

Sustainability of pasture species diversity in forage allowance-based stocking methods in subtropical grasslands of Northeast Argentina

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Received: March 6, 2025

Accepted: January 22, 2026

How to cite: Gándara, L.; Ferrari Usandizaga, S. C.; Riva de Neyra, L. A.; Pereira, M. M.; Balbuena, O. and Carvalho, P. C. F. 2026. Sustainability of pasture species diversity in forage allowance-based stocking methods in subtropical grasslands of Northeast Argentina. *Revista Brasileira de Zootecnia* 55:e20250040. <https://doi.org/10.37496/rbz5520250040>

Editors:

Gustavo José Braga
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ABSTRACT - This study evaluated the effects of two forage allowance levels (5 and 10 kg DM/100 kg LW/day) and mowing on species diversity, botanical composition, and structural attributes in native subtropical grasslands of Northeast Argentina. Over three grazing cycles, all treatments maintained high species diversity (Shannon-Wiener ≈ 2 ; richness >30). Significant cycle effects were observed for species richness and evenness, which increased in the third cycle. Lower forage allowance favored short *Poaceae* and legumes, while higher allowance maintained taller swards and slightly higher evenness. Grassland growth, expressed as available forage biomass, showed similar patterns among treatments and increased from the first to the third cycle, indicating sustained biomass production across grazing intensities. Sward height increased across cycles in all treatments, reflecting structural changes in the pasture canopy. Bare soil decreased, particularly under higher allowance combined with mowing, indicating improved ground cover. These findings demonstrate that adaptive stocking based on forage allowance can maintain plant diversity while sustaining forage biomass production and promoting structural recovery of the pasture canopy and ground cover during the study period.

Keywords: diversity, livestock, native pasture, tropical pasture

1. Introduction

Grassland botanical composition and diversity are linked to ecological benefits and long-term sustainability (Bengtsson et al., 2019). Resource availability and species adaptability to the environment explain the relationships between species richness, ecosystem functioning, and stability (Cleland, 2011; Hobohm and Vanderplank, 2021). A well-distributed prevalence of species ensures soil protection against erosion and maintains soil structure, water retention, aeration, and evapotranspiration capacity (Bengtsson et al., 2019). Additionally, soil processes such as carbon and nitrogen dynamics depend on

the functional diversity of soil organisms, which in turn rely on symbiotic relationships with specific plant species (Bengtsson et al., 2019).

Cattle perceive variations in food abundance, quality, and accessibility at various scales, constructing their diet throughout selection processes (Drescher, 2003). The intensity and duration of defoliation significantly affect botanical diversity, potentially maintaining or increasing richness, or leading to the replacement of desirable species by resistant or non-grazed species (Milchunas et al., 1988; Herrero-Jáuregui and Oesterheld, 2018). In subtropical humid grasslands, moderate to high grazing intensity can reduce burning (Espíndola, 2021), increase light input to lower plant strata, and incorporate nutrients into soils through manure (Milchunas and Lauenroth, 1993; Collins et al., 1998).

According to Observatorio Ganadero (2013), livestock in Argentina's NEA region has grown over the decades, with Corrientes province holding eight percent of the 52,052,740 cattle nationwide (Pellerano et al., 2023), mostly supported by natural grasslands over about 5,150,000 hectares (Kurtz et al., 2015; Ministerio de Agricultura, Ganadería y Pesca, Subsecretaría de Ganadería, 2020). According to Deregibus (2000), the grasslands of Corrientes are under a super-humid regime (annual rainfall exceeding 1200 mm). They predominantly consist of C4 grasses, exhibiting high growth rates from spring to autumn and reduced growth during winter (Bernardis et al., 2005; Gándara et al., 1990). Annual herbage production can reach up to 10,000 kg of dry matter per hectare (Pizzio et al., 1999). Extensive information is available on the grasslands of Corrientes regarding productivity, botanical composition, nutritional value, and responses to climatic variability (Royo Pallarés et al., 2005).

In this context, traditional extensive grazing systems in Corrientes often rely on seasonal adjustments to cope with forage scarcity. During periods of low herbage production, particularly in winter, producers typically implement strategies such as strategic destocking, nutritional supplementation, and the purchase of hay or silage. These practices aim to sustain animal performance while preventing overgrazing, however they may not fully address the long-term ecological integrity of the grassland. Thus, exploring alternative management approaches that prioritize botanical diversity and ecosystem resilience is essential to ensure the sustainability of both production and biodiversity.

However, there have been no previous studies with experimental control of stocking rates based on actual forage allowance and the grassland growth curve. The study was conducted on a site that had been managed under a traditional conservative system for two decades, using a fixed stocking rate of 300 kg live weight/ha. Traditional extensive grazing systems in Northeastern Argentina (NEA) region—particularly in Corrientes, Chaco, and Formosa—are typically managed with a constant stocking rate of approximately 0.6 animals per hectare (equivalent to 300 kg live weight/ha) during the productive season, while fields are generally rested during winter due to limited forage growth (Pizzio et al., 2021). This seasonal management pattern aligns with the rest periods implemented in the present study, thereby providing a relevant framework for comparing the 10 kg dry matter (DM)/100 kg live weight (LW)/day treatment with conventional practices. Based on this context, we hypothesized that supplying 10 kg DM/100 kg LW/day would promote species richness and floristic composition patterns similar to those observed in the initial state of the grassland, potentially mirroring outcomes associated with long-term conservative management. To test this hypothesis, we evaluated four management strategies defined by a factorial combination of two forage allowance levels (5 kg vs. 10 kg DM/100 kg LW/day) and two mowing conditions (with vs. without mowing). This experimental design aimed to identify alternative strategies that may better align with the productive objectives and ecological constraints of livestock systems operating under similar environmental conditions.

2. Material and methods

2.1. Location and description of the sites

The experimental site is located on the grounds of the Corrientes Experimental Station of the National Institute of Agricultural Technology (INTA), in Corrientes, in the Northeast region of Argentina (NEA).

The location of the pasture was 27° 40'01"S, 58° 47'11"W, on a plain at 69 m.a.s.l. (meters above sea level) with Köppen Cfa climate classification (Kottek et al., 2006). Data from the INTA Agrometeorological Information and Management System from the last 20 years describe an average annual precipitation of 1298 mm and an average annual temperature of 21 °C (averages of 25.6 °C in summer and 15.5 °C in winter) (INTA, 2018). Escobar et al. (1996) classified the soil as a Treviño series soil, which is an Argiudol Aquic (USDA, 2022) with 1.2 to 1.7% surface organic matter and pH 5.6 to 6.0, and with a Bt horizon at 40-90 cm depth with pH 7.0 to 7.4, and 0 to 0.3% organic matter at 90 cm depth. The evaluated grassland consisted of an over 20-year rotationally used pasture with a fixed cattle load of 0.63-0.67 livestock units per hectare (LSU/ha), following the method of Love (2005). At the start of the experiment, the vegetation was dominated by bunchgrasses (*Sorghastrum setosum* and *Andropogon lateralis*). The common species were grasses such as *Paspalum notatum*, *P. plicatulum*, and *Axonopus affinis*, and the companions were *Eleocharis nodulosa*, *E. viridans*, *Leersia hexandra*, *Schizachyrium microstachyum*, *P. paniculatum*. Some Fabaceous species such as *Desmodium incanum* and *Vicia epetiolari*, and Cyperaceous were occasionally present.

2.2. Climatic conditions during the experimental cycles

Precipitation data from the three evaluated cycles (October–May of 2016–17, 2017–18, and 2018–19) (INTA, 2018) were compared with historical averages reported by Castro et al. (1991), which define the mean annual precipitation for Corrientes province as 1298 mm. During the first and third cycles, total precipitation reached 1754.5 mm and 1726.2 mm, respectively—both exceeding the historical average—and were classified as highly humid periods. In contrast, the second cycle recorded 1120.7 mm and was considered a climatically normal.

Monthly rainfall peaks were observed in April 2017 (547.5 mm), January 2018 (327.75 mm), and January 2019 (552.4 mm), highlighting interannual variability in rainfall distribution. The cumulative average for winter precipitation (June–October), historically estimated at 264.2 mm, was surpassed in 2016 with 558.25 mm. Winters of 2017 (267.25 mm) and 2018 (190.00 mm) were classified as climatically normal and slightly less humid, respectively. Spring rainfall patterns (September–November) showed notable interannual variability across the three experimental cycles. In 2016, October recorded the highest precipitation (112.3 mm), in 2017, the peak occurred in November (110.2 mm), and in 2018, it shifted to October again (120.8 mm). September tended to be drier, particularly in 2018 (75.0 mm). Temperature patterns remained within historical norms, and without extreme deviations observed during the study period.

2.3. Experimental design and treatments

The experiment followed a 2 × 2 full factorial design to evaluate the effects of forage allowance and shrub control via mowing. Two forage allowance levels (low and high) were combined with two mowing conditions (mowed and not mowed), resulting in four treatment combinations: 1. High forage allowance without mowing; 2. High forage allowance with mowing; 3. Low forage allowance without mowing; 4. Low forage allowance with mowing.

Forage allowance levels were defined as 10 kg and 5 kg of dry matter (DM) per 100 kg of live animal weight (LW) per day. These corresponded to average stocking rates of 304 and 590 LW/ha/day, respectively, equivalent to approximately 0.61 and 1.2 animal units per hectare (AU/ha), where 1 AU represents a 500-kg cow under maintenance conditions. The high allowance (10 kg DM/100 kg LW/day) reflected traditional management intensity (~300 kg LW/ha), while the low allowance (5 kg DM/100 kg LW/day) represented double the grazing pressure (~600 kg LW/ha).

The trial spanned three productive seasons: October–May of 2016–17, 2017–18, and 2018–19. Grazing was suspended between June and September due to reduced forage growth.

Stocking was adjusted following the Put and Take method (Mott, 1960), using heifers averaging 180–220 kg and 12–15 months of age. Two sites (~30 ha each) within the same experimental station were subdivided into twelve paddocks (≥3 ha each), allowing for three replicates per treatment.

Shrub control through mowing was initially implemented at the beginning of the first year (January 2016) to standardize field conditions. It was intended to be repeated every December in subsequent years. However, due to excessive soil moisture caused by unusually high rainfall in 2016 and 2018, mowing could not be carried out during the first and third cycles. As a result, mowing was applied as a treatment only during the second cycle. Direct measurements of sward height in the mowing treatment plots were approximately 35 cm before and 20 cm after mowing. Systematic measurements of sward height were conducted throughout the experimental cycles.

Monthly forage availability was estimated using exclusion cages (1 m × 1 m × 1 m per replicate), which allowed the quantification of herbage accumulation under ungrazed conditions. These measurements were used to adjust the stocking rate dynamically, ensuring that each treatment received a fixed forage allowance of either 5 or 10 kg of dry matter per 100 kg of live weight per day. Herbage accumulation within cages, harvested at 5 cm above ground level, served as the basis for stocking rate adjustments, following the forage growth curve.

2.4. Botanical analysis

Determinations of relative species abundance were performed based on the method described by Mannetje and Haydock (1963), with identification of the present species and establishing a ranking based on the estimation of ground coverage *in situ* in the field and determination of dry matter percentages. To estimate botanical composition, the dry-weight-rank method (Mannetje and Haydock, 1963) was employed due to its suitability for evaluating species contributions in grassland communities with high diversity and structural heterogeneity. This approach facilitated the stratification of species into dominance categories based on visually assessed rank positions within 0.25 m² quadrats, calibrated against biomass samples. Species ranked first were designated as Dominant, typically contributing 50–70% of the dry matter within each sampling unit. Common Species, defined as second in rank, accounted for approximately 20–40% of total biomass, while companion species occupied the third rank, contributing around 10%. Species that were infrequent but identified were classified as occasional species. These estimations were calibrated against a set of harvested quadrats. Additional data such as frequency (how often a species appears) were recorded. During active grazing seasons, eight random sampling points per paddock were evaluated monthly, hand-clipped to 5 cm above ground level to simulate complete forage removal by grazing animals and to determine the actual dry matter contribution of each species. Trained observers performed direct visual estimations of species cover within quadrats; they also registered the bare soil percent (ground free of living plants) and the sward height. The collected data were processed and analyzed with the Botanal method (Tothill et al., 1992), to provide a detailed description of botanical composition. Comparing biomass with other observations enabled corrections for potential issues such as small quadrat size and observer bias, thereby enhancing the reliability of estimating how frequently a species appeared among the top three rankings.

Differences between treatments in species dominance relationships were determined, and dominance-diversity curves were developed using the mean abundance values of the species.

Species were classified by family (*Poaceae*, *Fabaceae*, *Cyperaceae*, and others). *Poaceae* species were subgrouped in short and tall. Also, species were grouped as well accepted and low accepted based on their forage quality and palatability (Pizzio et al., 2021).

2.5. Statistical analysis

Diversity indices (Shannon–Wiener, Simpson, Pielou's Evenness) were calculated using the Vegan package in R (Oksanen et al., 2019) and compared using Hutcheson's t-test.

Olmstead and Tukey diagram was obtained, comparing the initial against the final botanical composition. Due to the large number of species present, only those contributing more than 10% of the total dry matter in each sample were considered for the analysis of botanical composition. Kolmogorov-Smirnov tests were used to analyze the distribution of the data.

Species abundance distributions were modeled using rank-abundance curves (Moreno et al., 2011), fitted to four ecological models (pre-emption, log-normal, Zipf, Zipf–Mandelbrot) and selected via AIC, BIC, and deviance.

Diversity, considering the relationship between species number and their abundances, was represented with the Shannon–Wiener index calculated using the natural logarithm. Group differences were tested with Hutcheson’s method (Magurran, 1988; Hammer et al., 2001). To evaluate the effect of treatments through cycles on diversity, simple linear regression analyses were performed between the diversity index (dependent variable) and months (independent variable).

Linear mixed-effects models (MixedLM, Python statsmodels) were used to evaluate bare soil percentage, sward height, proportion of accepted and low accepted species, number of total species and the botanic composition by family, and relationships among botanical variables (bare soil, species richness, sward height). The fixed effects were treatment, cycle and month; the random effect were replicate and paddock; and the optimization was through L-BFGS algorithm, with significance obtained by Wald z-tests.

The effect of the treatment by cycle in the botanic composition was studied. Model diagnostics included QQ-plots and residuals vs. fitted plots. Pairwise mean comparisons were performed using Tukey’s method ($\alpha = 0.05$), and significance was assessed via Type III ANOVA.

Graphics were performed using both Navure (version 3.1.0) and R (version 4.3.0; R Core Team, 2023).

3. Results

We established two grazing intensities based on the monthly measured forage allowance (Figure 1), high (low forage allowance of 5 kg DM/100 kg LW/ha/day) and moderate to low (high forage allowance of 10 kg DM/100 kg LW/ha/day). Despite interannual and seasonal variations, the grassland growth curves did not show significant differences due to grazing intensity or mowing (Figure 1; Table 1). However, a clear upward trend was observed across cycles (Figure 1; Table 1), indicating the sustainability of all the treatments.

The dominant species (relative frequencies > 10%) were *Sorghastrum setosum* and *Desmodium incanum* (Figure 2). The common species group (5–10% frequencies) included *Andropogon lateralis*, *Paspalum notatum*, *P. plicatulum*, *Axonopus fissifolius*, and *Leersia hexandra* (Figure 2). The third and fourth ranks highlighted the diversity of companion species, mainly from the *Cyperaceae* family (< 5% frequency and > 2.5% abundance) and occasional species (lower frequencies and abundance) (Figure 2).

While the frequencies of occurrence did not show differences among forage allowance treatments, treatments with low forage allowance increased the abundance of occasional *Poaceae* species (Figure 2). Initially, these species had an abundance below 2, but by the end of the treatment, they reached 2 to 2.5. These treatments also affected the *Fabaceae* group: the dominant species, such as *Desmodium incanum*, decreased in frequency from 1.25 to 1.1, while occasional species increased in abundance from 1.3 to 2.1. High forage allowance treatments did not significantly change the abundance or frequency of these groups (Figure 2).

The species were classified by families, with the three-year mean contribution of the *Poaceae* group being 80–85% in all treatments, *Fabaceae* 6–9%, *Cyperaceae* 9–12%, and others about 5%. The response of different functional groups to mowing and forage allowance treatments (10 vs. 5 kg DM/100 kg LW/day) was evaluated over three consecutive assessment cycles. The results revealed distinct patterns of persistence and productivity influenced by both management intensity and forage supply (Figure 3). The tall *Poaceae* group, mainly represented by *Sorghastrum setosum* (the dominant species as observed in Figure 2), had the highest contribution in all treatments. The contribution of short *Poaceae* group increased, whereas that of the tall *Poaceae* contribution decreased under low forage allowance (5 kg DM/100 kg LW/ha/day), without mowing. A forage allowance of 10 kg DM/100 kg LW/ha/day combined with mowing resulted in an increased contribution of tall *Poaceae* and a decreased contribution of short *Poaceae* (Figure 3).

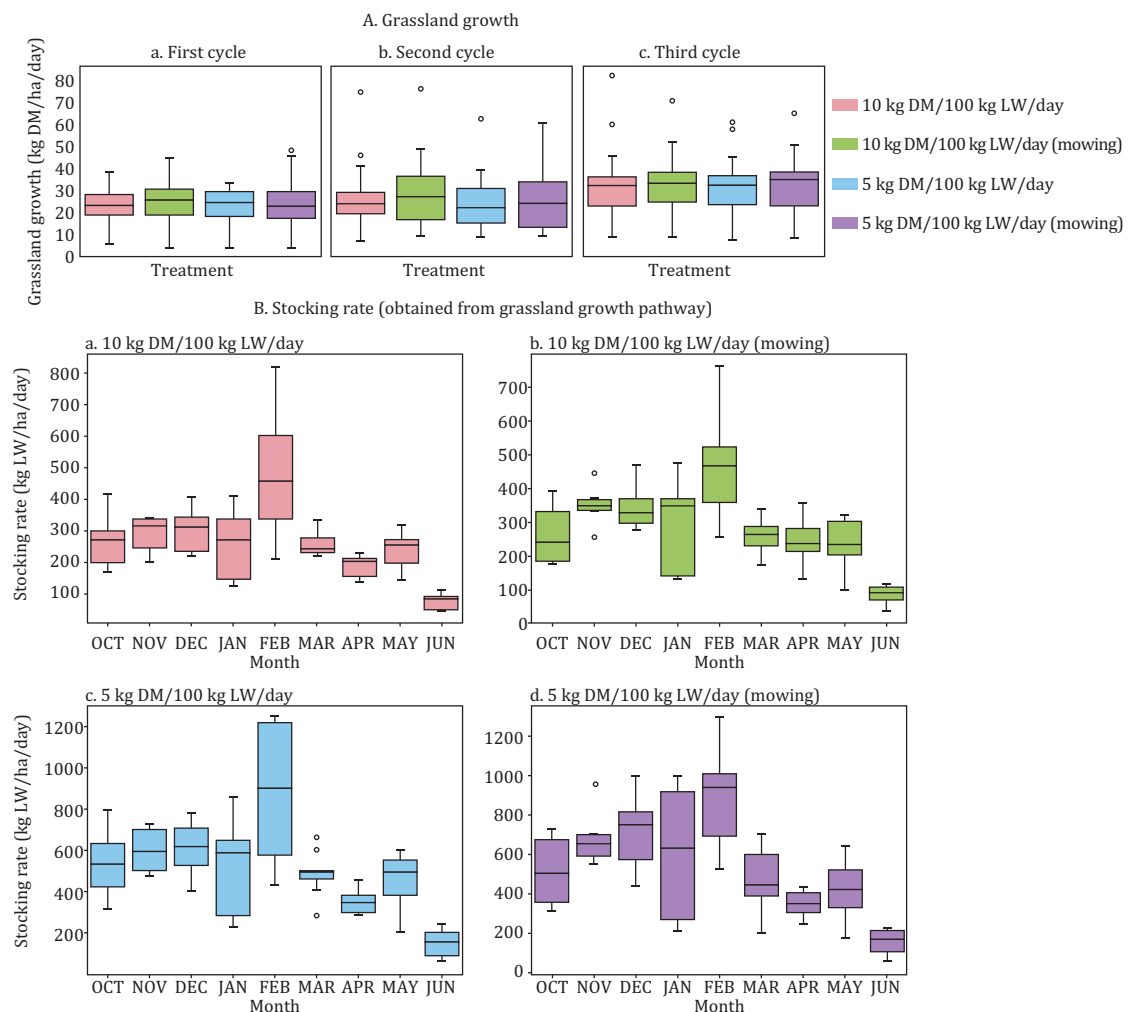


Figure 1 - (A) Forage growth (DM/ha/day) across treatments, averaged by cycle. **(B)** Corresponding stocking rate (LW/ha/day) calculated from forage growth under high (10 kg DM/100 kg LW/day) and low (5 kg DM/100 kg LW/day) forage allowance treatments.

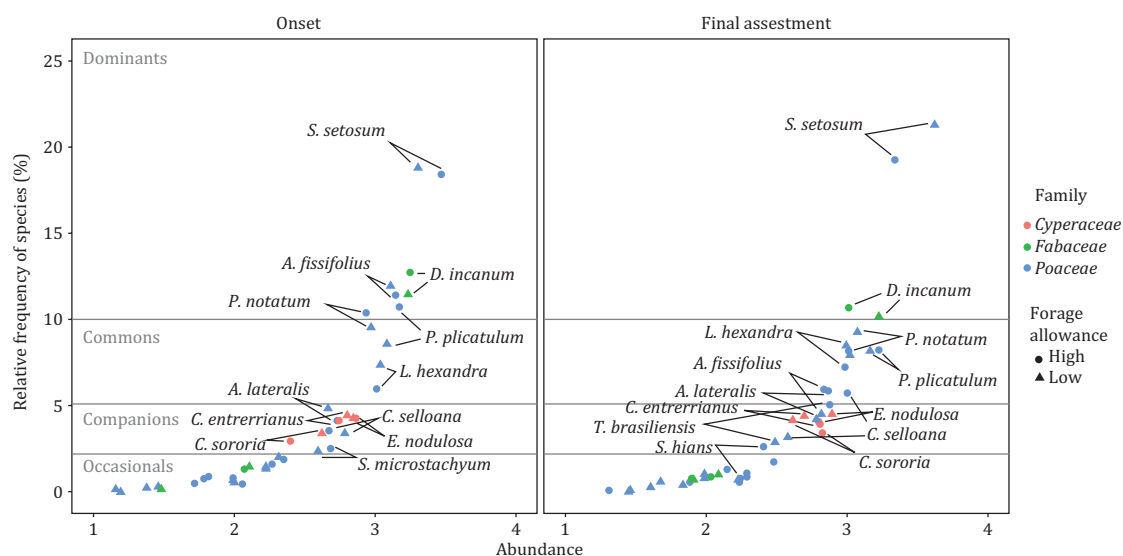
Table 1 - Descriptive statistics of structural and compositional dynamics in response to grazing intensity and mowing practices across three grazing cycles. Management treatments combining forage allowance (10 kg vs. 5 kg DM/100 kg LW/day) and mowing (with vs. without). Variables include stocking rate (kg LW/ha), grassland growth (kg DM/ha/month), sward height (cm), bare soil percentage (%), and mulching (%). Values are presented as means, ranges (min-max), and standard deviations (SD) for each treatment and cycle.

Variable	Treatment	Cycle	Mean	Rank (min-max)	SD
Stocking rate	10 kg DM/100 kg LW/day	First	225.9	(45 - 331)	84.5
Stocking rate	10 kg DM/100 kg LW/day (mowing)	First	239.4	(47 - 356)	104.3
Stocking rate	5 kg DM/100 kg LW/day	First	435.8	(79 - 606)	162.5
Stocking rate	5 kg DM/100 kg LW/day (mowing)	First	456.1	(86 - 709)	217.7
Stocking rate	10 kg DM/100 kg LW/day	Second	250.6	(51 - 524)	132.2
Stocking rate	10 kg DM 100 kg LW/day (mowing)	Second	274.6	(57 - 571)	150.7
Stocking rate	5 kg DM/100 kg LW/day	Second	482.9	(114 - 1067)	280.5
Stocking rate	5 kg DM/100 kg LW/day (mowing)	Second	494.7	(107 - 985)	286.8
Stocking rate	10 kg DM/100 kg LW/day	Third	290.0	(56 - 627)	166.3
Stocking rate	10 kg DM/100 kg LW/day (mowing)	Third	296.5	(75 - 549)	149.6
Stocking rate	5 kg DM/100 kg LW/day	Third	562.3	(127 - 1097)	291.9
Stocking rate	5 kg DM/100 kg LW/day (mowing)	Third	594.6	(144 - 1083)	301.0

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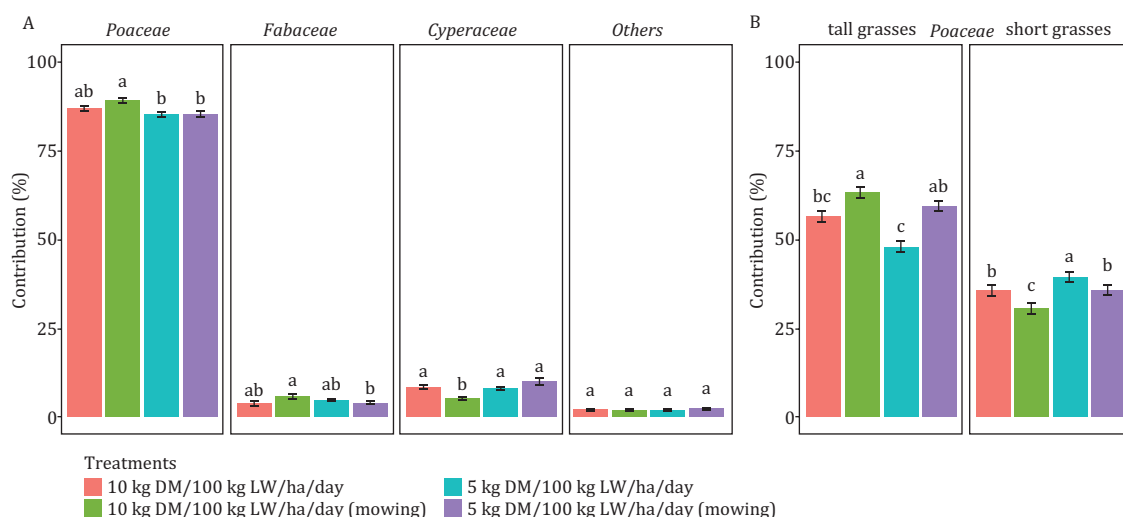
Table 1 (Continued)

Variable	Treatment	Cycle	Mean	Rank (min-max)	SD
Growth of grassland	10 kg DM/100 kg LW/day	First	22.6	(5 - 33)	8.5
Growth of grassland	10 kg DM/100 kg LW/day (mowing)	First	23.9	(5 - 36)	10.4
Growth of grassland	5 kg DM/100 kg LW/day	First	21.8	(4 - 30)	8.1
Growth of grassland	5 kg DM/100 kg LW/day (mowing)	First	22.8	(4 - 35)	10.9
Growth of grassland	10 kg DM/100 kg LW/day	Second	25.1	(5 - 52)	13.2
Growth of grassland	10 kg DM/100 kg LW/day (mowing)	Second	27.5	(6 - 57)	15.1
Growth of grassland	5 kg DM/100 kg LW/day	Second	24.1	(6 - 53)	14.0
Growth of grassland	5 kg DM/100 kg LW/day (mowing)	Second	24.7	(5 - 49)	14.3
Growth of grassland	10 kg DM/100 kg LW/day	Third	29.0	(6 - 63)	16.6
Growth of grassland	10 kg DM/100 kg LW/day (mowing)	Third	29.7	(8 - 55)	15.0
Growth of grassland	5 kg DM/100 kg LW/day	Third	28.1	(6 - 55)	14.6
Growth of grassland	5 kg DM/100 kg LW/day (mowing)	Third	29.7	(7 - 54)	15.0
Sward height	10 kg DM/100 kg LW/day	First	30.9	(11 - 48)	10.4
Sward height	10 kg DM/100 kg LW/day (mowing)	First	28.5	(16 - 43)	7.6
Sward height	5 kg DM/100 kg LW/day	First	23.3	(12 - 33)	6.4
Sward height	5 kg DM/100 kg LW/day (mowing)	First	23.2	(13 - 35)	5.3
Sward height	10 kg DM/100 kg LW/day	Second	39.3	(29 - 47)	5.4
Sward height	10 kg DM/100 kg LW/day (mowing)	Second	39.6	(30 - 54)	6.7
Sward height	5 kg DM/100 kg LW/day	Second	32.9	(20 - 43)	5.9
Sward height	5 kg DM/100 kg LW/day (mowing)	Second	31.9	(24 - 39)	4.7
Sward height	10 kg DM/100 kg LW/day	Third	48.7	(30 - 62)	8.8
Sward height	10 kg DM/100 kg LW/day (mowing)	Third	47.4	(30 - 64)	8.1
Sward height	5 kg DM/100 kg LW/day	Third	42.3	(31 - 55)	7.1
Sward height	5 kg DM/100 kg LW/day (mowing)	Third	39.3	(25 - 54)	7.7
Bare soil	10 kg DM/100 kg LW/day	First	4.2	(0 - 20)	4.5
Bare soil	10 kg DM/100 kg LW/day (mowing)	First	3.9	(0 - 15)	4.3
Bare soil	5 kg DM/100 kg LW/day	First	3.5	(0 - 18)	4.3
Bare soil	5 kg DM/100 kg LW/day (mowing)	First	4.5	(0 - 13)	4.2
Bare soil	10 kg DM/100 kg LW/day	Second	1.8	(0 - 10)	2.5
Bare soil	10 kg DM/100 kg LW/day (mowing)	Second	1.0	(0 - 9)	1.8
Bare soil	5 kg DM/100 kg LW/day	Second	3.8	(0 - 25)	4.2
Bare soil	5 kg DM/100 kg LW/day (mowing)	Second	4.9	(0 - 15)	4.5
Bare soil	10 kg DM/100 kg LW/day	Third	1.5	(0 - 8)	2.1
Bare soil	10 kg DM/100 kg LW/day (mowing)	Third	0.8	(0 - 6)	1.4
Bare soil	5 kg DM/100 kg LW/day	Third	2.4	(0 - 18)	3.9
Bare soil	5 kg DM/100 kg LW/day (mowing)	Third	3.2	(0 - 15)	3.3
Mulching	10 kg DM/100 kg LW/day	First	14.1	(0 - 60)	12.4
Mulching	10 kg DM/100 kg LW/day (mowing)	First	19.9	(0 - 48)	11.4
Mulching	5 kg DM/100 kg LW/day	First	16.0	(0 - 48)	12.9
Mulching	5 kg DM/100 kg LW/day (mowing)	First	20.6	(0 - 50)	12.5
Mulching	10 kg DM/100 kg LW/day	Second	18.2	(0 - 41)	9.7
Mulching	10 kg DM/100 kg LW/day (mowing)	Second	23.8	(0 - 43)	8.8
Mulching	5 kg DM/100 kg LW/day	Second	17.7	(0 - 50)	10.0
Mulching	5 kg DM/100 kg LW/day (mowing)	Second	18.7	(0 - 38)	8.6
Mulching	10 kg DM/100 kg LW/day	Third	12.8	(0 - 28)	8.4
Mulching	10 kg DM/100 kg LW/day (mowing)	Third	16.3	(0 - 38)	8.6
Mulching	5 kg DM/100 kg LW/day	Third	11.0	(0 - 30)	8.6



Two treatments were evaluated: high forage allowance (10% of total animal weight) and low forage allowance (5%). Relative frequency was measured as the percentage of sample points where a species was recorded, while abundance was determined by the total number of individuals of each species across all samples. Species were categorized based on their contribution to the botanical composition into dominants, commons, companions, and occasional, according to their relative frequency and abundance values.

Figure 2 - Olmstead and Tukey diagram illustrating the changes in botanical composition of a grassland in Corrientes after three years of management with variable cattle stocking rates, regulated based on forage allowance.

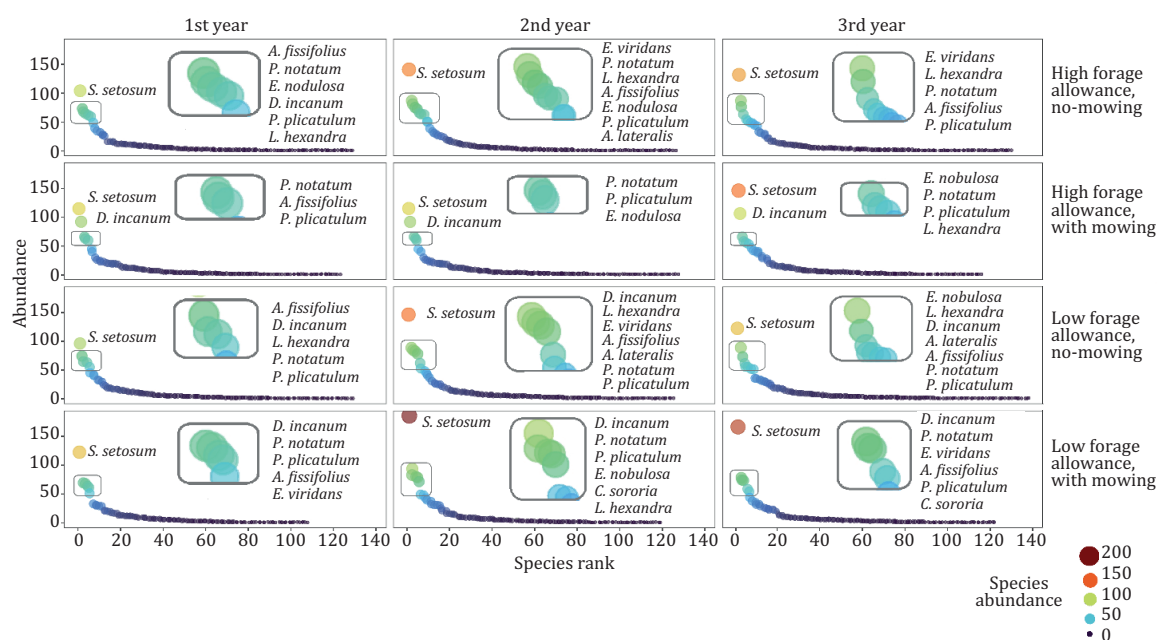


Different letters indicate statistical differences among treatments ($P \leq 0.05$).

Figure 3 - Estimation of the percentual contribution to the dry matter in the treatments of the (A) botanical families (*Poaceae*, *Fabaceae*, *Cyperaceae* and other herbaceous species) and (B) contributions within the *Poaceae* group, considering bunchgrasses (tall grasses) and inter-mound species (short grasses).

The abundance of botanical species and their ranking over the three productive cycles studied are represented in Figure 4. Across all years and treatments rank abundance curves exhibited an invariant pattern, regardless of treatment or cycle: a steep initial slope (indicating a marked dominance of a few highly-frequent-species), followed by a gradual flattening toward the tail (representing numerous low-frequency companion or present species) (Figure 4).

As is represented in Figure 4, *Sorghastrum setosum* consistently occupied the first position (rank 1) across all three cycles and treatments. Species such as *Paspalum notatum* and *Axonopus fissifolius* were more abundant in treatments with high forage allowance and no mowing, whereas *Eleocharis nodulosa* and *Desmodium incanum* were more prevalent in treatments with mowing practices. Under low forage allowance, mowing tended to increase the abundance of those species, as well as the *Poaceae* *A. fissifolius* and *Paspalum* sp. Conversely, species from high-moisture soils, including grasses like *Leersia hexandra* and *Cyperaceous* species like *E. nodulosa*, tend to decrease with mowing. Mowing effects were not statistically significant in treatments with high forage allowance, showing year-to-year species variations without a consistent pattern.



The diagram depicts changes in species relative abundance and diversity across treatments and years, highlighting the consistent dominance of species such as *S. setosum*, *P. notatum*, and *D. incanum*.

Figure 4 - Rank-abundance diagram of grassland species in Corrientes, illustrating the effects of management strategies combining high and low forage allowance (10 and 5 kg DM/100 kg LW/day, respectively), with or without mowing, over a three-year period.

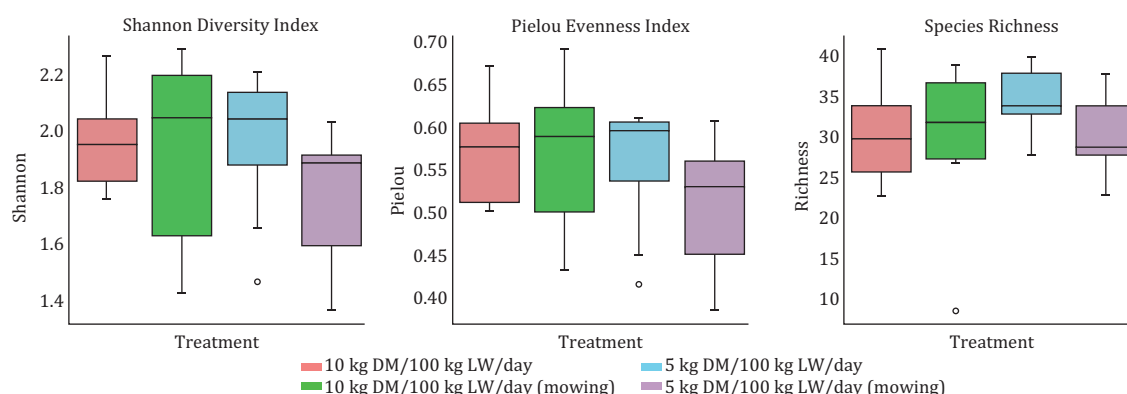
The Welch F-test was used for comparing the diversity index of the treatments (means of the three evaluated cycles, Figure 5a). The ANOVA revealed no significant global differences in diversity indices between treatments. Shannon-Wiener results in an F Welch value of 0.43 ($P = 0.737$), for species richness F Welch was 0.61 ($P = 0.625$), and for Pielou's evenness: was 0.59 ($P = 0.635$). The mean alpha-diversity observed was above 2 (Shannon Diversity index in Figure 5 and Table 2), the species richness (Figure 5 and Table 2) was above 30, considering only the species with a contribution in DM of more than 10%, both reflecting a high diversity of the grassland. Evenness was above 0.5, reflecting

a tendency of evenness over the dominance of only one species (Figure 5 and Table 2). Despite general means of treatments do not show significant differences, significant effects were found in the analysis cycle to cycle. In that sense, species richness and evenness showed significant increases in both parameters from first to third cycle (Shannon–Wiener $P = 0.045$, species richness $P = 0.046$, Pielou's evenness $P = 0.004$).

Table 2 - Interpretation of temporal and treatment-related effects on botanical diversity and species compositional balance. Mean values ($\pm$ standard deviation) of three diversity indices—Shannon–Wiener (Shannon W.), Pielou's Evenness (Pielou's E.), and Species Richness (S. Richness)—across three grazing cycles under four management treatments combining forage allowance (5 kg vs. 10 kg DM/100 kg LW/day) and mowing (with vs. without).

Cycle	Treatment	Index	Mean $\pm$ SD	Tukey
First	5 kg DM/100 kg LW/day	Shannon W.	2.21 $\pm$ 0.01	a
First	10 kg DM/100 kg LW/day	Shannon W.	2.09 $\pm$ 0.19	ab
First	10 kg DM/100 kg LW/day (mowing)	Shannon W.	1.98 $\pm$ 0.48	ab
First	5 kg DM/100 kg LW/day (mowing)	Shannon W.	1.97 $\pm$ 0.09	b
Second	10 kg DM/100 kg LW/day	Shannon W.	2.16 $\pm$ 0.06	a
Second	5 kg DM/100 kg LW/day	Shannon W.	2.03 $\pm$ 0.04	ab
Second	10 kg DM/100 kg LW/day (mowing)	Shannon W.	2.01 $\pm$ 0.31	ab
Second	5 kg DM/100 kg LW/day (mowing)	Shannon W.	1.87 $\pm$ 0.07	b
Thrid	5 kg DM/100 kg LW/day	Shannon W.	2.08 $\pm$ 0.06	a
Third	10 kg DM/100 kg LW/day	Shannon W.	2.03 $\pm$ 0.06	ab
Third	10 kg DM/100 kg LW/day (mowing)	Shannon W.	1.92 $\pm$ 0.26	ab
Third	5 kg DM/100 kg LW/day (mowing)	Shannon W.	1.75 $\pm$ 0.19	b
First	5 kg DM/100 kg LW/day	Pielou's E.	0.59 $\pm$ 0.02	a
First	10 kg DM/100 kg LW/day (mowing)	Pielou's E.	0.58 $\pm$ 0.13	a
First	10 kg DM/100 kg LW/day	Pielou's E.	0.57 $\pm$ 0.07	a
First	5 kg DM/100 kg LW/day (mowing)	Pielou's E.	0.56 $\pm$ 0.07	a
Second	10 kg DM/100 kg LW/day	Pielou's E.	0.61 $\pm$ 0.06	a
Second	10 kg DM/100 kg LW/day (mowing)	Pielou's E.	0.56 $\pm$ 0.08	ab
Second	5 kg DM/100 kg LW/day	Pielou's E.	0.55 $\pm$ 0.03	ab
Second	5 kg DM/100 kg LW/day (mowing)	Pielou's E.	0.51 $\pm$ 0.02	b
Third	10 kg DM/100 kg LW/day	Pielou's E.	0.57 $\pm$ 0.05	a
Third	5 kg DM/100 kg LW/day	Pielou's E.	0.56 $\pm$ 0.06	ab
Third	10 kg DM/100 kg LW/day (mowing)	Pielou's E.	0.55 $\pm$ 0.07	ab
Third	5 kg DM/100 kg LW/day (mowing)	Pielou's E.	0.49 $\pm$ 0.02	b
First	5 kg DM/100 kg LW/day	S. Richness	44.0 $\pm$ 5.66	a
First	10 kg DM/100 kg LW/day	S. Richness	39.5 $\pm$ 13.44	ab
First	5 kg DM/100 kg LW/day (mowing)	S. Richness	35.5 $\pm$ 10.61	ab
First	10 kg DM/100 kg LW/day (mowing)	S. Richness	31.0 $\pm$ 6.93	b
Second	5 kg DM/100 kg LW/day	S. Richness	41.5 $\pm$ 4.19	a
Second	5 kg DM/100 kg LW/day (mowing)	S. Richness	40.5 $\pm$ 3.54	ab
Second	10 kg DM/100 kg LW/day	S. Richness	37.0 $\pm$ 15.56	ab
Second	10 kg DM/100 kg LW/day (mowing)	S. Richness	36.0 $\pm$ 1.00	b
Third	5 kg DM/100 kg LW/day	S. Richness	42.5 $\pm$ 6.44	a
Third	5 kg DM/100 kg LW/day (mowing)	S. Richness	37.0 $\pm$ 7.07	ab
Third	10 kg DM/100 kg LW/day	S. Richness	36.5 $\pm$ 10.61	ab
Third	10 kg DM/100 kg LW/day (mowing)	S. Richness	32.33 $\pm$ 3.16	b

Tukey's post hoc test results are indicated by letter groupings (a, ab, b), where different letters denote statistically differences ($\alpha = 0.05$) within each cycle and index.

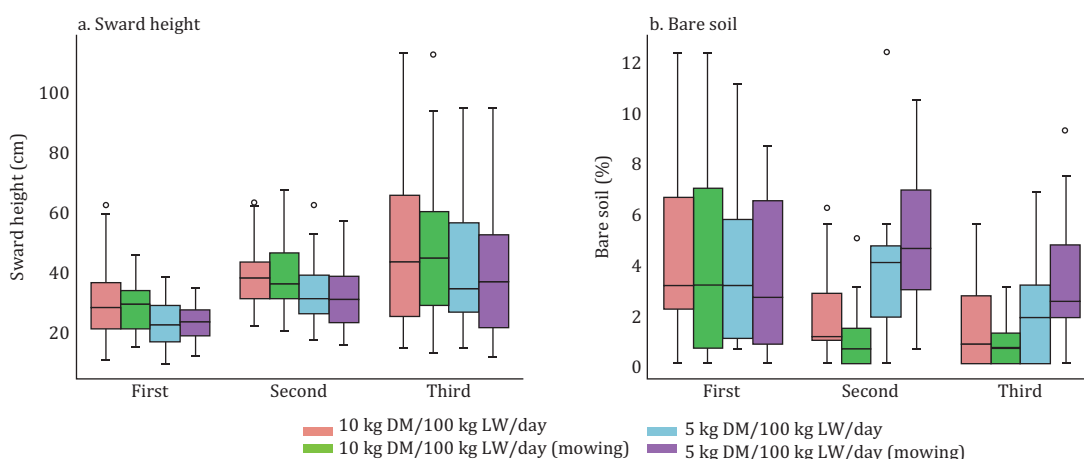


Boxes represent the interquartile range, horizontal lines indicate medians, and whiskers denote variability beyond the upper and lower quartiles.

Figure 5 - Comparison of diversity metrics across treatments, including Shannon diversity index, Pielou's evenness index, and species richness.

Sward height increased consistently from Cycle 1 to Cycle 3 in all treatments (Figure 6a; Table 1). In Cycle 1, high-allowance plots ranged approximately 15–45 cm (means ~30 cm), whereas low-allowance plots ranged 15–30 cm (means ~25 cm). In Cycle 2, high-allowance plots ranged 30–50 cm (means ~40 cm) and low-allowance plots 20–40 cm (means ~30 cm). In Cycle 3, high-allowance plots ranged 30–65 cm (means ~50 cm) and low-allowance plots 25–55 cm (means ~40 cm). Mowing applied only in Cycle 2 did not produce detectable homogenization of canopy height in Cycle 2 nor residual structural effects in Cycle 3 (Table 1).

Bare soil percentage in the high allowance treatments presents a significant tendency to diminish from first cycle to third cycle (Figure 6b; Table 1). Low allowance treatments were not effective in reducing bare soil (Figure 6b), at least during the evaluation period. Spearman correlations showed negative association between sward height and bare soil ($\rho = -0.65$), positive associations with mulch ($\rho = +0.58$), species richness ($\rho = +0.61$), and diversity indices (Shannon-Wiener $\rho = +0.59$, Simpson $\rho = +0.56$).



Boxes represent interquartile ranges, horizontal lines indicate medians, whiskers denote variability outside the upper and lower quartiles, and circles indicate outliers.

Figure 6 - Sward height (a) and bare soil percentage (b) under different grazing and mowing treatments across three grazing cycles.

However, treatment-level differences in diversity were driven not only by canopy height but also by compositional shifts under grazing intensity. In particular, 5 kg DM/100 kg LW/day treatments increased the relative contribution of short *Poaceae* and native legumes, which can raise Shannon–Wiener index and species richness while tending to maintain lower average sward height (Tables 1 and 2; Figures 3, 5 and 6a).

4. Discussion

4.1. Beyond the traditional grazing

This study aimed to propose an alternative pasture management system for native subtropical grasslands, which has not been tested in the NEA region. This approach, while not yet definitive, is oriented toward an adaptive, ecologically informed, and more efficient use of available forage, with the goal of achieving consistently high production. It is important to note that the treatment with 10 kg DM/100 kg LW/day resembles the grazing pressure of traditional extensive management systems in the NEA. These systems aim for the simplicity of maintaining constant stocking rates at around 300 kg LW/ha throughout most of the production cycle, but grazing must be drastically reduced during the winter through livestock sales or supplemental feeding strategies (Pizzio et al., 2021). This reinforces the importance of comparing adaptive grazing strategies with established regional practices. The initial observed diversity reflects the legacy effects of sustained low-intensity grazing for over 20 years. Long-term studies will be needed to confirm whether mowing, reduced forage allowance, or alternating systems can progressively improve species richness and functional heterogeneity. However, despite the short period covered by this study, trends observed by the third cycle, showing significant increases in species richness and evenness, suggest delayed treatment effects and indicate that diversity parameters may increase with the implementation of adaptive regimes such as the one proposed.

4.2. Diversity and system stability

Diversity, determined by the Shannon–Wiener index, was less sensitive than species richness and evenness to management changes. However, it is important to note that the observed shifts in composition may require longer timeframes to become statistically and ecologically meaningful. The treatment with 5 kg DM/100 kg LW/day showed the lowest variability in diversity indices across cycles, suggesting that consistent grazing pressure may enhance community stability.

In a very similar grassland in Corrientes, Pizzio et al. (2016) reported a decline in initial diversity that was inversely related to a continuous, fixed stocking rate. Nonetheless, species richness remained constant. Kurtz et al. (2018) found that both high-impact grazing pulses and continuous low stocking rates had similar effects on diversity in another Corrientes grassland, resulting in a maintained diversity value of 2.5.

Low forage allowance without mowing was more effective in maintaining diversity and reducing the dominance of tall species. The combination of high forage allowance and mowing tended to promote species turnover and recruitment. In contrast, the treatment with the highest forage allowance and no mowing showed limited improvement in diversity indices, suggesting that excessive biomass accumulation without structural disruption may inhibit species turnover and favor dominance by a few competitive species. These results support the concept of intermediate disturbance, as proposed by Carvalho et al. (2007) and Peláez et al. (2021), further supported by modeling approaches showing that moderate grazing promotes coexistence (Pulungan et al., 2019). These findings suggest that intermediate grazing levels enhance diversity by creating favorable conditions for less dominant species, particularly those with lower intrinsic growth rates, to establish in areas opened by grazing.

The shape of the rank–abundance curve conveys critical information about species diversity and community structure (Magurran, 1988; Moreno et al., 2011). In the present study, all treatments and years exhibited extended curves, indicating high species richness. This distribution suggests that the most abundant species have marked differences in relative abundance, while the less abundant

species show greater evenness (Mouillot and Lepretre, 2000). In all treatments and years, very similar distributions were observed, with a tendency toward greater stability and higher evenness under low forage allowance without mowing.

The rank–abundance relationship can be considered in terms of resource partitioning, where species abundance sometimes reflects the niche space occupied (Magurran, 1988). Short grasses and other main native forage species became more abundant, whereas tall grasses and Juncaceae species became less abundant under low forage allowance without mowing. These results are consistent with other studies conducted in humid subtropical environments, suggesting that high-intensity grazing favors diversity and colonization by native grasses and legumes (Díaz et al., 2007; Lezama et al., 2014; Kaufmann et al., 2019; Ratajczak et al., 2022; Avramidou et al., 2024).

According to Zhang et al. (2023) maintaining an appropriate diversity of soil microorganisms, enhanced by cattle feces, is fundamental. A previous study has shown that large herbivores influence plant communities beyond mere defoliation, generating micro-disturbances and nutrient-rich patches through trampling and the deposition of urine and feces, favoring the proliferation of less represented (and often highly palatable) native species (Ratajczak et al., 2022). These mechanisms concurrently suppress dominant tall grasses and reduce the incidence of ruderal weeds (Fernández et al., 2023). In line with these findings, our study documented a decline in tall dominant species and *Cyperaceae* weeds, accompanied by a relative increase in short *Poaceae* species and legumes, suggesting a positive response to selective pressures introduced by more intense grazing.

However, the effect of mowing differs from that of grazing. Mowing resulted in a greater contribution to DM and persistence of less-preferred herbaceous species (including coarse tall grasses, *Cyperaceae* species, and ruderal species). Conversely, treatments without mowing, particularly those with 5 kg DM/100 kg LW/day, showed a significantly lower contribution of tall grasses and a higher contribution of short grasses and legumes. Moreover, mowing appears to stimulate the regrowth of tall grasses. This aspect could be further evaluated in future studies, focusing on its role in maintaining a vegetative mosaic favorable to selective grazing and on assessing forage quality in terms of digestibility and protein content.

4.3. Functional composition, soil cover, structural dynamics and growth of sward

It has been demonstrated by Soares et al. (2005) and Neves et al. (2009) that seasonal adjustment of forage allowance levels, particularly increasing allowance during periods of low pasture growth, can improve pasture structure. Similarly, Fedrigo et al. (2018) showed that long-term high-intensity grazing with 4 kg DM/100 kg LW/day was detrimental, whereas 8–12 kg DM/100 kg LW/day preserved diversity.

This is an interesting perspective, but it also requires more intensive monitoring of forage availability and continuous adjustment of stocking rates. Our results could complement these findings by incorporating the monitoring of plant diversity and soil cover, and by supporting the design of longer-term studies aimed at developing simpler methods to establish locally adapted strategies that promote long-term ecosystem stability and productivity. Similarly, Briske et al. (2008) emphasize that the effectiveness of grazing systems depends more on the adaptability and consistency of management than on the specific strategy employed. Studies such as Teague et al. (2011) have shown that adaptive grazing strategies, including mowing and rotational practices, can improve vegetation structure, soil health, and biodiversity when consistently applied. This is also supported by Pizzio et al. (2021), advocating for process-based technologies such as rotational rest and deferred grazing as foundational tools for sustainable intensification in the Corrientes region. Nevertheless, the search for strategies that simplify forage allowance variation in a programmatic and reproducible manner should be considered the next step in the evolution of traditional grassland management practices.

Theoretically, mowing can reduce the structural dominance of tall bunchgrasses, increase light penetration to lower strata, and promote the establishment of short grasses and legumes (Collins et al., 1998; Milchunas and Lauenroth, 1993). In our case, the inability to apply mowing in all cycles likely

constrained its ecological impact, thereby masking its potential effects on botanical composition and soil cover. We recommend that future studies ensure the long-term and uninterrupted implementation of mowing to fully assess its role in enhancing pasture structure, species turnover, and overall diversity.

A previous study has emphasized the limitations of traditional intensification models that rely heavily on external inputs and promote homogeneity in pasture structure (Carvalho, 2005). The author argued for a paradigm shift toward recognizing pastures as ecosystems, where energy flow and structural complexity are central to sustainability. Our findings align with this perspective, demonstrating that all four treatments tend to preserve or enhance functional diversity and soil cover, whereas treatments with lower forage allowance may support higher levels of cattle productivity. Additionally, the increased dispersion and widening of sward height ranges across cycles are consistent with grazing patch dynamics rather than degradation. Selective foraging generates fine-scale spatial heterogeneity, promoting localized increases in low-growing Poaceae and legumes without reducing species richness (Adler et al., 2001; Golluscio et al., 2005). Classic grazing-mosaic theory (Milchunas and Lauenroth, 1993; Collins et al., 1998) supports this interpretation, aligning with the stable richness observed in our study.

Bare soil percentage decreased from the first to the third cycle, with the most pronounced reduction observed under mowing combined with high forage allowance. Mowing may enhance ground cover when forage supply supports rapid regrowth, while a reduction in allowance retards vegetative closure. Moreover, mowing applied only in Cycle 2—and the initial leveling cut applied uniformly to all plots in January 2016—did not produce canopy height homogenization in Cycle 2 nor residual effects in Cycle 3, indicating that differences height dispersion across cycles were primarily driven by forage accumulation rather than by mowing.

Grassland growth varied seasonally but not among treatments. From the first to the third cycle, growth trend increased, especially under high forage allowance without mowing. It is important to note that grassland growth, as evaluated in this study, refers to forage biomass production rather than canopy or sward height. While sward height is a useful structural descriptor, it does not necessarily reflect forage biomass, as biomass accumulation depends on additional factors such as ground cover, species composition, and the proportion of bare soil.

Studies on humidity gradients (Milchunas and Lauenroth, 1993; Herrero-Jáuregui and Oesterheld, 2018; Zhang et al., 2023) have concluded that humidity plays a crucial role in determining whether grazing benefits or harms biodiversity and species richness.

The bare soil analysis complements the botanical composition findings, revealing that the evaluation cycle significantly influenced soil exposure. The consistent increase in bare soil percentage during the second cycle (which is typical of wetter years) across all treatments may reflect environmental conditions rather than treatment effects. This temporal pattern underscores the importance of monitoring grazing impacts over time, as soil exposure can affect erosion risk and pasture resilience. Despite these fluctuations, the system maintained high species richness and diversity, suggesting that adaptive grazing strategies may mitigate negative impacts on soil cover while supporting productive goals.

4.4. Resilience and applicability

The study covered three productive cycles at a single site, and mowing could be applied consistently only during the second cycle due to excessive rainfall. These constraints limit the generalization of treatment effects and hinder the isolation of mowing impacts. Longer-term, multi-site trials, including consistent mowing and direct measures of forage quality, are recommended to validate the observed trends and improve the transferability of the results.

Our findings reinforce that aligning cattle load with grassland growth, by improving forage use efficiency without compromising species diversity. Across all treatments, species richness remained above 30, and Shannon–Wiener indices hovered around 2.0. Grassland growth was stable across treatments

and showed a consistent increase through cycles (Figure 1). This reflects efficient nutrient cycling, indicating that grazing intensification does not compromise productivity. These findings highlight that adaptive forage allowance strategies meet the essential requirements for maintaining high stocking rates without compromising ecosystem integrity. Longer-term studies are necessary to determine whether any of the proposed management strategies is significantly better at maintaining diversity or promoting grassland growth.

Treatments with low forage allowance favored desirable native short grasses and legumes (e.g., *Paspalum*, *Axonopus*), improving pasture quality without reducing alpha diversity. This adaptive strategy allows for substantially higher stocking rates, potentially double those of conventional fixed-load systems, without compromising ecological integrity.

While the results are promising, their applicability to other subtropical grasslands worldwide will depend on the degree of similarity in environmental conditions, including soil type, moisture availability, and temperature. Local adaptations may be required to fine-tune grazing intensity and timing, especially in regions with different seasonal growth patterns. Furthermore, interannual climatic variability, such as fluctuations in rainfall or prolonged droughts, may affect plant community responses over time. Therefore, long-term monitoring is essential to ensure that biodiversity and productivity gains are sustained under changing environmental conditions. Nevertheless, our findings provide a valuable and scalable framework for a more resilient and efficient grazing system, in terms of available forage, which could be adapted to regional characteristics.

5. Conclusions

Pasture diversity remained high across all treatments, with Shannon–Wiener index values near 2 and species richness consistently above 30 species throughout the three grazing cycles.

Significant cycle effects were detected, as both species richness and evenness increased in the third cycle, regardless of forage allowance or mowing. The 5 kg DM/100 kg LW/day treatment showed the highest species richness and greater relative contributions of short *Poaceae* and native legumes, while the 10 kg DM/100 kg LW/day treatment showed slightly higher evenness values.

Grassland growth, evaluated as available forage biomass, increased from Cycle 1 to Cycle 3 and did not differ among forage allowance or mowing treatments, indicating that higher grazing intensities did not compromise biomass production during the study period.

Sward height increased from Cycle 1 to Cycle 3 in all treatments, but lower forage allowance consistently restricted vertical canopy development without reducing species richness or diversity. These structural differences in sward height should be interpreted as changes in canopy architecture rather than as direct proxies for forage biomass production.

The combination of high forage allowance and mowing resulted in the greatest reduction of bare soil, highlighting the importance of adaptive grazing strategies for maintaining ground cover and ecological integrity.

Data availability

The entire datasets supporting the results of the present study was made available on the Repositorio Digital of the Instituto Nacional de Tecnología Agropecuaria and can be accessed at <https://repositorio.inta.gob.ar/xmlui/handle/20.500.12123/23995>.

Author contributions

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Methodology: Gándara, L. and Carvalho, P. C. F. **Project administration:** Gándara, L. **Supervision:** Balbuena, O. and Carvalho, P. C. F. **Visualization:** Ferrari Usandizaga, S. C. and Riva de Neyra, L. A. **Writing – original draft:** Gándara, L. and Ferrari Usandizaga, S. C. **Writing – review & editing:** Gándara, L.; Ferrari Usandizaga, S. C.; Riva de Neyra, L. A.; Pereira, M. M.; Balbuena, O. and Carvalho, P. C. F.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgments

We thank Francisco Nuñez, Paolo Sussini, María Paz Sanchez, Ditmar Kurtz, Francisco Casco, María Cristina Goldfarb, and Fernando Gándara. All of them highly contributed in one way or another providing support during the research, technical assistance, and insightful comments. Also, we are especially grateful to the Instituto Nacional de Tecnología Agropecuaria which made the present study possible by providing human, animal, physical, and material resources.

Financial support

This research was supported by the Instituto Nacional de Tecnología Agropecuaria.

Declaration of generative AI in scientific writing

The authors declare that they have not used AI to create any part of the content included in this manuscript. However, this tool was used as a backup to verify the correct use of the language in which this manuscript is written. This means that in certain cases it was used to resolve doubts about the most appropriate terminology or the grammatical construction of some sentences. Also, in some cases it was used to resolve the format of the citations in the list of bibliographic references.

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