguminosas (*Desmodium ovalifolium, Stylosanthes guianensis* cv. “Pucallpa” e *Pueraria phaseoloides* - ‘Kudzu’) a diferentes níveis de fertilização com fósforo e sua combinação com cálcio, enxofre e potássio. Utilizou-se um delineamento em blocos casualizados com três repetições na Estação Experimental “La Esperanza”, em Puerto Bermúdez, Peru. Foram estabelecidos dez tratamentos de fertilização, variando de nenhuma fertilização a aplicações combinadas de 60 kg ha^{-1} de P_2O_5, 750 kg ha^{-1} de Ca, 20 kg ha^{-1} de S e 40 kg ha^{-1} de K_2O. Os resultados mostraram diferenças significativas na produção de matéria seca entre espécies e tratamentos ($p < 0,05$). Entre as gramíneas, a *Brachiaria decumbens* alcançou seu maior rendimento com o tratamento 10 (2953 kg ha^{-1}), enquanto entre as leguminosas, a *Stylosanthes guianensis* se destacou com 2682 kg ha^{-1} no tratamento 8. Essas descobertas destacam a importância da fertilização equilibrada na produtividade forrageira, fornecendo informações essenciais para otimizar o manejo agronômico em solos tropicais de baixa fertilidade.
Palavras-chave: gramíneas forrageiras; leguminosas forrageiras; produtividade forrageira; solos tropicais.

1. INTRODUCTION

Livestock production in tropical regions largely depends on the availability and quality of forage, which forms the basis of animal feed. However, the productivity of forage species in tropical soils is often limited by low soil fertility and acidity, which restricts the availability of essential nutrients for plant growth (FAGERIA; BALIGAR, 2008; SÁNCHEZ, 2019). In particular, phosphorus (P) is one of the most limiting macronutrients in these ecosystems, as it tends to become insoluble due to the presence of iron and aluminium oxides, reducing its availability to plants (NOVAIS et al., 2007).

This element is essential for root growth, protein synthesis, and efficiency in the absorption of other nutrients. Still, in highly weathered tropical soils, its availability is reduced due to its fixation by iron and aluminium oxides (MIELKI et al., 2016).

Previous studies have demonstrated that phosphorus fertilisation significantly improves biomass production in forage grasses and legumes, increasing dry matter yield and pasture persistence (RAO et al., 2015; MOREIRA et al., 2018). Furthermore, research has indicated that combining phosphorus with other nutrients such as calcium (Ca), sulphur (S), and potassium (K) can enhance plant growth by improving nutrient absorption and water use efficiency (AZEVEDO et al., 2019; LÓPEZ et al., 2020). However, the response to fertilisation varies considerably between species, depending on their nutrient acquisition strategies and soil interactions (SINGH et al., 2016).

Despite these findings, questions remain regarding the optimal phosphorus dose and its interaction with other nutrients in acidic tropical soils. In grasses of the *Brachiaria genus*, some studies have reported a positive response to phosphorus fertilisation in terms of biomass accumulation, but with variable phosphorus use efficiency among species (RAO et al., 2015). In the case of forage legumes, phosphorus has been observed to be crucial for biological nitrogen fixation and root growth. Still, its response depends on the calcium content in the soil (MOREIRA et al., 2018). These differences highlight the need to evaluate the impact of fertilisation on multiple species and specific edaphoclimatic conditions.

In this context, the present study aimed to evaluate the effect of different levels of phosphorus fertilisation and its combination with Ca, S, and K on dry matter yield in two grass species (*Brachiaria decumbens* CIAT 606 and *Brachiaria dictyoneura* CIAT 6133) and three legumes (*Desmodium ovalifolium* CIAT 350, *Stylosanthes guianensis* CIAT 184 cv. "Pucallpa" and *Pueraria phaseoloides* CIAT 9900 "Kudzu"). The research was conducted at the "La Esperanza" Experimental Station in Puerto Bermúdez, an ecosystem characterised by high rainfall and low natural soil fertility.

This study aims to generate relevant information to optimize pasture fertilisation in tropical soils, thereby providing guidelines to enhance forage productivity and the sustainability of livestock systems in the Peruvian Amazon.

2. MATERIALS AND METHODS

The study was conducted at the "La Esperanza" Experimental Station, located in Puerto Bermúdez, Oxapampa province, Pasco department, Peru. This area belongs to a tropical rainforest ecosystem, characterized by an altitude of 300 m above sea level, an average annual precipitation of 3,312 mm, and an average temperature of 25.8°C.

2.1. Climatological characteristics of the Pichis-Puerto Bermúdez Valley

High temperatures with moderate seasonal variation characterize the climate in the study area. The average annual temperature is 25.8°C, with maximum temperatures reaching up to 31.5°C (typically observed in September and October) and minimum temperatures dropping to 19.2°C (common in June and July). Rainfall shows marked seasonality, ranging from 120 mm (the driest month, August) to 500 mm (the wettest month, December), with a pronounced rainy season from October to April.

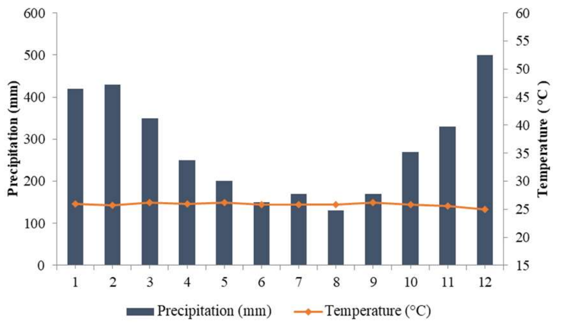

Figure 1. Climatological characteristics of the Pichis Valley.
Figura 1. Características climatológicas da área do Vale do Pichis.

2.2. Soil characterization

The soil of the experimental plots showed the characteristics presented in Table 1. The soil of the experimental plots exhibited the following characteristics: high acidity, high exchangeable acidity, low levels of essential nutrients (Ca, Mg, and K), high aluminium saturation (Al Sat.), low base saturation, and low effective cation exchange capacity, with moderate organic matter content at the surface and low levels at depth.

Table 1. Chemical characteristics of the soils in the study area.
Tabela 1. Características químicas dos solos na área de estudo.

stratum	pH	meq/100 g					Al Sat.	B.Sat.	O.M.
		Acidity	Ca	Mg	K	ECEC*	(%)	(%)	(%)
0 - 19	4.1	5.6	0.27	0.18	0.10	6.15	91	9	2.3
20 - 46	4.6	4.4	0.53	0.17	0.08	5.18	85	15	**1.3**

*ECEC - Effective Cation Exchange Capacity - B.S. Base Saturation - O.M. Organic Matter;

2.3. Treatment characteristics

The treatments consisted of different combinations of fertilizers based on P_2O_5 with Ca, S, and K_2O. The treatments ranged from total absence of fertilisation (Treatment 1) to specific combinations of nutrients, with Treatment 10 including 60 kg ha^{-1} of P, 750 kg ha^{-1} of Ca, 20 kg ha^{-1} of S, and 40 kg ha^{-1} of K_2O, representing a complete and balanced fertilization. Five forage species were evaluated, divided into two groups: grasses and legumes. The grasses included *Brachiaria decumbens* CIAT 606 and *Brachiaria dictyoneura* CIAT 6133, while the assessed legumes were *Desmodium ovalifolium* CIAT 350, *Stylosanthes guianensis* CIAT 184 cv. "Pucallpa", and *Pueraria phaseoloides* CIAT 9900 "Kudzu" (Figure 2). A randomised complete block experimental design with three replications was used. Each experimental plot measured 2 x 2 metres (4 m²).

Table 2. Fertilization levels (kg ha^{-1}).
Tabela 2. Níveis de fertilização (kg ha^{-1}).

Treatment	P_2O_5	Ca	S	K_2O
1	0	0	0	0
2	20	0	0	0
3	40	0	0	0
4	60	0	0	0
5	60	0	20	40
6	0	750	0	0
7	20	750	0	0
8	40	750	0	0
9	60	750	0	0
10	60	750	20	40

Figure 2. Images of the forage plants evaluated in the experimental plots.
Figura 2. Imagens das plantas forrageiras avaliadas nas parcelas experimentais.

The treatments consisted of applying different levels of phosphorus (P_2O_5), calcium (Ca), sulphur (S), and potassium (K) fertilization. Ten treatments were established with combinations of these nutrients, ranging from no fertilisation to the maximum application of 60 kg ha^{-1} of P_2O_5, 750 kg ha^{-1} of Ca, 20 kg ha^{-1} of S, and 40 kg ha^{-1} of K_2O. The fertilizer sources used were triple superphosphate for phosphorus, dolomitic lime for calcium, magnesium sulphate for sulphur, and potassium chloride for potassium.

Soil preparation was performed by mechanical tillage using a rotary cultivator, followed by the application of fertilizers as topdressing and manual broadcasting of seeds (2.5 kg of viable seed ha^{-1}) in May. Both inputs were incorporated into the soil with a rake to establish a target density of 20–30 plants m^{-2}. Dry matter yield was evaluated at eight-week intervals over two years, with uniformity cuts conducted after each evaluation and adjusted to the growth habit of each species. Weed control was performed by manual weeding quarterly.

An analysis of variance (ANOVA) was performed to evaluate differences among treatments and to determine whether variations in dry matter yield across fertilizer doses were statistically significant or attributable to random variation. Multiple mean comparisons were conducted using Tukey’s honestly significant difference (HSD) test. All analyses were carried out at a 5% significance level.

3. RESULTS

3.1. Dry matter yield in grasses

In *B. decumbens*, the highest yield was observed with treatment 10, reaching 2953 ± 5.31 kg ha^{-1}, followed by treatments 3 and 4 with 2725 ± 5.31 kg ha^{-1} and 2623 ± 4.92 kg ha^{-1}, respectively (Table 3). Treatments 2, 9, 8, and 5 showed intermediate yields ranging from 2513 to 2074 kg ha^{-1}. The lowest values corresponded to treatments 6, 1, and 7, with yields below 2014 kg ha^{-1}, with treatment 7 showing the lowest value (1997 ± 0.11 kg ha^{-1}). The values shown suggest a primary positive response to phosphorus fertilization, with increased yields when a balanced combination of nutrients is applied.

Table 3. Dry matter yield (kg ha^{-1}) of two grasses evaluated with different fertilization levels.
Tabela 3. Rendimento de matéria seca (kg ha^{-1}) de duas gramíneas avaliadas com diferentes níveis de fertilização, espécies avaliadas sob diferentes tratamentos.

Brachiaria decumbens CIAT 606		*Brachiaria dictyoneura* CIAT 6133	
Treatment	Yield	Treatment	Yield
10	2,953 ± 5.44^{a}	8	2768 ± 4.90^{a}
3	2,725 ± 5.31^{ab}	10	2762 ± 7.12^{ab}
4	2623 ± 4.92^{abc}	1	2692 ± 5.56^{abc}
2	2513 ± 2.62^{abcd}	2	2682 ± 3.3^{abcd}
9	2428 ± 0.47^{abcd}	9	2740 ± 2.87^{abcd}
8	2102 ± 6.65^{abcd}	5	2540 ± 2.83^{abcd}
5	2074 ± 7.13^{abcd}	3	2490 ± 2.05^{abcd}
6	2014 ± 6.94^{d}	4	2452 ± 4.50^{abcd}
1	2008 ± 5.73^{d}	7	2251 ± 1.89^{cd}
7	1997 ± 0.11^{d}	6	2267 ± 1.63^{d}

Note: Letters with the same value in the column indicate no significant differences (Tukey test, $p > 0.05$).
Nota: Letras com o mesmo valor na coluna indicam que não há diferenças significativas (teste de Tukey, p > 0,05).

In contrast, *B. dictyoneura* showed a different response, with treatment 8 (40 kg ha^{-1} of P_2O_5 + 750 kg ha^{-1} of Ca) generating the highest yield (2768 ± 4.90 kg ha^{-1}), closely followed by treatments 10 and 1 with 2762 ± 7.12 and 2692 ± 5.56 kg ha^{-1}, respectively. Interestingly, the therapy without fertilization (1) produced a relatively high yield in this species, suggesting that *B. dictyoneura* might have greater nutrient use efficiency or better adaptation to low fertility conditions compared to *B. decumbens*.

3.2. Dry matter yield in legumes

The dry matter yields obtained in legumes, as a result of the application of fertilizers in different combinations, are shown in Table 4. In the species *Desmodium ovalifolium*, treatment 5 had the highest yield (1973 ± 2.45 kg ha^{-1}), followed by treatment 7 (1933 ± 5.79 kg ha^{-1}), while the treatments with the lowest yields were treatment 1 (1552 ± 5.44 kg ha^{-1}) and treatment 2 (1514 ± 4.50 kg ha^{-1}). There are significant differences between treatments, especially between those with the highest and lowest yields.

The species *Stylosanthes guianensis* cv. Pucallpa exhibited a more homogeneous performance, as almost all treatments showed high and similar yields, with no significant differences among them. Treatment 8 had the highest yield (2682 ± 3.30 kg ha^{-1}), while treatment 5 had the lowest (2208 ± 1.70 kg ha^{-1}).

In the legume *Pueraria phaseoloides* – Kudzu, treatment 10 had the highest yield (1398 ± 4.64 kg ha^{-1}), followed by treatment 9 (1254 ± 5.89 kg ha^{-1}), while treatment 4 had the lowest yield (839 ± 6.16 kg ha^{-1}), with significant differences compared to the others.

3.3. ANOVA in Grasses

This analysis compared how different grass species responded to the same fertilizer doses, allowing for the identification of which species were more sensitive or resistant to changes in fertilisation. The results of the analysis are presented in Table 5.

Table 4. Dry matter yield (kg ha-1) of three legumes evaluated with different fertilization levels.
Tabela 4. Rendimento de matéria seca (kg ha-1) de três leguminosas avaliadas com diferentes níveis de fertilização.

Desmodium ovalifolium		*Stylosanthes guianensis* cv. Pucallpa		*Pueraruia phaseoloides* Kudzu	
Treatment	Yield	Treatment	Yield	Treatment	Yield
5	1973 ± 2.45ᵃ	8	2682 ± 3.30ᵃ	10	1398 ± 4.64ᵃ
7	1933 ± 5.79ᵃᵇ	6	2536 ± 0.82ᵃ	9	1254 ± 5.89ᵃᵇ
10	1875 ± 3.40ᵃᵇᶜ	9	2480 ± 2.36ᵃ	6	1242 ± 1.41ᵃᵇᶜ
8	1872 ± 6.02ᵃᵇᶜᵈ	10	2470 ± 6.13ᵃ	1	1209 ± 1.25ᵃᵇᶜᵈ
6	1825 ± 1.41ᵃᵇᶜᵈᵉ	3	2430 ± 6.24ᵃ	7	1174 ± 4.32ᵃᵇᶜᵈᵉ
9	1825 ± 3.68ᵃᵇᶜᵈᵉ	7	2379 ± 4.50ᵃ	8	1176 ± 3.74ᵃᵇᶜᵈᵉ
4	1816 ± 5.31ᵃᵇᶜᵈᵉ	t	2317 ± 0.47ᵃ	5	1158 ± 4.11ᵃᵇᶜᵈᵉ
3	1762 ± 4.24ᵈ	4	2280 ± 4.19ᵃ	2	1067 ± 5.44ᵃᵇᶜᵈᵉ
1	1552 ± 5.44ᶜᵈᵉ	2	2264 ± 4.50ᵃ	3	1047 ± 1.25ᵇᶜᵈᵉ
2	1514 ± 4.50ᵉ	5	2208 ± 1.70ᵃ	4	839 ± 6.16ᵇᶜᵈᵉ

Note: Letters with the same value in the column indicate no significant differences (Tukey test, p > 0.05).
Nota: Letras com o mesmo valor na coluna indicam que não há diferenças significativas (teste de Tukey, p > 0,05).

Table 5. ANOVA Results.
Tabela 5. Resultados da ANOVA.

Source of variation	Sum of squares	df	Mean square	F-ratio	P-value
A: Fertilizer rates	2838110	9	315345	10.09	0.0000
B: Grass species	738816	1	738816	23.63	0.0000
Error	1532080	49	31267		
CV	0.17				
Total	5109001	59			

The p-values (p = 0.000, < 0.05) indicate that there are significant differences both among the fertilisation levels and among the studied species. This confirms that the analyzed factors have a substantial effect on dry matter production. The low coefficient of variation (CV) suggests that the data were relatively consistent.

3.4. ANOVA in Leguminous Species

This analysis helped determine whether increasing the fertiliser dose significantly improved yield or if, beyond a certain dose, no additional benefits were observed. This is crucial to avoiding excessive fertiliser use, which can be both costly and harmful to the environment. Table 6 presents the results of the analysis of variance.

Table 6. ANOVA Results.
Tabela 6. Resultados da ANOVA.

Source of variation	Sum of squares	df	Mean square	F-ratio	P-value
A: Fertilizer rates	938206	9	104245	9.75	0.0000
B: Legume species	23379100	2	11689500	1093.02	0.0000
Error	834186	78	10695	-	-
CV	0.24	-	-	-	-
Total	25151500	89	-	-	-

4. DISCUSSION

Figure 1 presents the climatological characteristics of the Pichis-Puerto Bermúdez Valley, highlighting high temperatures along with pronounced seasonality and high levels of rainfall, which typically extend from October to April, with significant local variations (ZUBIETA et al., 2017). These characteristics indicate a hydroclimatology typical of the Peruvian Amazon-Andean basin, where Andean influence is reflected in the seasonal variability of precipitation. At the same time, high temperatures and elevated rainfall levels are more characteristic of the Amazon region. However, both regions exhibit diurnal variability, noted by Segura et al. (2019) as a daily thermal amplitude exceeding 15°C in high Andean areas. In contrast, in the lower Amazon, this variation is less than 10°C.

The 0-19 cm and 20-46 cm strata (Table 1) correspond to extremely to strongly acidic soils (pH 4.1 and 4.6), as these values are below 5.5, as classified by Desta et al. (2021). These are related to the acidity values of 5.6 and 4.4, manifested by the presence of hydrogen (H^+) and aluminium (Al+3) ions, where Al^{+3} becomes dominant, saturating the soil, flocculating clays, which hinders their dispersion and promotes their accumulation (QUESADA et al., 2011). This can limit nutrient availability and increase toxicity.

The 0.27 meq/100 g value in the first stratum (Table 1) is very low and suggests a severe calcium deficiency. According to HAVLIN et al. (2016), soils with less than one meq/100 g of calcium may present compaction issues, low nutrient availability, and nutritional imbalances. The 0.53 meq/100 g value in the second stratum, although higher than the previous one, remains low and may indicate moderate calcium deficiency Fageria et al. (2011) state that levels below 2.0 meq/100 g may limit plant growth and cause symptoms such as deformed leaves or necrosis at the edges. Low calcium levels are characteristic of acidic soils. The optimal levels of exchangeable calcium in agricultural soils generally range between 2.5 and 10 meq/100 g (BRADY; WEIL, 2016; HAVLIN et al., 2016). According to FAGERIA et al. (2011), values below 2.5 meq/100 g are considered low and may indicate calcium deficiency, affecting plant growth and soil structure.

The magnesium values of 0.17 and 0.18 meq/100 g (Table 1) are relatively low, suggesting a possible deficiency of this element in the soil. According to the classification by Havlin et al. (2016), these levels of exchangeable magnesium fall into the low category, indicating that the soil may not supply sufficient magnesium for optimal crop growth. Low magnesium levels may limit plant growth, as magnesium is an essential nutrient for photosynthesis (chlorophyll formation) and enzyme activation (HAVLIN et al., 2016; WEIL; BRADY, 2016).

Soil potassium ranged between 0.08 and 0.10 meq/100 g (Table 1), which are very low values. According to CIAT (1993), a value of 0.2 meq/100 g is considered low, while 0.6

meq/100 g is considered high. These values, according to Enriquez et al. (2022), suggest a significant potassium deficiency, which could limit plant growth and development, as this nutrient is essential for physiological processes such as photosynthesis, osmotic regulation, and enzyme activation. Additionally, low potassium availability can reduce water-use efficiency and increase plant susceptibility to diseases and environmental stress (HAVLIN et al., 2016).

The Effective Cation Exchange Capacity (ECEC), which ranged between 5.18 and 6.15 meq/100 g (Table 1), according to Solly et al. (2020), is a key indicator of soil fertility, reflecting a moderate to medium capacity of the soil to retain and release exchangeable cations and supply them to plants, such as calcium (Ca^{+2}), magnesium (Mg^{+2}), potassium (K^{+}), and sodium (Na^{+}), which were essential for the sustainable growth of the grasses and legumes studied. The ECEC contributes to nutrient retention and interacts significantly with organic matter, as it stabilizes soil organic carbon by binding with cations (SOLLY et al., 2020).

Aluminium saturation, which showed concentrations of 85% and 91% (Table 1), corresponds to a high saturation level. According to Rheinheimer et al. (2024), values above 25% are associated with reduced crop yields, particularly in sensitive crops such as soybean and wheat, and also inferred for grasses and legumes. High levels of aluminium saturation are concerning in acidic soils, as they can inhibit root growth and nutrient absorption, leading to lower agricultural productivity (ZHANG et al., 2023).

Similarly, base saturation values of 9% and 15% (Table 1) indicate low nutrient availability, which may significantly affect soil fertility and plant growth. Base saturation is a critical indicator of soil health, reflecting the proportion of exchangeable bases relative to the total cation exchange capacity. A low base saturation (below 20%) suggests limited availability of essential nutrients such as calcium and magnesium, which are vital for plant health (WANG et al., 2020). Low base saturation, typical of acidic soils, may induce aluminium toxicity, further inhibiting plant growth (LAWRENCE et al., 2018). According to Kabała; Łabaz (2018), it is closely related to soil pH; lower pH values correspond to lower base saturation. For example, a pH below 5.5 usually indicates a base saturation of less than 50%, which aligns with the values of 4.1 and 4.6 (WANG et al., 2019).

The organic matter content of 1.3% (Table 1) is generally considered low, potentially limiting nutrient availability and soil fertility. In contrast, the 2.3% content (Table 1) is closer to moderate levels, indicating better soil health (PETŐ et al., 2019). Organic matter is key to nutrient release, soil structure improvement, and water retention (LEE et al., 2016). Organic matter, according to Pandao et al. (2024), includes plant and animal residues at various decomposition stages, has a high organic carbon content, plays an important role in soil health, and contributes to its structure, moisture retention, and nutrient content. Fernández et al. (2016) established that molisols require at least 3% organic matter to resist compaction. Consequently, values of 1.3% and 2.3% indicate insufficient capacity to maintain an optimal soil structure. Cruz-Macías et al. (2020) warn that maximum aluminium saturation is reached at 4.14% organic matter in acidic soils, suggesting that neither 1.3% nor 2.3% is adequate to mitigate aluminium toxicity.

The treatments outlined in Table 2 prioritize phosphorus as the principal fertilizer, owing to its role in regulating physiological and biochemical functions crucial for plant growth (Bechtaoui et al., 2021), specifically the synthesis of nucleic acids and plant energy generation (CARSTENSEN et al., 2018; POWERS et al., 2020). Furthermore, according to Béné et al. (2015) and Sun et al. (2016), it plays a pivotal role in the formation and robust development of the root system, ultimately influencing crop yield.

The incorporation of Ca^{+2} in the treatments (Table 2) is of paramount importance, as calcium (Ca+2) is an essential element for plants. As noted by Weng et al. (2022), it is involved in photosynthesis and nutrient uptake, affecting plant growth. At a concentration of 5 mmol L^{-1}, it enhances the absorption of C, N, P, K, and Ca by various seedling organs, promoting growth through improved photosynthesis and stress resistance. Additionally, as per Gorobets et al. (2024), it influences the activation of specific enzymes involved in cellular metabolism.

Sulphur, being an indispensable element for plant growth, was included in the treatments (Table 2). As indicated by Baruah et al. (2024), it is vital for synthesizing crucial components such as amino acids and enzymes. However, its limited availability in acidic soils impedes crop development and yield. Colovic et al. (2018) assert that it is a critical macronutrient, forming a fundamental part of methionine (Met), cysteine (Cys), phytohormones (ethylene), signaling molecules (hydrogen sulphide, H_2S), antioxidants (GR, GSH), secondary metabolites, heavy metal chelators (PC, metallothioneins), the thioredoxin system, sulpholipid prosthetic groups, and various coenzymes and vitamins.

The beneficial effects of potassium (K+) on plant responses to fertilizers containing it (Table 2), as detailed by Mostofa et al. (2022), encompass physiological and biochemical mechanisms involved in photosynthesis, osmoprotection, stomatal regulation, water and nutrient uptake, nutrient translocation, and enzyme activation. Consequently, McDonnell et al. (2018) demonstrated that K+ application yields a curvilinear increase in yield with higher potassium doses. In Megathyrsus maximus cultivars (Zuri, Tamani, Massai, and Mombaça), K fertilization influenced productivity, with recommended K_2O dosages, implying similar benefits for both grass and legume species (REIS et al., 2023).

Comparatively (Table 3), *B. decumbens* exhibited a marginally superior potential in maximum yield compared to *B. dictyoneura* under optimal fertilization conditions (treatment 10). However, *B. dictyoneura* showed greater stability in its response to different treatments, with less variation between maximum and minimum values.

Notably, both species responded similarly to the treatments, consistently showing higher productivity under treatments 10, 3, and 4, while treatments 1 and 7 resulted in the lowest yields for both grasses. These yield differences between treatments were statistically significant ($p < 0.05$), as indicated by the superscripts in Table 3, suggesting that appropriate selection of the fertilisation regime is crucial for optimizing dry matter production in these forage species.

The statistical analysis, represented by the superscripts in Table 3, indicates significant differences between treatments ($p < 0.05$). For *B. decumbens*, treatments 10, 3, and 4 were statistically superior to those with lower yields. In *B. dictyoneura*, the variation in statistical significance was less pronounced between treatments, reinforcing the observation that this species exhibits greater productive stability under diverse nutritional conditions.

The positive response to phosphorus fertilization observed particularly in *B. decumbens* (treatments 2, 3, and 4) confirms phosphorus's importance as a limiting nutrient in tropical soils, indirectly suggesting potential benefits in biomass increase, with yields exceeding 37.2 and 91.1 kg ha^{-1} of the hybrid signal grass (*Urochloa spp.*) cv. Mavuno, as investigated by Prudencio et al. (2023). Da Silva et al. (2019), researching *Brachiaria brizantha* cv. Mg-5, achieved higher dry matter yields with high doses exceeding 600 kg.ha^{-1} of P_2O_5, a value 10 times greater than that used in this study; similarly, Porto et al. (2012) in *Brachiaria brizantha cv.* Marandu observed significant dry matter production with elevated phosphorus levels. The data also reveal that calcium addition (750 kg ha^{-1}) showed variable effects depending on the species and nutrient combination. Treatment 10, including a balanced combination of P, Ca, S, and K, proved generally effective, underscoring the importance of balanced fertilisation for optimizing the production of these forage grasses.

These results provide valuable insights for the agronomic management of tropical pastures, highlighting species-specific differences in response to varying fertilisation regimes and the importance of adapting fertilisation strategies according to the cultivated *Brachiaria* species.

The results in Table 4 indicate that fertilization has a significant impact on legume yield, though the response varies with nutrient type and quantity. Generally, treatments including a combination of nutrients, particularly those incorporating P, Ca, S, and K_2O, tended to produce higher yields. This suggests balanced and comprehensive fertilisation is essential for optimizing dry matter production in these legumes.

These findings (Table 4) are highly relevant to sustainable agriculture and pasture management, providing valuable information on maximizing forage crop productivity through appropriate nutrient application. Additionally, the results could be used to develop specific fertilisation recommendations to enhance resource efficiency and contribute to the sustainability of agricultural systems.

In summary (Table 4), *Stylosanthes guianensis* showed the highest yields and least variability among treatments, suggesting it is less sensitive to fertilization levels. Costa et al. (2018) in *Stylosanthes capitata* showed significant increases in green dry matter yield with P levels of 40 to 120 kg of P_2O_5 ha^{-1}, with optimal yields achieved at specific P doses. Another study on *Stylosanthes hamata* indicated that P application up to 80 kg.ha^{-1} significantly increased dry matter yield, especially during the first establishment year (OMOREGIE & OMUETI, 2022). In contrast, *Desmodium ovalifolium* and *Pueraria phaseoloides* legumes showed greater yield variability, indicating they respond more markedly to different fertilizer levels. The highest-yielding treatments could be considered optimal for each species. A study on *Desmodium ovalifolium* CIAT-350 revealed that 50 kg of P_2O5 ha^{-1} application improved dry matter yield (COSTA et al., 2015). Research on *Pueraria phaseoloides* (Kudzu) indicated it also benefits from P application, though specific yield data were less prominent compared to *Stylosanthes* (GARCÍA-FERRERA et al., 2015).

The analysis of variance shown in Table 5 indicates that both fertilizer doses and grass species significantly affect dry matter yield, as both have p-values < 0.05. Therefore, both factors (fertilizer dose and grass species) must be considered in managing and cultivating these grasses to optimize yield. In summary, the results indicate that dry matter yield variation can be significantly attributed to both fertilizer doses and the grass species under investigation.

The results in Table 6 indicate that fertilizer dose has a significant but less pronounced effect than legume species, with an F-value of 9.75 and a p-value of 0.0000. This means fertilizer doses affect the dependent variable, but to a lesser extent than legume species. Legume species have a very strong and highly significant effect, with an F-value of 1093.02 and a p-value of 0.0000, indicating that legume species explain a large portion of dry matter yield variability. The low CV value suggests relatively low variability relative to the mean, enhancing the results' precision.

5. CONCLUSIONS

Both grasses exhibit significant variations in their yield due to the applied phosphorus fertilization. However, *Brachiaria decumbens* appears to be more productive overall, which can position it as a preferred option for applications where high dry matter yields are sought, under the evaluated conditions, granting it significant potential for use in agricultural systems where efficient forage or pasture production is valued.

For each legume, treatments are observed that consistently produce good yields, especially the higher treatments in *Stylosanthes guianensis*, while the lower treatments tend to have significantly lower yields. Therefore, this indicates that phosphorus fertilization plays a crucial role in the development of these legumes.

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