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Forage peanut as a sustainable alternative to nitrogen fertilization for maintaining pasture productivity after recovery

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ABSTRACT - The objective of this study was to investigate the influence of nitrogen (N) input via fertilizer or through the inclusion of an N-fixing legume mixed with grass on canopy structural characteristics, forage production, and stocking rate in grazing systems. Three pastures type (PT), with Marandu palisadegrass (*U. brizantha*), were assessed: i) monoculture without N fertilizer application (Unfertilized); ii) monoculture fertilized with 150 kg N ha^{-1} year^{-1} (N-fertilized); iii) and mixed pasture with forage peanut (*A. pintoi*), without N fertilizer (Mixed). The treatments were managed under mob stocking with variable stocking rate. The canopy height target was between 25 and 30 cm (pre-grazing), and 15 cm (post-grazing). Beef cow-calf pairs were used (529 ± 49 kg cows and 80 ± 29 kg calves) for grazing. The pre-grazing total herbage mass was not influence for the PTs ($P = 0.111$), which averaged 7,234 kg ha^{-1}. The greatest and lowest pre-grazing herbage mass were recorded for the N-fertilized and Unfertilized. The N-fertilized and Mixed had the greatest post-grazing herbage mass ($P = 0.012$). The legume proportion in the Mixed was on average 30.5%. The N-fertilized and Mixed showed the greatest herbage accumulation rate. The lowest herbage accumulation rate was recorded in the Unfertilized. Stocking rate was reduced by 35.7 and 78.5% in the Mixed and Unfertilized, respectively, compared with the N-fertilized pasture, with the Unfertilized averaging 0.9 AU ha^{-1}. Overall, N-input is crucial for maintaining and supporting adequate carrying capacity in pasture ecosystems. Thus, forage peanut legume provides a way to add N with lower economic and environmental costs.

Keywords: *Arachis pintoi*, beef cattle, *Brachiaria*, degraded pasture, mixed pasture

1. Introduction

Brazilian beef production is predominantly pasture-based with very low nutrient replacement, which results in low productivity indices (Boddey et al., 2004; Martha et al., 2012). This results in a scenario where a large percentage of Brazilian pastures are in some stage of degradation (Santos et al., 2024). Therefore, to sustain the same cattle herd, clearing new areas has been required to compensate for the increasing pasture deficit caused by degradation and to accommodate herd growth (Santos et al., 2024). In view of this situation, Brazil is committed to recovering these degraded pasture areas by

2030 through its Nationally Determined Contribution (NDC), aiming for sustainable livestock farming (Silva et al., 2018). Thus, soil correction, adequate soil preparation, and the use of quality seeds are important steps in pasture recovery. However, discussions often focus on these initial actions as one-time measures, with little attention given to long-term nutrient replacement strategies necessary to maintain pasture persistence and productivity over time. Evidence from previous studies suggests that, without nutrients inputs, pasture productivity may decline significantly within a few years after recovery, highlighting the need for sustained nutrient management to ensure long-term success (Monaghan et al., 2005; Thomas et al., 2021; Carneiro et al., 2022).

Among the various nutrients, nitrogen (N) is particularly important due to its high demand by forage plants (Delevatti et al., 2019). In grass monocultures pastures, the only feasible way to supply N and to avoid further degradation is through the application of N fertilizers (Cassim et al., 2024). Nitrogen fertilizer is produced using the Haber-Bosch process, which combines N_2 from the atmosphere with hydrogen, typically derived from natural gas (Galloway et al., 2017; Cassim et al., 2024). This process is energy-intensive and contributes significantly to the greenhouse gas (GHG) emissions (Robertson and Grace, 2004). As the demand for fertilizers increases, this may lead to competition within agriculture and rising prices for these inputs, all while contributing to greater GHG emissions associated with livestock production (Godde et al., 2021; Homem et al., 2024; Vos et al., 2025).

Legumes in pastures are a technology that is being reborn in Brazil, focusing on sustainable animal production since legumes deliver greater ecosystem services (Boddey et al., 2020; Dubeux Jr et al., 2024). Recent studies have demonstrated the viability of this technology in tropical regions, focusing on compatibility between grasses and legumes (Tamele et al., 2018), grazing management (Gomes et al., 2018; Rodrigues da Cruz et al., 2024), N balance in the soil-plant-animal system (Homem et al., 2021c), animal productivity (Homem et al., 2021a), fatty acid profile of meat (Schmitz et al., 2023) and environmental sustainability (Homem et al., 2024). However, there is still limited information in the literature regarding pasture and animal productivity in mixed grass-legume systems evaluated over time.

Therefore, we hypothesize that introducing forage peanut into pastures is a viable strategy to supply N and maintain forage and animal productivity at levels similar to those achieved with N fertilization. Thus, the objective of this study was to investigate the influence of N input via fertilizer or biological N fixation on canopy structural characteristics, forage production, and the stocking rate.

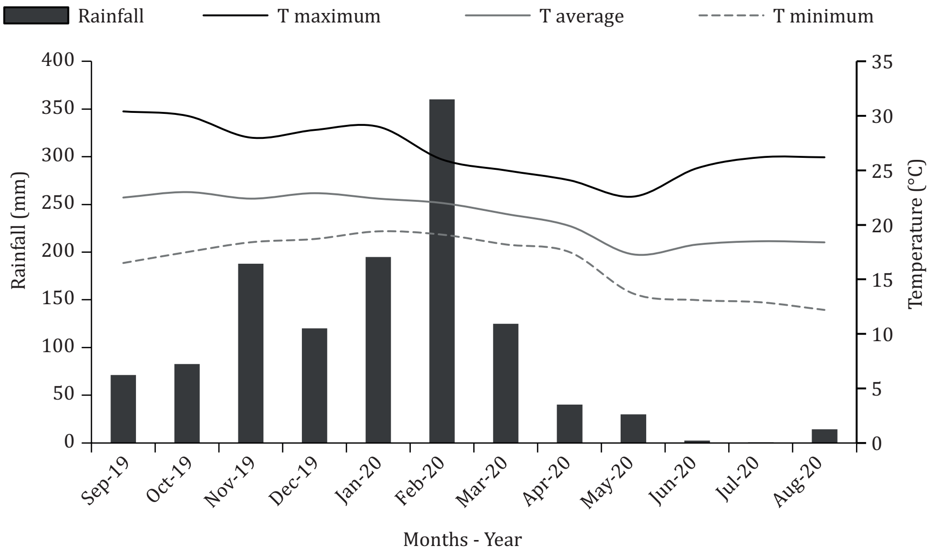
2. Material and methods

2.1. Institutional animal care and use approval

The experimental procedures for this study were approved by the Ethics and Animal Welfare Committee of the Universidade Federal de Lavras (protocol number 064/2015).

2.2. Experimental site

The study was carried out at the Experimental Farm of the Universidade Federal de Lavras, Brazil (21°14' S, 44°58' W; 918 m above sea level). This area has a humid subtropical mesothermal climate with dry winters (Köppen–Geiger climate classification: Cwa; Sá Júnior et al., 2012). Meteorological data were obtained from a weather station located 1,000 m from the experimental area (Figure 1). The soil in the area is a Ferralsol (WRB/FAO classification). Soil texture is clayey, and the clay content is similar throughout the profile (a characteristic of this soil type): 563 g clay kg^{-1} soil (0–10 cm), 562 g clay kg^{-1} soil (10–20 cm) and 574 g clay kg^{-1} soil (20–40 cm). Soil analyses were conducted according to Embrapa standard techniques (Claessen et al., 1997). The soil (0–20 cm) had the following properties: $pH_{(H2O)}$ = 6.0; exchangeable Al, Ca, Mg, 0.07, 2.4 and 0.7 cmolc dm^{-3}, respectively; available P (Mehlich-I method) 7.6 mg dm^{-3}, exchangeable K 82.8 mg dm^{-3} and organic matter 31.0 g kg^{-1}.



Data were obtained from a meteorological station located 1000 m from the experimental site.

Figure 1 - Rainfall and minimum, average, and maximum temperatures during the experimental period in Lavras, MG, Brazil.

The establishment of *Urochloa brizantha* (Hochst. ex A. Rich.) R. Webster cv. Marandu in the experimental area occurred in January 2014. In December 2015, the legume (*Arachis pintoi* Krapov. & W.C. Greg. cv. BRS Mandobi) was established in four previously defined pastures. Details of the experimental pasture establishment are described in Homem et al. (2021a,b). Annually, after establishment, maintenance fertilizations were carried out, always at the beginning of spring of each year. Each year the fertilizer applications were 22 kg ha^{-1} of P and 44.5 kg ha^{-1} K as simple superphosphate and potassium chloride, respectively. Nitrogen fertilizer was applied according to the production system studied. The experimental period was between December 2019 and June 2020, divided into two seasons, and considered from December to March (summer), from March to June (autumn). Management was the same in both seasons.

2.3. Treatments

Treatments were three pasture types (PTs): i) Marandu palisadegrass monoculture without N fertilizer application (Unfertilized); ii) Marandu palisadegrass fertilized with 150 kg N ha^{-1} year^{-1} (as urea), applied in three doses of 50 kg N ha^{-1} each in December, January, and March annually (N-Fertilized); iii) Marandu palisadegrass and forage peanut mixed pasture, without N fertilizer application (Mixed).

All treatments were managed under “mob stocking” simulating a rotational stocking system with variable stocking rate (Allen et al., 2011), in which each pasture served as an independent experimental unit. Each pasture measured 1.0 ha approximately and was assigned to one of the pasture types (N-fertilized, Mixed, or Unfertilized). A total of four pastures per treatment were used (Homem et al., 2021a,b). Grazing cycles were managed based on canopy height, with animal entry occurring when the pasture reached a pre-grazing height of 25 to 30 cm. This target range was defined based on the concept of 90–95% light interception (Trindade et al., 2007; Gomes et al., 2018). The post-grazing height target was 15 cm, aiming to maximize forage intake while maintaining sufficient residual structure for regrowth (Rodrigues da Cruz et al., 2024). The canopy heights were monitored weekly, with a “sward stick” (Barthram, 1985), measuring 100 points in each pasture, and the canopy height corresponded to the arithmetic mean of all points. On average, the canopy heights were 26.2 cm at the pre-grazing condition and 17.7 cm at the post-grazing condition. For grazing, 36 beef cows with calves of the Tabapuã breed were used (529 ± 49 kg cows and 80 ± 29 kg calves of body weight; BW). The animals had access to water and mineral salt (assurance levels per kilogram of product: 110-g Ca [max], 90-g Ca [min], 100-mg Co [min], 1500-mg Cu (min), 25-g S [min], 600-mg F [max], 60-g P [min], 301-mg I [min], 20-mg Se [min], 211-g Na [min], and 2500-mg Zn [min]) *ad libitum*. The calves had access to creep-feeding, where they were supplemented with around 0.7% of their BW per day (Probeef Bambini Creep®, Cargill/Nutron, Itapira, São Paulo, Brazil).

2.4. Experimental evaluations

Total herbage mass was sampled using four 1 × 0.5 m frames (pre- and post-grazing) per pasture, once during each grazing cycle. Sampling sites were selected based on the average canopy conditions within each pasture, including canopy height and, in the Mixed pastures, the legume proportion estimated by visual assessment. After harvesting the forage, botanical separations were performed. The fresh material was weighed and subsampled using approximately 250 g of fresh material for assessing dry matter (DM) concentration. A further subsample of approximately 2 kg of fresh material was taken for manual separation of morphological components. Grass samples were separated into stem (stem + sheath), leaf (leaf blade) and dead material. Legume samples were separated into stolon and leaf (stipule + petiole + leaflet). Forage samples were oven-dried at 55 °C for 72 h to a constant weight. Grass mass was defined as the sum of leaf and stem mass, excluding dead material. Legume mass was defined as the sum of leaf and stolon mass. Herbage mass was calculated as the sum of grass and legume mass, while total herbage mass included herbage mass plus dead material. Morphological composition was determined based on the mass of leaf, stem, and dead material, separated into grass and legume components. Herbage and grass accumulation were quantified by the difference between the mass in the current pre-grazing and the post-grazing conditions of the previous cycle. The accumulation rate was estimated by dividing the forage accumulation by the number of regrowth days.

The cows/calves were weighed in the morning, every 30 d throughout each season, without feed or water restriction. The weight was used to quantify the stocking rate. The stocking rate (AU/ha; where 1 AU = 500 kg body weight, as per Allen et al., 2011) was estimated for each season by dividing the total live weight of all animals present in the pasture by the area required to support them. The required area was calculated by multiplying the area of a single pasture by the estimated number of paddocks needed to support the animals throughout a grazing cycle. The number of paddocks was estimated by dividing the rest period by the occupation period and then adding one, following the principles of rotational stocking management.

2.5. Statistical analysis

The experimental design was randomized complete blocks with three treatments (pasture type; N-Fertilized, Unfertilized, and Mixed), four replications (pastures), and repeated measurements over time (seasons of the year). Data were analyzed by fitting mixed models (Littell et al., 2000), using the MIXED procedure of SAS (SAS Institute, Cary, NC). The effects of types of pasture, seasons, and their interactions were considered fixed and the effect of block as a random effect. The Akaike information criterion was used to choose the best (co)variance structure (Akaike, 1974). All variance components were estimated using the restricted maximum likelihood method. The averages were estimated using the LSMEANS statement, and comparisons were made between treatments using Fisher's protected least significant difference (LSD) test. Significance was declared at P<0.10. The statistical model for data analysis was as follows:

$$Y_{ijk} = \mu + B_i + PT_j + \gamma_{ij} + S_k + (PT \times S)_{jk} + \varepsilon_{ijk}$$

in which Y_{ijk} = value observed in the i-th block of the j-th PT of the k-th season; μ = overall average; B_i = random effect associated with the i-th block, i = 1, 2, 3, 4; PT_j = fixed effect associated with j-th pasture types, j = 1, 2, 3; γ_{ij} = random error associated with the i-th block in the j-th PT; S_k = fixed effect associated with k-th season, $k = 1$ and 2; $(PT \times S)_{jk}$ = fixed effect of interaction j-th PT with the k-th season; ε_{ijk} = random error associated with the i-th block, the j-th PT and the k-th season.

3. Results

The grazing cycles varied among treatments due to differences in forage growth. On average, the rest periods were 40 d for the N-fertilized pasture, 47 d for the Mixed pasture, and 68 d for the Unfertilized pasture. There were no differences between PTs for the canopy height in the pre- and post-grazing conditions (P = 0.115 and P = 0.370, respectively; Figure 2) and the averages were 26.4 and 17.6 cm, respectively. In the pre-grazing condition, the PTs did not influence the total herbage mass (P = 0.111; mean of 7,234 kg ha^{-1}), but PT treatments promoted changes in the morphological composition of the forage (Table 1). The greatest green grass mass in the pre-grazing condition was recorded for the N-fertilized pasture, followed by the Unfertilized pasture and the lowest values in the Mixed pasture. The leaf mass was greater in the N-fertilized pasture compared with the other pastures, while stem and dead material mass did not differ among PTs under pre-grazing conditions. Concerning the seasons evaluated, the greatest total herbage mass (P = 0.039) and dead material mass (P = 0.078) were obtained in the summer (means of 7816 and 3064 kg ha^{-1}, respectively). There was no season's effect for the green grass, leaf, and stem mass in the pre-grazing condition (P≥0.108; Table 1).

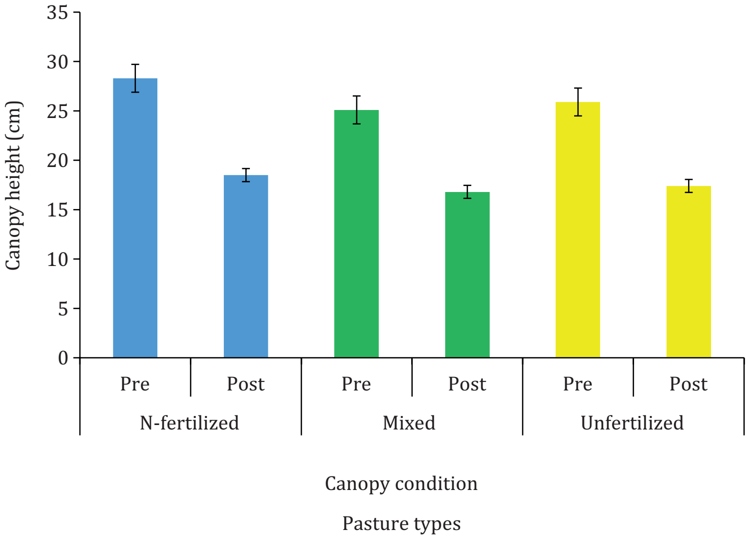


Figure 2 - Canopy height in pre- and post-grazing conditions for three pasture types: N-fertilized, mixed (forage peanut + grass), and unfertilized pastures.

Table 1 - Structural characteristics in the pre-grazing condition of Marandu palisadegrass pastures with application or not of N fertilizer or mixed with forage peanut during the seasons of the experimental period

Variable	Pasture types (PT)			Seasons (S)		SEM	P-value		
	N-fertilized	Mixed	Unfertilized	Summer	Autumn		PT	S	PT × S
Total herbage mass (kg ha^{-1})	7963	6750	6989	7816A	6754B	591	0.111	0.039	0.595
				Botanical composition					
Green grass mass (kg ha^{-1})	5131a	3059c	3935b	4222	3861	257	<0.001	0.205	0.450
Legume mass (kg ha^{-1})	-	1371	-	1434	1308	200	-	-	-
				Morphological composition					
Leaf mass (kg ha^{-1})	2837a	1915b	2026b	2437	2082	208	0.004	0.108	0.691
Stem mass (kg ha^{-1})	2293	2515	1933	2272	2223	207	0.144	0.827	0.525
Dead material mass (kg ha^{-1})	2833	2319	3052	3064A	2405B	406	0.247	0.078	0.100

SEM - standard error of the mean.
a–c - Least squares mean within a row with different lowercase, and uppercase letters differ at P≤0.10.

The herbage mass (green grass mass + legume mass), in both pre- and post-grazing conditions ranged according to the PTs ($P = 0.051$ and $P = 0.012$, respectively; Figure 3). In pre-grazing conditions, the greatest and lowest herbage mass were recorded for the N-fertilized and Unfertilized pastures, (5131 and 3282 kg ha^{-1} respectively), but these values did not differ from the Mixed pasture (4430 kg ha^{-1}; Figure 3). This occurred because the legume mass in the pre-grazing condition for the Mixed pasture was 1371 ± 200 kg ha^{-1} (Table 1), which corresponded to a legume proportion of 30.5% of the herbage mass. In the post-grazing condition, the N-fertilized and Mixed pastures had the greatest herbage mass (Figure 3). In general, the legume proportion corresponded to approximately 30% of the herbage mass for the pre- and post-grazing conditions (Table 1).

Herbage and grass accumulation rates ranged depending on PTs and seasons ($P<0.100$). The greatest grass accumulation rate was recorded for the N-fertilized pasture (42.1 kg ha^{-1} day^{-1}) and the lowest rates were observed in the other PTs (23.5 kg ha^{-1} day^{-1}), which, in turn, corresponded to a rate approximately 43% lower than that obtained in the N-fertilized pasture (Figure 4). Although the grass accumulation rate in the Mixed pasture was lower, the herbage accumulation rate (37.0 kg ha^{-1} day^{-1}) was similar to that of the N-fertilized pasture, as forage peanut contributed with 37.8% of the total herbage accumulated. The total herbage and grass accumulation rates increased 66.8 and 71.6% in the summer, respectively, when compared with the rates in the autumn ($P\leq0.023$).

The stocking rate varied among PT treatments ($P<0.001$) and across seasons ($P = 0.008$). The greatest and lowest stocking rates were recorded in the N-fertilized (4.2 AU ha^{-1}) and Unfertilized pastures (0.9 AU ha^{-1}), respectively, with an intermediate value for the Mixed pasture (2.7 AU ha^{-1}; Figure 4). In relation to the N-fertilized pasture, the stocking rate reduced by 35.7 and 78.5% in the Mixed and Unfertilized pastures, respectively. The greatest stocking rate was obtained in the summer, which was 26.7% greater than in the autumn.

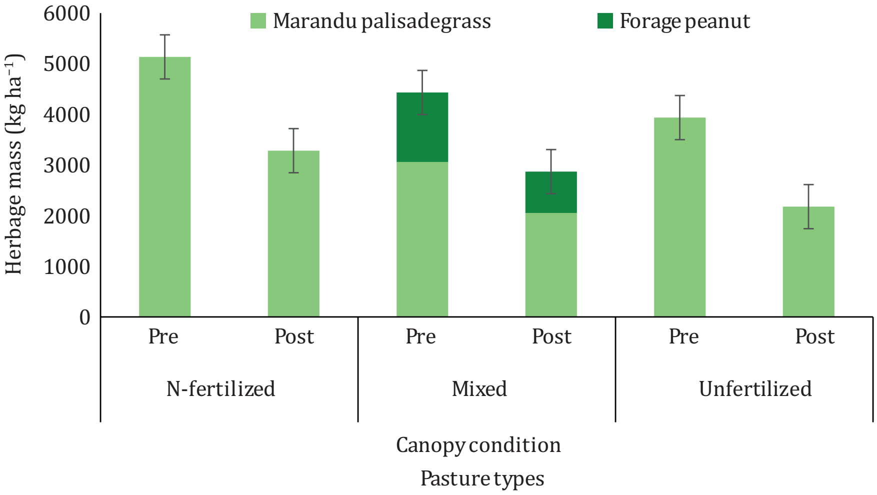
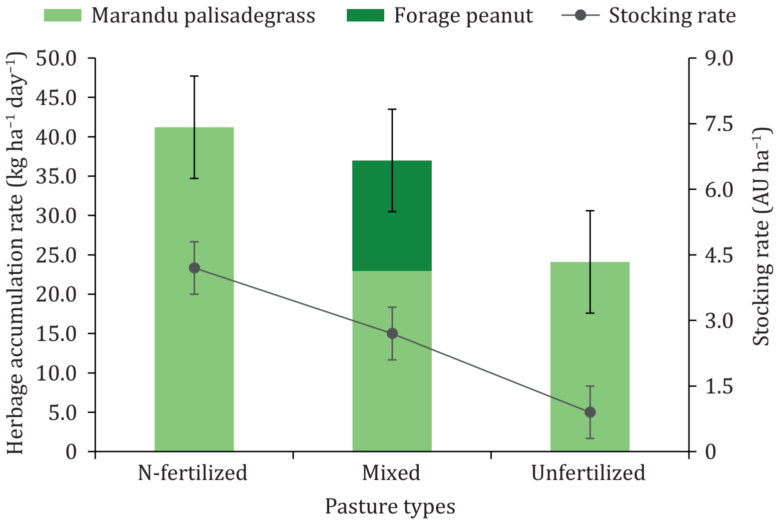


Figure 3 - Herbage mass in pre- and post-grazing conditions for three pasture types: N-fertilized, mixed (forage peanut + grass), and unfertilized pastures. The contribution of Marandu palisadegrass and forage peanut is represented separately in the mixed pasture.



Light green bars represent the accumulation rate of Marandu palisadegrass, dark green bars represent forage peanut, and the gray line indicates the average stocking rate. Vertical bars denote the standard error of the mean.

Figure 4 - Herbage accumulation rate (kg ha^{-1} day^{-1}) and stocking rate (AU ha^{-1}) in pastures with three types of nitrogen input: N-fertilized, mixed (palisadegrass + forage peanut), and unfertilized.

4. Discussion

There has been much discussion in Brazil concerning the recovery of degraded pastures to increase animal production in a sustainable manner (Feltran-Barbieri and Féres, 2021). Undoubtedly, the recovery of degraded pastures in Brazil is a win-win strategy that could boost livestock husbandry and avoid deforestation in Brazil. It must be a priority strategy of the agribusiness sector (Gianetti and Filho, 2024). However, a major aspect of maintaining productive pasture still needs to be addressed: nutrient replacement, especially nitrogen (N).

Pasture recovery, as an isolated strategy, cannot sustain increased production over the years (Homem et al., 2021c). In the present study, the pasture was established in the 2014/2015 during the rainy season, and the applied treatments began in the following year. Pastures were managed under continuous stocking with variable stocking rate during the rainy period from 2016/2017 to 2018/2019, with similar canopy height targets (Homem et al., 2021a). Thus, Homem et al. (2021a) reported the lowest stocking rate in the Unfertilized pasture, which was 2.3 AU ha^{-1} on average, compared with the Mixed pasture, with 2.8 AU ha^{-1}, and the N-fertilized pasture, with 3.8 AU ha^{-1}. The stocking rate in the Unfertilized pasture was approximately twice the average for Brazilian pastures, indicating that recovery of degraded pastures can increase forage and animal production (Latawiec et al., 2014; Arantes et al., 2018). However, the present study shows data from the following year, in which the stocking rate of the Unfertilized pasture decreased to 0.9 AU ha^{-1}. This demonstrates that five years after the grass establishment, pasture productivity declined considerably, approaching the average Brazilian stocking rate.

In pastures with N fertilizer application, the stocking rate was maintained over time, with the N-fertilized pasture supporting 4.2 AU ha^{-1}, compared with 0.9 AU ha^{-1} in the Unfertilized pasture. This difference is further supported by the forage accumulation rate, which was lowest in the absence of additional N. Although different stocking methods were used before this study, comparisons between the years studied may be valid, as similar canopy height targets were maintained across treatments

(Homem et al., 2021a). It is also important to note that without proper management, a decline in productivity may occur shortly after recovery of degraded pastures.

A study conducted at the same experimental site by Homem et al. (2021c). assessed the N balance in the soil-plant-animal system, considering N inputs (e.g., fertilizer application and biological N fixation) and outputs (e.g., product and N-losses). Their findings support the present results, showing that the Unfertilized pasture had a negative N balance, with higher outputs than inputs. In contrast, both the N-fertilized and Mixed pastures exhibited positive N balances, indicating greater N input into the ecosystem than losses. This indicates that the beneficial effects of recovering degraded pastures are limited without N replacement (Feltran-Barbieri and Féres, 2021; Homem et al., 2021c). After a few years, the pasture is likely to revert to low productivity and re-enter the degradation process, even with good grazing management, as observed in the present study.

The Brazilian National Determined Contribution (NDC) has set a target to recover 30 million hectares of degraded pasture by 2030, aiming to mitigate greenhouse gas emissions (Silva et al., 2018; Feltran-Barbieri and Féres, 2021). If Brazil achieves this target, it will require an annual consumption of over 10 million tons of N fertilizer to supply 150 kg N ha^{-1} yr^{-1}, according to this study. This amount is equivalent to approximately 75% of the N fertilizer used in the country for all crops (FAO, 2023). Even with a minimum application rate of 50 kg N ha^{-1} yr^{-1} for the recovery of degraded pastures, N fertilizer consumption would need to increase by 25%. This would impact input costs economically, which could be reflected in food prices. Therefore, it is evident that incorporating legumes into pastures should be adopted as public policy. Legumes can fix N through their association with rhizobia, reducing or eliminating the pasture's N requirements (Homem et al., 2021c). This promotes increased forage accumulation, higher stocking rates, and extended pasture persistence (Homem et al., 2021a), resulting in positive economic and environmental impacts. Furthermore, Brazil stands out for its successful use of biological nitrogen fixation in agriculture, particularly in soybean production (Rezende et al., 2021; Telles et al., 2023). However, this sustainable approach has not been widely adopted in pasture systems. The present study highlights the viability of using grass-legume mixed pastures to positively impact forage productivity and carrying capacity positively.

The PTs studied minimally affected the canopy structure. Despite differences in forage accumulation rates, the similar target canopy heights between treatments resulted in comparable canopy structures. The only notable difference was the increased percentage of leaf mass in the N-fertilized pasture. Similar results were observed in previous studies conducted in the same area (Homem et al., 2021b). Using canopy height targets to control forage regrowth and defoliation is highly effective. This study set the target height based on achieving 95% light interception (LI) for palisadegrass monoculture pastures (Trindade et al., 2007) and mixed pastures with forage peanut (Gomes et al., 2018). Managing mixed pastures with forage peanut at the same canopy height as monoculture pastures can facilitate the adoption of this technology by farmers.

In Brazil, farmers traditionally use grass pastures in monoculture and sometimes manage these pastures effectively. Therefore, if legumes are adopted as a public policy to promote sustainable livestock farming, farmers should find it relatively easy to assimilate the management practices. This is because the same management recommendations used for monoculture grass pastures can be applied to mixed pastures with forage peanut (Gomes et al., 2018; Tamele et al., 2018). Based on the results presented, forage peanut is a valuable tool for many regions of Brazil. Although this study was conducted in the Atlantic Forest Biome, other research suggests that the benefits of forage peanut may also be observed in the Amazon Biome (Andrade et al., 2021). It is also important to note that, while this study presents data from a single year, the experimental systems have been maintained over several years, supporting the reliability and consistency of the observed responses.

5. Conclusions

Our findings support the hypothesis that introducing forage peanut into pastures is an efficient strategy to maintain forage and animal productivity at levels comparable to nitrogen fertilization.

The introduction of forage peanut into grazing systems presents a viable alternative to meeting nitrogen needs while reducing economic costs and environmental impacts. In Brazil, efficient nitrogen utilization is crucial for livestock sustainability. To enable this strategy, future research should prioritize the development and availability of seeds or seedlings for farmers, as well as the improvement of techniques for mixed pasture establishment and the incorporation of forage peanut into existing pastures. These efforts can contribute to the sustainable intensification of livestock production, promoting environmental and productive benefits.

Data availability

The data supporting this study will be shared upon reasonable request to the corresponding author.

Author contributions

Conceptualization: Casagrande, D. R.; Gionbelli, M. P.; Boddey, R. M.; Paiva, A. J. and Homem, B. G. C. **Data curation:** Guimarães, G. D.; Santos, L. R. and Borges, L. P. C. **Formal analysis:** Gionbelli, M. P.; Paiva, A. J. and Homem, B. G. C. **Funding acquisition:** Casagrande, D. R. **Investigation:** Casagrande, D. R. and Homem, B. G. C. **Methodology:** Casagrande, D. R.; Guimarães, G. D.; Santos, L. R.; Borges, L. P. C.; Boddey, R. M. and Homem, B. G. C. **Project administration:** Casagrande, D. R. and Boddey, R. M. **Supervision:** Casagrande, D. R. and Gionbelli, M. P. **Writing – original draft:** Casagrande, D. R.; Gionbelli, M. P.; Boddey, R. M.; Paiva, A. J. and Homem, B. G. C. **Writing – review & editing:** Santos, L. R.; Gionbelli, M. P.; Boddey, R. M.; Paiva, A. J. and Homem, B. G. C.

Conflict of interest

The authors declare no conflict of interest.

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References

Akaike, H. 1974. A new look at the statistical model identification. IEEE Transactions on Automatic Control 19:716-723. https://doi.org/10.1109/TAC.1974.1100705

Allen, V. G.; Batello, C.; Berretta, E. J.; Hodgson, J.; Kothmann, M.; Li, X.; McIvor, J.; Milne, J.; Morris, C.; Peeters, A. and Sanderson, M. 2011. An international terminology for grazing lands and grazing animals. Grass and Forage Science 66:2-28. https://doi.org/10.1111/J.1365-2494.2010.00780.X

Andrade, C. M. S.; Assis, G. M. L.; Gonçalves, R. C.; Ferreira, A. S. and Oliveira, Y. M. F. 2021. Competitive and spreading abilities of forage peanut in tropical mixed pastures. Grass and Forage Science 76:494-507. https://doi.org/10.1111/GFS.12548

Arantes, A. E.; Couto, V. R. M.; Sano, E. E. and Ferreira, L. G. 2018. Livestock intensification potential in Brazil based on agricultural census and satellite data analysis. Pesquisa Agropecuária Brasileira 53:1053-1060. https://doi.org/10.1590/S0100-204X2018000900009

Barthram, G. T. 1985. Experimental techniques: the HFRO sward stick. p.29-30. In: Alcock, M. M. (ed.). Biennial report of the Hill Farming Research Organization. Hill Farming Research Organization, Midlothian.

Boddey, R. M.; Casagrande, D. R.; Homem, B. G. C. and Alves, B. J. R. 2020. Forage legumes in grass pastures in tropical Brazil and likely impacts on greenhouse gas emissions: A review. Grass and Forage Science 75:357-371. https://doi.org/10.1111/gfs.12498

Boddey, R. M.; Macedo R.; Tarré, R. M.; Ferreira, E.; Oliveira, O. C.; Rezende, C. P.; Cantarutti, R. B.; Pereira, J. M.; Alves, B. J. R. and Urquiaga, S. 2004. Nitrogen cycling in *Brachiaria* pastures: The key to understanding the process of pasture decline. Agriculture, Ecosystems & Environment 103:389-403. https://doi.org/10.1016/j.agee.2003.12.010

Carneiro, J. S. S.; Costa Leite, R.; Ferreira Junior, J. M.; Gomes de Faria, A. J.; Godinho Silva, S. H.; Clementino dos Santos, A. and Ribeiro da Silva, R. 2022. Diagnosis of the spatial variability of soil nutrients and economics of precision management in degraded pastures. Grasses 1:30-43. https://doi.org/10.3390/grasses1010003

Cassim, B. M. A. R.; Lisboa, I. P.; Besen, M. R.; Otto, R.; Cantarella, H.; Inoue, T. T. and Batista, M. A. 2024. Nitrogen: from discovery, plant assimilation, sustainable usage to current enhanced efficiency fertilizers technologies – A review. Revista Brasileira de Ciência do Solo 48:e0230037. https://doi.org/10.36783/18069657rbcs20230037

Claessen, M. E. C.; Barreto, W. O.; Paula, J. L. and Duarte, M. N. 1997. Manual de métodos de análise de solo. Centro Nacional de Pesquisa de Solos, Rio de Janeiro.

Delevatti, L. M.; Cardoso, A. S.; Barbero, R. P.; Leite, R. G.; Romanzini, E. P.; Ruggieri, A. C. and Reis, R. A. 2019. Effect of nitrogen application rate on yield, forage quality, and animal performance in a tropical pasture. Scientific Reports 9:7596. https://doi.org/10.1038/s41598-019-44138-x

Dubeux Jr, J. C. B.; Jaramillo, D. M.; Santos, E. R. S.; Garcia, L.; Queiroz, L. M. D.; Bretas, I. L.; Souza, C. H. L. and Trumpp, K. R. 2024. Sustainable intensification of livestock systems using forage legumes in the Anthropocene. Grass and Forage Science 79:481-498. https://doi.org/10.1111/gfs.12696

FAO - Food and Agriculture Organization. 2023. The state of food security and nutrition in the world 2023. Urbanization, agrifood systems transformation and healthy diets across the rural–urban continuum. FAO, Rome. https://doi.org/10.4060/cc3017en

Feltran-Barbieri, R. and Féres, J. G. 2021. Degraded pastures in Brazil: improving livestock production and forest restoration. Royal Society Open Science 8:201854. https://doi.org/10.1098/rsos.201854

Galloway, J. N.; Leach, A. M.; Erisman, J. W. and Bleeker A. 2017. Nitrogen: the historical progression from ignorance to knowledge, with a view to future solutions. Soil Research 55:417-424.

Gianetti, G. W. and Ferreira Filho, J. B. S. 2024. Pasture recovery, emissions, and the Brazilian Paris agreement commitments. Land Use Policy 141:107118. https://doi.org/10.1016/j.landusepol.2024.107118

Godde, C. M.; Mason-D'Croz, D.; Mayberry, D. E.; Thornton, P. K. and Herrero, M. 2021. Impacts of climate change on the livestock food supply chain; a review of the evidence. Global Food Security 28:100488. https://doi.org/10.1016/j.gfs.2020.100488

Gomes, F. K.; Oliveira, M. D. B. L.; Homem, B. G. C.; Boddey, R. M.; Bernardes, T. F.; Gionbelli, M. P.; Lara, M. A. S. and Casagrande, D. R. 2018. Effects of grazing management in brachiaria grass-forage peanut pastures on canopy structure and forage intake. Journal of Animal Science 96:3837-3849. https://doi.org/10.1093/jas/sky236

Homem, B. G. C.; Borges, L. P. C.; Lima, I. B. G.; Guimarães, B. C.; Spasiani, P. P.; Ferreira, I. M.; Meo-Filho, P.; Berndt, A.; Alves, B. J. R.; Urquiaga, S.; Boddey, R. M. and Casagrande, D. R. 2024. Forage peanut legume as a strategy for improving beef production without increasing livestock greenhouse gas emissions. Animal 18:101158. https://doi.org/10.1016/j.animal.2024.101158

Homem, B. G. C.; Lima I. B. G.; Spasiani, P. P.; Borges, L. P. C.; Boddey, R. M.; Dubeux, J. C. B.; Bernardes, T. F. and Casagrande, D. R. 2021a. Palisadegrass pastures with or without nitrogen or mixed with forage peanut grazed to a similar target canopy height. 2. Effects on animal performance, forage intake and digestion, and nitrogen metabolism. Grass and Forage Science 76:413-426. https://doi.org/10.1111/gfs.12533

Homem, B. G. C.; Lima, I. B. G.; Spasiani, P. P.; Ferreira, I. M; Boddey, R. M.; Bernardes, T. F.; Dubeux, J. C. B. and Casagrande, D. R. 2021b. Palisadegrass pastures with or without nitrogen or mixed with forage peanut grazed to a similar target canopy height. 1. Effects on herbage mass, canopy structure and forage nutritive value. Grass and Forage Science 76:400-412. https://doi.org/10.1111/gfs.12532

Homem, B. G. C.; Lima, I. B. G.; Spasiani, P. P.; Guimarães, B. C.; Guimarães, G. D.; Bernardes, T. F.; Rezende, C. P.; Boddey, R. M. and Casagrande, D. R. 2021c. N-fertiliser application or legume integration enhances N cycling in tropical pastures. Nutrient Cycling in Agroecosystems 121:167-190. https://doi.org/10.1007/s10705-021-10169-y

Latawiec, A. E.; Strassburg, B. B. N.; Valentim, J. F.; Ramos, F. and Alves-Pinto, H. N. 2014. Intensification of cattle ranching production systems: socioeconomic and environmental synergies and risks in Brazil. Animal 8:1255-1263. https://doi.org/10.1017/S1751731114001566

Littell, R. C.; Pendergast, J. and Natarajan, R. 2000. Modelling covariance structure in the analysis of repeated measures data. Statistics in Medicine 19:1793-1819.

Martha, G. B.; Alves, E. and Contini, E. 2012. Land-saving approaches and beef production growth in Brazil. Agricultural Systems 110:173-177. https://doi.org/10.1016/j.agsy.2012.03.001

Monaghan, R. M.; Paton, R. J.; Smith, L. C.; Drewry, J. J. and Littlejohn, R. P. 2005. The impacts of nitrogen fertilisation and increased stocking rate on pasture yield, soil physical condition and nutrient losses in drainage from a cattle-grazed pasture. New Zealand Journal of Agricultural Research 48:227-240. https://doi.org/10.1080/00288233.2005.9513652

Rezende, V. T.; Bonaudo, T.; Alves, R. B.; Nacimento, R. A. and Gameiro, A. H. 2021. Cascade effect of nitrogen on Brazilian soybean production chain. Nitrogen 2:128-138. https://doi.org/10.3390/nitrogen2020009

Robertson, G. P. and Grace, P. R. 2004. Greenhouse gas fluxes in tropical and temperate agriculture: The need for a full-cost accounting of global warming potentials. Environment, Development and Sustainability 6:51-63. https://doi.org/10.1023/B:ENVI.0000003629.32997.9e

Rodrigues da Cruz, P. J.; Silva, D. V.; Lima, I. B. G.; Alves, G. C.; Homem, B. G. C.; Alves, B. J. R.; Boddey, R. M.; Sbrissia, A. F. and Casagrande, D. R. 2024. Marandu palisade grass-forage peanut mixed pastures: Forage intake, animal behaviour, and canopy structure as affected by grazing intensities. Grass and Forage Science 79:666-667. https://doi.org/10.1111/gfs.12688

Sá Júnior, A.; Carvalho, L. G.; Silva, F. F. and Alves, M. C. 2012. Application of the Köppen classification for climatic zoning in the state of Minas Gerais, Brazil. Theoretical and Applied Climatology 108:1-7. https://doi.org/10.1007/s00704-011-0507-8

Santos, C. O.; Pinto, A. S.; Santos, M. P.; Alves, B. J. R.; Ramos Neto, M. B. and Ferreira, L. G. 2024. Livestock intensification and environmental sustainability: An analysis based on pasture management scenarios in the brazilian savanna. Journal of Environmental Management 355:120473. https://doi.org/10.1016/j.jenvman.2024.120473

Silva, R. O.; Barioni, L. G.; Pellegrino, G. Q. and Moran, D. 2018. The role of agricultural intensification in Brazil's Nationally Determined Contribution on emissions mitigation. Agricultural System 161:102-112. https://doi.org/10.1016/j.agsy.2018.01.003

Schmitz, G. R.; Paris, W.; Kuss, F.; Nörnberg, J. L.; Costa, O. A. D.; Souza, S. S. and Menezes, L. F. G. 2023. Legume inclusion or nitrogen fertilization on Aruana grass overseeded with temperate grasses: Performance, carcass characteristics, and fatty acid profile of the meat of beef steers. Revista Brasileira de Zootecnia 52:e20210051. https://doi.org/10.37496/rbz5220210051

Tamele, O. H.; Lopes de Sá, O. A. A.; Bernardes, T. F.; Lara, M. A. S. and Casagrande, D. R. 2018. Optimal defoliation management of brachiaria grass-forage peanut for balanced pasture establishment. Grass and Forage Science 73:522-531. https://doi.org/10.1111/gfs.12332

Telles, T. S.; Nogueira, M. A. and Hungria, M. 2023. Economic value of biological nitrogen fixation in soybean crops in Brazil. Environmental Technology & Innovation 31:103158. https://doi.org/10.1016/j.eti.2023.103158

Thomas, C. L.; Darch, T.; Harris, P.; Beaumont, D. A. and Haefele, S. M. 2021. The distribution of soil micro-nutrients and the effects on herbage micro-nutrient uptake and yield in three different pasture systems. Agronomy 11:1731. https://doi.org/10.3390/agronomy11091731

Trindade, J. K.; Da Silva, S. C.; Souza Júnior, S.; Giacomini, A. A.; Zeferino, C. V.; Guarda, V. D. A. and Carvalho, P. C. F. 2007. Composição morfológica da forragem consumida por bovinos de corte durante o rebaixamento do capim-marandu submetido a estratégias de pastejo rotativo. Pesquisa Agropecuária Brasileira 42:883-890. https://doi.org/10.1590/S0100-204X2007000600016

Vos, R.; Glauber, J.; Hebebrand, C. and Rice, B. 2025. Global shocks to fertilizer markets: Impacts on prices, demand and farm profitability. Food Policy 133:102790. https://doi.org/10.1016/j.foodpol.2024.102790