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The savanna vegetation under cattle grazing in Central Brazil

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Abstract
The ecological impact of cattle grazing on Brazilian savannas is poorly known. This study aimed to evaluate vegetation structure, diversity, and fuel load in savannas under rotational grazing. We studied three adjacent, fire-excluded savanna fragments in Central Brazil: one subjected to rotational grazing, one excluded from grazing for 2.5 years, and one ungrazed. For vegetation sampling, we used the line-point intercept method. Fuel load was quantified by measuring the dry mass of necromass, live graminoids, and other plants with a stem diameter < 6 mm. There were no differences in vegetation cover above 2 m height among sites. Below 2 m, total cover was three times greater in the ungrazed site than in the grazed, while the short-term exclusion site showed intermediate values. Graminoids had the highest absolute cover in the ungrazed site for 2.5 years (97%), followed by the ungrazed (86%) and grazed (60%) sites. Species richness decreased from 133 species in ungrazed to 100 species in ungrazed for 2.5 years and 96 species in grazed site. Fuel load was 61% lower in the grazed site compared to the ungrazed site. These findings suggest that Cerrado savannas have the potential to be used as intermittent pastures on private farms, as they did not severely impact vegetation structure and diversity, and reduced fuel loads in fire-excluded savanna fragments. Future studies should explore varied grazing regimes and different regions to assess the feasibility of using cattle as a conservation ally.

Keywords Brazilian savanna · Ecological integrity · Legal Reserve · Native rangelands · Sustainable land management · Cerrado

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Introduction

Cattle ranching is the most extensive form of global land use, covering approximately one-quarter of the Earth's terrestrial surface (Schieltz and Rubenstein 2016). In Brazil, the area dedicated to cattle grazing, encompassing planted pastures and native grassy ecosystems, reaches 172.3 million hectares (IBGE 2017). Cattle production contributed to 6.6% of Brazil's Gross Domestic Product (GDP) in 2022 (CEPEA and CNA 2023). Within the Cerrado biome (biome *sensu* IBGE 2004, 2019), 53 million hectares are used for cattle grazing in planted pastures, and 19 million are native savannas and grasslands used as pastures (IBGE 2017; Strassburg et al. 2017).

Cattle grazing in native savannas and grasslands of Cerrado was once prevalent until the mid-1970s and was characterized by extensive cattle ranching at low densities (Dias 2006; Satumino et al. 1976). Nowadays, grazing in native savannas and grasslands is sporadic and is primarily practiced by smallholders and traditional communities (Lima et

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al. 2022; Nogueira 2017). However, cattle grazing in native vegetation is also observed in large farms for short periods when planted pastures are allowed to regenerate (Soterroni et al. 2019).

Historically, cattle ranching has been linked to deforestation and biodiversity loss (Morand 2020; Dick et al. 2021). In many countries, including Brazil, this activity is predominantly perceived by conservationists, researchers, and the broader public as incompatible with nature conservation (Sklenicka 2016; Perrotton et al. 2017; Barradas et al. 2020). However, the impact of cattle grazing and trampling on the ecological integrity of native vegetation varies significantly across ecosystems (Schieltz and Rubenstein 2016; Jia et al. 2018). Appropriate livestock management has been employed as a conservation and restoration tool for grassland ecosystems worldwide. It aids in fuel reduction, controlling dominant and invasive exotic species, and maintaining species richness. Examples include the subtropical grasslands of Argentina, Uruguay, and southern Brazil (Pucheta et al. 1998; Altesor et al. 2005; Sühs et al. 2020); Mediterranean grasslands in Israel (Sternberg et al. 2000), savannas in Kenya (Oba et al. 2001); savannas and rangelands in the United States of America (Bakker et al. 2006; Raynor et al. 2018; Watson et al. 2024), and in the Cerrado savannas of Brazil (Durigan et al. 2022).

Open ecosystems, characterized by a dominant layer of shade-intolerant herbaceous and shrub species, are intrinsically linked to biomass consumption by fire and large herbivores (Overbeck et al. 2022). These agents act as frequent disturbances, inhibiting tree canopy closure (Bond 2021). Ecosystems such as the grasslands and savannas of the Cerrado biome evolved under and are maintained by fire (Ribeiro and Walter 2008; Simon et al. 2009; Tomas et al. 2021). Fire prevents woody encroachment, thereby preserving the ecological integrity of open ecosystems (Pivello 2011; Mariano et al. 2019). It enhances forage quality by eliminating lignified biomass unpalatable to cattle and promoting palatable new sprouts (Archibald 2003; Furquim et al. 2024). Moreover, frequent fire reduces fuel loads, preventing high-intensity fires that cause significant plant mortality (Fidelis et al. 2018; Barradas et al. 2020).

However, fire suppression policies have become widespread across private lands and protected areas (Eloy et al. 2019a). In the absence of fire, livestock can reduce biomass in a manner analogous to fire (Rouet-Leduc et al. 2021; Tomas et al. 2024); however, this effect depends on biomass quality. When accumulated biomass becomes highly lignified, its low nutritive value limits cattle intake and selectivity, constraining their ability to reduce standing biomass effectively (Duncan et al. 2020). Furthermore, grazing regimes can significantly modulate livestock impacts on the composition, structure, and diversity of plant communities (Milchunas et al. 1988; Cingolani et al.,. Light grazing in secondary Cerrado savannas can reduce exotic grass biomass, lower flammability, limit woody and exotic grass invasion, and promote native forb richness relative to grazing exclusion (Campos et al. 2026). By contrast, long-term grazing exclusion can facilitate shrub encroachment and alter species richness and functional-type frequencies, potentially reducing some herbaceous components and tree seedling survival in many Neotropical savannas (Mochi et al. 2022).

The Cerrado biome covers approximately 23% of Brazil's territory and is one of the 36 global biodiversity hotspots (Mittermeier et al. 2011). It harbors about 12,800 plant species, of which around 4,800 are endemic (Strassburg et al. 2017). The biome is predominantly covered by savannas, featuring a continuous ground layer of grasses and shrubs interspersed with scattered trees (Overbeck et al. 2022). Managed cattle grazing in the Cerrado can facilitate farmers' compliance with the Native Vegetation Protection Law (Brasil 2012) and the National Plan for Native Vegetation Recovery (Planaveg 2017), which are policy instruments that guide conservation and restoration efforts on private lands. Grazing can mitigate the impact of fire suppression and add economic value to Legal Reserves. Legal Reserves (RLs) are areas within rural properties, mandated by Brazilian federal legislation to preserve native vegetation, associated ecosystem services, and biodiversity (Brasil 2012; Metzger et al. 2019).

In a context where cattle are still predominantly perceived as a degrading factor but also hold potential for ecological restoration and add economic value to Legal Reserves (Tomas et al. 2024), it is crucial to understand their impact on the ecological integrity of savannas in the Cerrado biome. The present study evaluated the (i) structure, richness, and species composition and (ii) available fuel load in three savanna fragments: Grazed, Ungrazed for the last 2.5 years (Ungrazed-2.5y), and Ungrazed for at least 30 years (Ungrazed). Our hypotheses were: (i) cattle grazing decreases vegetation cover and diversity in the ground layer (Stahlheber and D'Antonio, 2013; Sabo, 2019); (ii) after only 2.5 years of cattle removal, vegetation recovery is high due to the ability of plants to resprout and colonize (Horstmann et al. 2023); and (iii) cattle grazing reduces fuel load (Eloy et al. 2019b; Rouet-Leduc et al. 2021).

Materials and methods

Study area

The study was conducted at the Sucupira Farm (Fig. 1), a 1,799-hectare property owned by the Empresa Brasileira de

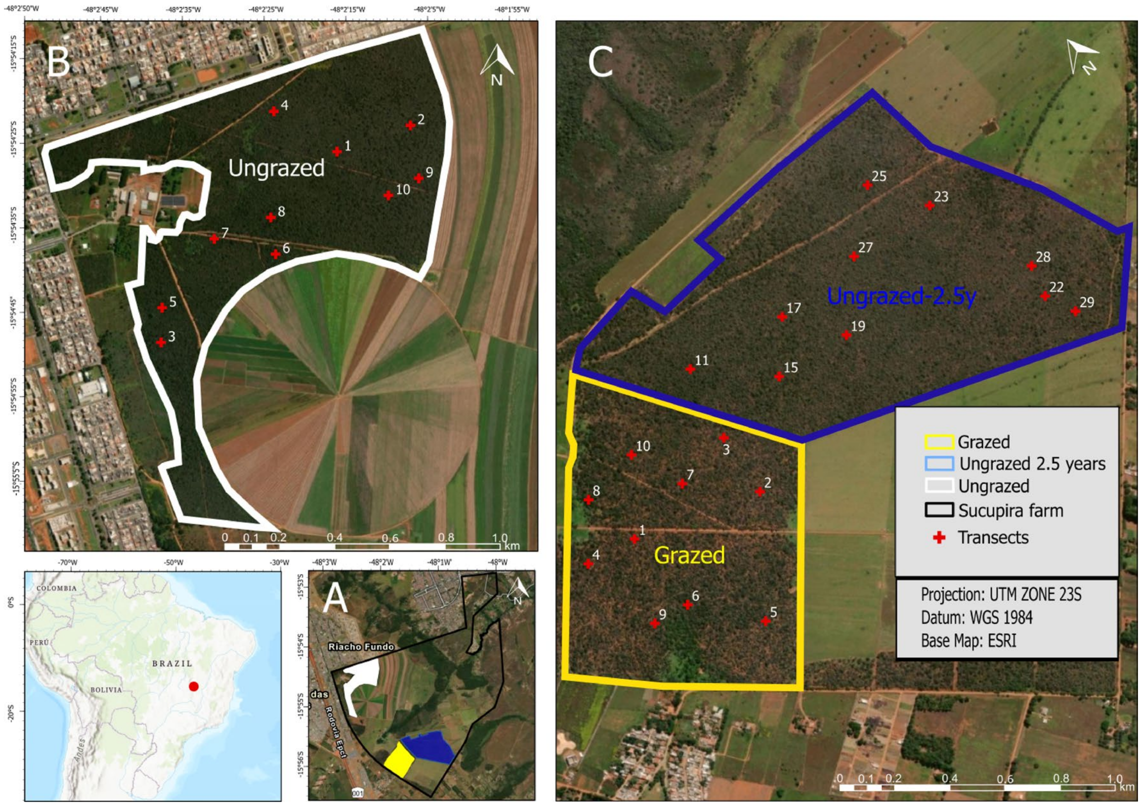

Fig. 1 (**A**) Location of the Sucupira Farm, DF, Brazil. (**B**) The white polygon indicates the ungrazed savanna area (Ungrazed). (**C**) The yellow and blue polygons indicate the areas currently grazed by cattle (Grazed) and ungrazed for 2.5 years (Ungrazed-2.5y), respectively. Grazed Red crosses in **B** and **C** indicate the location of the sampling transects

Pesquisa Agropecuária (Embrapa), in the Federal District, Brazil. The average altitude is 1,100 m, with mean annual precipitation ranging from 1,089 to 1,987 mm. Rainfall is concentrated between October and March, accounting for 85% of annual precipitation (ANA, 2024). Mean temperatures for the coldest and warmest months are 19 °C and 23 °C, respectively (INMET 2022). The sampled areas exhibit flat topography and Red-Yellow Latosol soils. The farm's vegetation comprises diverse formations, including forests, savannas, and grasslands (*sensu* Ribeiro and Walter 2008). The farm comprises 322 ha of savannas, 346 ha of crops, and 428 ha of cultivated pastures with *Urochloa* grasses (*Urochloa brizantha* (Hochst. ex A.Rich.) R.D.Webster and *Ungrazed. decumbens* (Stapf) R.D.Webster). A constant density of approximately 200 adult Nellore cattle is maintained, along with cattle of other breeds, horses, and sheep, all grazing the cultivated pastures.

Characterization of the sampled areas

At Sucupira Farm (Fig. 1A), we identified three Cerrado *sensu stricto* fragments, the primary type of savanna within the Cerrado biome (sensu Ribeiro and Walter 2008), with varying cattle grazing regimes: one fragment without grazing for at least 34 years (Ungrazed); one grazed for at least 34 years (Grazed) and one excluded from grazing for 2.5 years before the study (Ungrazed-2.5y).

The Ungrazed fragment covers 93 ha and is surrounded by crop cultivation (Fig. 1B). The other two fragments originated from a single area separated by a fence approximately 10 years ago for cattle management. Following separation, these two savanna fragments were grazed by 120–140 adult Nellore cattle for approximately 15 days every three months. The Grazed fragment (Fig. 1C, Grazed), encompassing 66 ha, maintained this grazing regime (2.0 heads·ha^{-1}) until the study date. The Ungrazed-2.5y fragment, covering 114 ha, had been grazed (2.0 heads·ha-1) until 2.5 years before the study, when it became a Legal Reserve, and managers opted to remove the cattle. Neither grass seeding nor any management to stimulate grass expansion was implemented in either fragment. Cultivated pastures surround both fragments. Cattle use the fragments uniformly, as verified by paths and dung; however, small patches (ca. 4 m²) of dense shrubs and small trees are avoided. The three fragments have been affected only by fire on their edges and have not undergone timber extraction for at least 30 years. All transects were established in areas excluding these edges, ensuring no fire occurrence for at least 30 years, since fire is intentionally prevented in these private lands to avoid accidental burning of adjacent cultivated pastures. This study is pseudoreplicated, as all transects representing each treatment were established within a single savanna fragment. However, it represents a unique opportunity to evaluate the effects of cattle grazing on savannas, due to the long-term controlled grazing conditions.

Data collection

To characterize the plant communities, we sampled the vegetation cover using line-point intercept sampling (Herrick et al. 2017) from March to May 2023. In each of the three areas, we randomly distributed 10 transects, each 25 m long, with a minimum distance of 100 m between them. Every 50 cm along the transect, a 2-m pin was placed vertically on the ground, and all species that touched the pin, or its vertical projection, were recorded to species name and height (a total of 500 points per area). We recorded bare soil when no plant touched the pin or its vertical projection. Most individuals and species were identified in the field whenever possible or collected for later identification. Voucher specimens of all sampled species were deposited in the CEN herbarium at Embrapa Genetic Resources and Biotechnology. The classification of families follows APG IV (The Angiosperm Phylogeny Group 2016), and the species nomenclature follows Flora of Brazil 2020 (BFG 2022).

Fuel load (dry mass) was estimated by harvesting aboveground fine fuel biomass at ground level, including graminoids and other plants < 6 mm in diameter, and necromass, in 50 cm² plots at 5-m intervals along each transect (a total of 50 plots per area). Fine fuel load represents the fraction of aboveground biomass that is entirely available for combustion, encompassing both live and dead vegetation with a diameter of less than 6 mm at the soil surface (Luke and McArthur 1978). Aboveground biomass was cut at ground level with pruning shears, and necromass was collected by hand and separated into paper bags (Kauffman et al. 1994). The samples were dehydrated in an oven at 60 °C for 48 h and then weighed using a balance with two-decimal-place precision. The fuel load mass ($Mg \cdot ha^{-1}$) was calculated based on these data. Fine fuel was categorized into monocotyledons, dicotyledons, and necromass.

Data analyses

The comparison of vegetation vertical structures among the three areas was analyzed based on plant touches in the height profile, with heights grouped into 100-cm classes. Histograms were generated using the frequency of cover by height with the ggplot2 package function "geom_freqpoly" (Wickham et al. 2016). The Kolmogorov-Smirnov (K-S) test was applied to compare the frequency distributions of cover in the height profile. Since the K-S analysis detected differences among the areas and the histogram showed that the differences occurred only below 2 m (see Results), the following analyses were focused on the plant community ≤ 2 m in height.

To assess the impact of cattle on the cover of life forms and regeneration strategies among areas, we used counts of life forms and regeneration strategies per transect. We fitted a generalized linear model (GLM) for each life form and regeneration strategy using the 'glm' function in the 'lme4' package with a 'Poisson' distribution and a logarithmic link function. We conducted a Tukey test for posterior comparisons ($p < 0.05$) using the 'emmeans' package. Data were transformed into absolute cover values by exponentiating the log-transformed abundance values (lsmeans), expressed as percentages, after normalization, relative to the total number of touches in each transect. Finally, absolute cover percentages across life forms and treatments were visualized using a dot plot, with error bars indicating the 95% confidence intervals.We used 21 rarefaction curves (q = 0, richness) for the occurrence data, following the methods proposed by Chao et al. (2014). The analysis was conducted using the "iNEXT.Sam" and "plot.iNEXT" functions of the iNEXT package, version 2.0.9 (Hsieh et al. 2016). These procedures allowed for a systematic comparison of the richness of different life forms in terms of area, considering sample size standardization. Additionally, the results were graphically represented with 95% confidence intervals obtained through the bootstrap method (Hsieh et al. 2016), ensuring the robustness of comparisons among the different samples. We extracted the lower and upper bounds of the 95% confidence intervals and the mean of the rarefactions, for each life form.

To compare the plant composition among the three areas, we calculated absolute cover, relative cover, relative frequency, and the Cover Value Index (CVI) for each species in each area. The Cover Value Index (CVI) is calculated based on the Relative Frequency (RF) and Relative Dominance (RD) of each species in a given area. RF represents the proportion of plots in which a species occurs relative to the total number sampled, while RD reflects the proportion of the area covered by the species. The CVI is then calculated by summing the two values, providing a composite measure of the relative importance of each species in the studied vegetation, ranging from 0 to 200. We classified the species according to growth forms (trees, shrubs, subshrubs, graminoids, herbs, lianas, and palms) and regeneration strategies (seeder or sprouter) based on the literature (Hoffmann 1998; Alonso and Machado 2007; Pilon et al. 2021), field observations, and the authors' experience.

A species cover matrix for each area was used to compare species similarity among the three areas, and the matrices were transformed into presence-absence data. The similarity was estimated using the Chao-Sørensen index (Chao et al. 2005, 2006). We constructed a table showing the relative cover of species to understand the composition of the dominant species in each area. We selected the species by ranking the most dominant species until they accounted for 70% of the total cover in each area.

To compare fuel load among the three areas, we used a fuel table ($Mg \cdot ha^{-1}$) per area and per class (eudicotyledons, monocotyledons, necromass). We fitted a generalized linear model (GLM) for each class using the 'glm' function in the 'lme4' package, with a 'Gamma' distribution and an inverse link function. We conducted a Tukey test for posterior comparisons ($p < 0.05$) using the 'emmeans' package. Finally, we generated boxplots for each class. In all models, we analyzed and validated the assumptions according to the recommendations of Zuur et al. (2009). All analyses were performed using R version 4.2.2 (R Core Team 2023).

Results

The three areas showed similar cover above 2 m in height up to 14 m. Below 2 m in height, vegetation cover differed. Grazed had 137% of absolute plant cover (or 1.37 plants touching the pin at each point on average), Ungrazed-2.5y had 204% plant cover, and Ungrazed had 263%, which is double plant cover of Grazed (Grazed × Ungrazed-2.5y, D = 0.1635, $p < 0.001$; Grazed × Ungrazed, D = 0.1633, $p < 0.001$; Ungrazed-2.5y × Ungrazed, D = 0.8132, $p < 0.001$) (Fig. 2).

The plant cover by life forms ≤ 2 m was highest in the Ungrazed area, intermediate in the Ungrazed-2.5y, and lowest in the Grazed for subshrubs, shrubs, trees, and palms and did not differ for herbs and lianas (Fig. 3). Graminoids had the highest cover of all life forms (97% in the Ungrazed-2.5y 86% in the Ungrazed, and 60% in the Grazed; Fig. 3). Shrubs and subshrubs had the highest cover in the Ungrazed (58% and 53%, respectively), intermediate in the Ungrazed-2.5y (43% and 33%), and lowest in the Grazed (23% and 16%). Trees had the highest cover in the Ungrazed (49%) and the lowest in the Grazed (31%) and the Ungrazed-2.5y (25%) (all cover values are given in Supplementary Material A and GLM results are given in Supplementary Material B).

Across all strata, 191 species were found, belonging to 137 genera and 54 families. For the stratum ≤ 2 m, 179 species, 130 genera, and 53 families were recorded (see species list, life forms, vouchers, and the area of sampling in Supplementary Material C). There were 96 species in the Grazed area, 100 species in the Ungrazed-2.5y, and 133 species in the Ungrazed (Fig. 4). Fifty-six species were shared between the Grazed and the Ungrazed-2.5y, 61 species between the Grazed and the Ungrazed, and 76 species between the Ungrazed-2.5y and the Ungrazed. Forty-three species were common to all areas. Of the 53 families, 37 occurred in the Grazed, 49 in the Ungrazed-2.5y, and 50 in the Ungrazed. In all three areas, Fabaceae had the highest richness (22 species), followed by Poaceae (16), Asteraceae (11), and Myrtaceae (11). The Ungrazed and the Ungrazed-2.5y areas were the most floristically similar (Chao-Sørensen

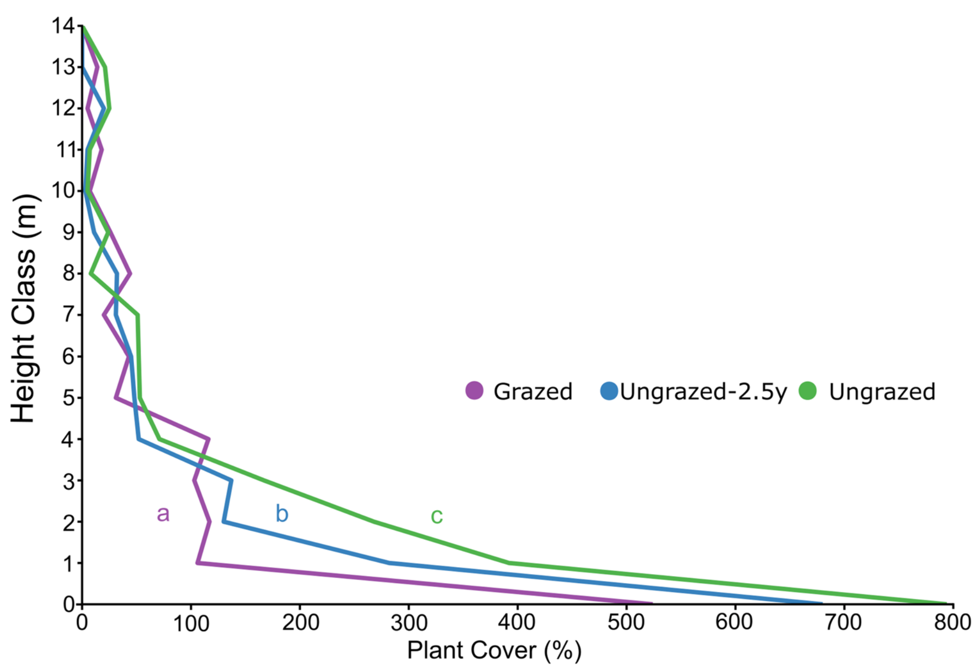

Fig. 2 Plant cover along the vertical vegetation profile in three studied areas of the Cerrado: grazed (Grazed), ungrazed for Ungrazed-2.5y years (U2.5-y), and ungrazed (Ungrazed). The lines represent the percentage of cover at each 1 m height class. Different letters (**a**, **b**, **c**) indicate a statistically significant difference in the distribution of height frequencies, as determined by the Kolmogorov-Smirnov test

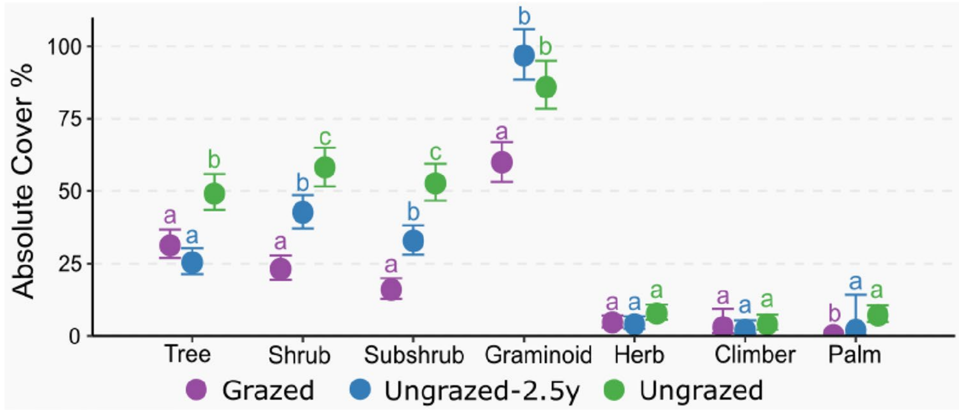

Fig. 3 Absolute life plant form cover (≤2 m height) in the three studied areas of the Cerrado: Grazed, Ungrazed-2.5y (U2.5-y), and Ungrazed. Values are average and 95% confidence intervals. Cover values may exceed 100% as multiple species from a life form can touch the pin at each point

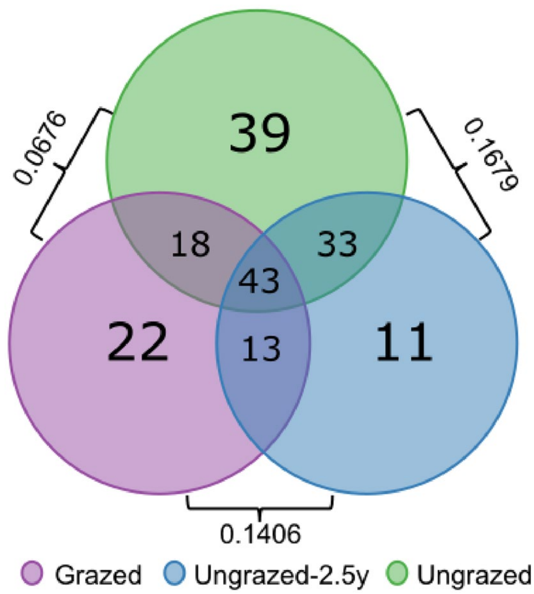

Fig. 4 Species richness of plants in three studied areas of the Cerrado. Values in the circles represent the number of species, and outside values represent the Chao-Sørensen similarity indices. Grazed, Ungrazed-2.5y (U2.5- y) and Ungrazed

index = 0.1679), followed by the Grazed and the Ungrazed-2.5y (0.1406) and the Grazed and the Ungrazed (0.0676) areas.

The analysis of species richness across life forms revealed distinct patterns (Fig. 5). The Ungrazed displayed the lowest graminoid richness with only seven species. In contrast, shrub richness in the Ungrazed was 1.5 times greater than in both the Grazed and the Ungrazed-2.5y. A similar trend emerged for subshrubs, with the Ungrazed exhibiting 1.3 times higher richness than the Ungrazed-2.5y and 1.5 times higher than the Grazed. Herb richness followed suit, with the Ungrazed having double the species richness of the Ungrazed-2.5y. Interestingly, palm distribution varied across the areas. No palms were found in Grazed, while the Ungrazed-2.5y and the Ungrazed harbored one and four species, respectively. Finally, no statistically significant differences in species richness were detected among the areas for lianas and trees.

The most dominant species was *Echinolaena inflexa*, a native stoloniferous resprouter grass, with 44% to 66% cover in the three areas. Some seeder graminoid species, *Axonopus capillaris* (7.4%), *Paspalum pilosum* (1.8%), and *Cenchrus polystachios* (5%) were exclusive to the Grazed. Among these, *Cenchrus polystachios* is the only exotic species found, which occurred in only one transect. Conversely, the longer lifespan species *Trachypogon* sp. and *Axonopus*

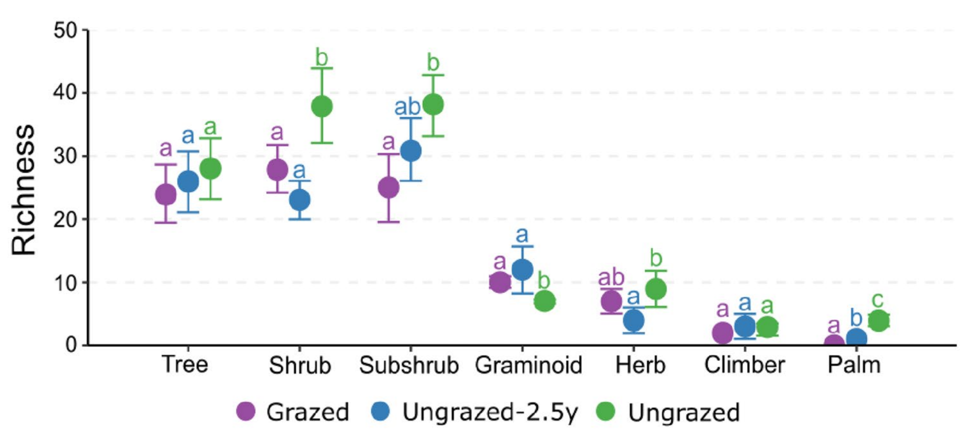

Fig. 5 Species richness of life form cover (≤2 m height) in the three studied areas of the Cerrado: Grazed, Ungrazed-2.5y (U2.5-y), and Ungrazed. Values are average and 95% confidence intervals. Cover values may exceed 100% as multiple species from a life form can touch the pin at each point

siccus (12.6% and 13.4% cover, respectively) were found only in the Ungrazed-2.5y and the Ungrazed (Table 1). Aside from graminoids, no other species reached an absolute cover exceeding 15.4% (or 8% relative cover). The tree species *Miconia albicans* and *M. fallax* had higher cover in the Ungrazed.

The fuel load of monocotyledons was higher in the Ungrazed-2.5y compared to the Grazed and the Ungrazed areas (averaging 1.3 Mg·ha^{-1}, 0.4 Mg ha^{-1}, and 0.5 Mg ha^{-1}, respectively). There was no difference between the Grazed and the Ungrazed (Fig. 6A). For eudicotyledons, the Grazed had a lower fuel load than the Ungrazed-2.5y and the Ungrazed (0.4 Mg ha^{-1}, 0.7 Mg ha^{-1}, and 0.8 Mg ha^{-1}, respectively; Fig. 6B). Necromass contributed to the fuel load by an order of magnitude more than living biomass. The Ungrazed had a higher fuel load than the Grazed and the Ungrazed-2.5y (23 Mg ha^{-1}, 10 Mg ha^{-1}, and 10 Mg ha^{-1}, respectively; Fig. 6C). Total fuel load followed the same pattern as necromass (Fig. 6D).

Table 1 Absolut cover (percentage) and predominant form of regeneration (regrowth - R; sowing - S) for the plant species sampled in the three studied Cerrado areas: Grazed, Ungrazed-2.5y, and Ungrazed

Life forms	Name	Regeneration strategy	Absolut Cover (%)			
			Grazed	Ungrazed-2.5y	Ungrazed	Total
Graminoid	*Echinolaena inflexa*	R	**44.4**	**66.4**	**57.2**	168
	Axonopus sp.	R	-	**12.6**	**13.4**	26
	Trachypogon sp.	R	-	**12.4**	**11.2**	23.6
	Axonopus capillaris	S	**7.4**	-	-	7.4
	Cenchrus polystachios	S	**5**	-	-	5
	Trachypogon sp.	R	-	**3.2**	1	4.2
	Paspalum pilosum	R	**1.8**	-	-	1.8
	Scleria scabra.	S	1	1.2	**4.4**	6.6
Subshrub	*Myrcia linearifolia*	R	1.2	**5.4**	**15**	21.6
	Croton goyazensis	R	0.8	**6.6**	**3.2**	10.6
	Diplusodon villosus	S	1	1.2	**5**	7.2
	Psidium sp.	R	1.4	2.8	**3**	7.2
	Mikania purpurascens	S	0.2	1.4	**3.4**	5
	Eugenia langsdorffii	R	**3.2**	0.2	0.2	3.6
	Myrciaria cuspidate	R	**2**	0.6	-	2.6
Tree	*Miconia albicans*	S	**5.4**	**4.6**	**15.4**	25.4
	Miconia fallax	R	**4.4**	**5.4**	**12.2**	22
	Ouratea hexasperma	R	0.2	1.4	**7.6**	9.2
	Roupala montana	R	**1.8**	**3**	**4**	8.8
	Myrsine monticola	S	0.4	2	**5.6**	8
	Zanthoxylum rhoifolium	S	**5.4**	0.2	-	5.6
	Qualea multiflora	R	**2**	0.4	2.2	4.6
	Kielmeyera coriacea	R	0.2	-	**3.6**	3.8
	Qualea grandiflora	R	**1.8**	0.2	-	2
Shrub	*Esenbeckia pumila*	R	**1.8**	**8.6**	-	10.4
	Protium ovatum	R	0.6	**4.4**	**4**	9
	Baccharis retusa	S	**2.6**	**5**	0.8	8.4
	Banisteriopsis stellaris	R	**2.6**	2.2	**3.6**	8.4
	Erythroxylum campestre	R	1	**3.8**	2.6	7.4
	Maprounea brasiliensis	R	1.2	1.8	**4**	7
	Jacaranda ulei	R	0.6	2.2	**3.8**	6.6
	Banisteriopsis malifolia	R	0.4	1	**4.4**	5.8
	Erythroxylum deciduum	R	**1.8**	1.2	0.8	3.8
	Periandra gracilis	R	**2**	0	0.2	2.2
Total	-	-	105.6	161	192	

Cover values in bold and underlined indicate the species with the highest cover in each area, collectively contributing to 70% of the total absolute cover in that area. The total cover values can exceed 100% because multiple species can touch the sampling rod at each point (see text for further details). Species were ordered by growth form, colonization strategy, and cover value

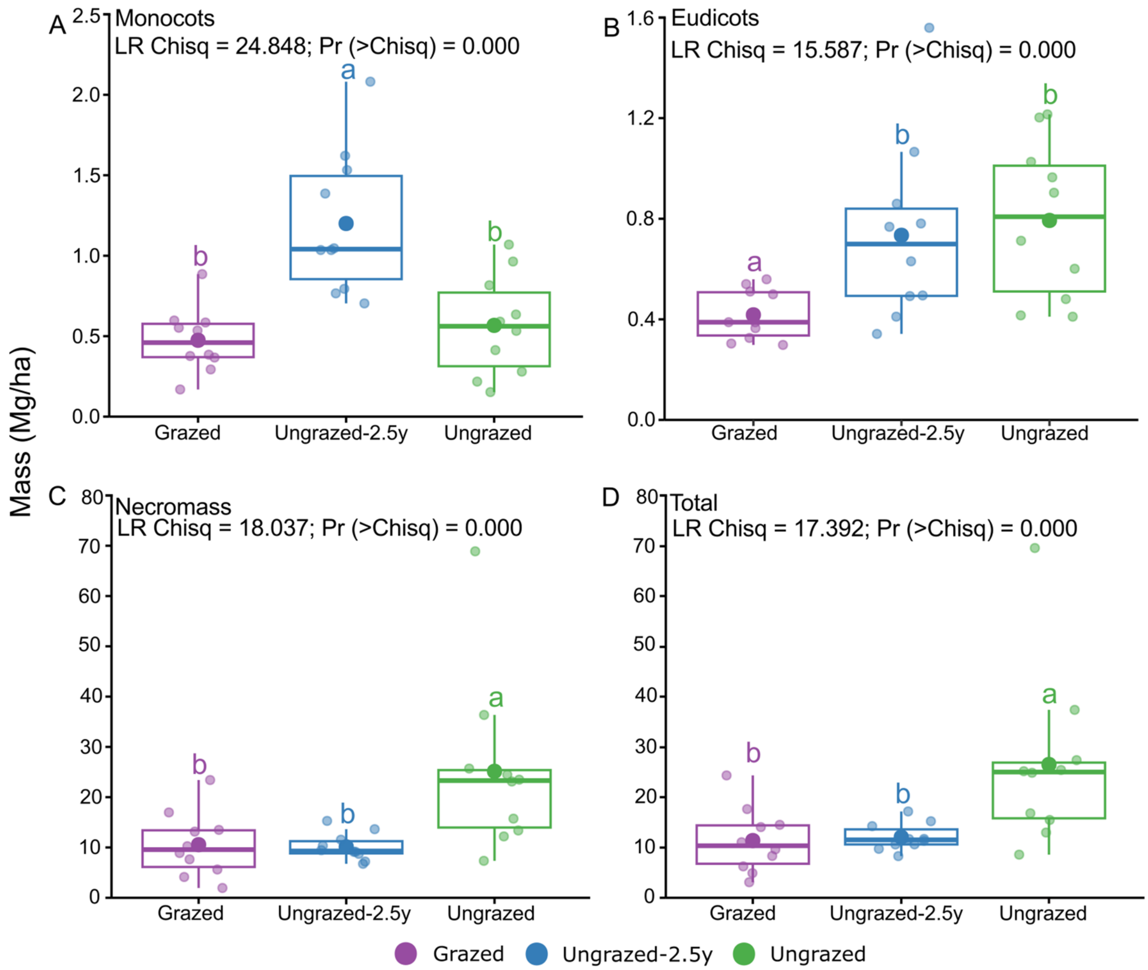

Fig. 6 Mass of fuel load by vegetation source (**a**. monocots; **b**. eudicots; **c**; necromass; **d.** total) for the three studied Cerrado areas. Grazed, Ungrazed-2.5y (U2.5-y) and Ungrazed

Discussion

Changes in the plant community

Our study revealed that grazed and ungrazed areas showed no significant differences in vegetation cover above 2 m. However, below 2 m, grazed areas exhibited reduced plant cover and richness. The Grazed had 48% less vegetation cover and 30% fewer species (96 species) in the low strata (≤2 m) than the Ungrazed (133 species). Notably, only 2.5 years after cattle exclusion, the Ungrazed-2.5y had intermediary vegetation cover and species composition. Still, only four species more than the Ungrazed. The results indicate a negative impact of cattle grazing on plant richness and, simultaneously, the potential to partially recover community attributes by removing cattle from the area after only a few years. The cattle presence and exclusion lengths should be tested to identify more sustainable grazing regimes that support community integrity and forage availability. The results also highlight the recovery potential of savanna vegetation both through the resprouting of plants kept pruned by cattle and seedling establishment of fast-growing seeder plants, such as grass, subshrub, and shrub species (Horstmann et al. 2023).

Our results provide support for the generalized grazing model (MSL) (Milchunas et al. 1988) and its modified synthesis (Cingolani et al. 2005), particularly regarding the prediction of continuous, productivity-mediated vegetation responses along grazing intensity gradients in systems with evolutionary exposure to herbivory, such as the Cerrado (Baggio et al. 2021). The observed gradient in vegetation structure and composition across the three treatments, with the 2.5-year exclusion site consistently exhibiting intermediate values for plant cover below 2 m and species richness, demonstrates a gradual, reversible response rather than threshold-driven transitions to alternative stable states (Cingolani et al. 2005; Targetti et al. 2010). This pattern aligns with the core MSL prediction that vegetation in systems with intermediate productivity and evolutionary history of megafaunal herbivory should respond predictably to grazing pressure without crossing irreversible thresholds (Milchunas et al. 1988).

Additionally, short-term grazing exclusion led to a peak in general graminoid cover. A global meta-analysis of plant trait responses to grazing revealed that the broad graminoid functional group is not valid, as grazing responses depend strongly on specific architectural traits, favoring stoloniferous grasses and reducing tussock grasses (Díaz et al. 2007). In our study, short-cycle and seeder grasses replaced long-cycle and resprouting grasses as the dominant species under grazing pressure. *Echinolaena inflexa* thrived in the area with cattle due to its ability to regrow and spread via stolons. Its high cover, resilience to grazing, and palatability make *E. inflexa* and the savannas it dominates a promising focus for enhancing the value of native species and ecosystems in sustainable grazing practices (Eiten 1972; Ribeiro and Walter 2008). Besides *E. inflexa*, seeder grasses such as *Axonopus capillaris* and *Cenchrus polystachios* occurred in the area with cattle. In contrast, ungrazed areas had favored long-lived, resprouting grasses such as *Axonopus* sp. and *Trachypogon* sp. (Horstmann et al. 2023).

For trees, shrubs, and subshrubs, the area without cattle had higher cover than the other areas. Cattle trampling in large herds likely kept the lower stratum of the Cerrado open (50% of the cover of mature areas). Some woody species had significantly less cover in the Grazed and Ungrazed-2.5y areas, including *Myrcia linearifolia*, *Miconia albicans*, *M. fallax*, and O. hexasperma. In comparison, others had higher cover in the Grazed area and the Ungrazed-2.5y (e.g., *Zanthoxylum rhoifolium*). The cover of seeder and resprouter species was similar between grazed and ungrazed areas, suggesting that these distinct regeneration mechanisms did not differ in response to grazing. These results corroborate a broader global pattern in which the response of woody plants to grazing is highly variable, as the increase in certain grazing-tolerant woody species is counterbalanced by the reduction of grazing-sensitive shrubs (Díaz et al. 2007). This highlights the need for more information on species regeneration strategies and other traits related to their responses to cattle grazing and trampling (Díaz et al. 2007). In the area without cattle for 2.5 years, shrub cover increased by 84% compared to the grazed area, either through the vegetative growth of existing species or the establishment of new individuals with a high colonization ability, indicating that these contrasting regeneration strategies can thrive after cattle exclusion or in a rotational system.

Fuel load

The grazed area had half the fuel load compared to the ungrazed area, primarily due to reduced necromass, which accounted for about 90% of the total fuel load across all areas. Cattle likely contribute significantly to this fuel reduction through (i) grazing, whichdecreases biomass, leading to less necromass production, and (ii) trampling by cattle, which breaks down leaf and branch necromass, promoting decomposition and increasing runoff during heavy rains. The ungrazed area accumulated an average of 23 $Mg{\cdot}ha^{-1}$ of fuel, which is high even compared to typical ungrazed Cerrado savannas. Savannas without fire and cattle for 18 years held 5.3 $Mg{\cdot}ha^{-1}$ of fuel (Miranda et al. 2002), while areas with varying fire regimes averaged 4.8 $Mg{\cdot}ha^{-1}$ (De Castro and Kauffman 1998; Gomes et al. 2020; Martins et al. 2017; Miranda et al. 2002). The absence of fire in the ungrazed area over at least the past 30 years, combined with likely more fertile soils at the sites studied compared to those in the studies mentioned above, may have allowed greater encroachment when fire was excluded, contributing to the high fuel accumulation. Fire frequency plays a crucial role in regulating biomass and species composition in the Cerrado savannas (Simon et al. 2009). High levels of necromass increase the risk and severity of fires, leading to high mortality in both plant and animal communities (Fidelis et al. 2018; Tomas et al. 2021). Managing cattle density to one head per hectare permanently could help minimize cattle impact on non-graminoid plants and reduce fuel loads, similar to the effects seen in Brazilian savannas invaded by exotic grasses (Durigan et al. 2022).

Limitations of the study and future research

In our study, only one type of cattle management was applied based on observing the forage availability in the savanna area. The grazing regime was intermittent, with high cattle density and short duration. Specifically, approximately 130 heads of cattle were released onto 66 hectares of savanna (equivalent to 2 heads·ha-1) for approximately 15 days every three months. The Cerrado savannas represent a vast and diverse socio-ecological landscape, with cattle grazing practices showing significant regional variation. For example, in the Jalapão region of the north/northeast Cerrado, cattle graze freely across a mosaic of savanna areas subjected to controlled burning, encouraging grass forage to sprout (Eloy et al. 2019b). In contrast, in northern Minas Gerais state (southeastern Cerrado) and Goiás state (central Cerrado), communal savanna areas permit cattle grazing during the dry season (Carvalho loy et al. 2014; Fernandes 2011; Lúcio et al. 2014). In large farms throughout the biome, unfenced Legal Reserves permit uncontrolled cattle access, although cultivated pastures are typically preferred for grazing throughout most of the year. Despite the documented heterogeneity in grazing practices, a significant knowledge gap remains regarding the ecological impacts of livestock within these diverse Cerrado grazing systems.

The studied savannas had virtually no exotic grass cover, unlike other savannas exposed to cattle grazing or those not grazed but surrounded by exotic pastures. The grazed savanna was bordered by pastures planted with *Urochloa* grasses. While cattle could carry seeds or seeds could spread through runoff, the savanna appears to have remained resilient to invasion. This low level of invasion may be due to the presence of native perennial stoloniferous grasses and the cattle's preference for grazing exotic grasses (Capó et al. 2016).

As a limitation, our study is based on a single temporal assessment and did not directly evaluate fire occurrence or grazing–fire interactions. But this is due to the pioneering nature of the study presented here. Therefore, no temporal trajectories were measured, and we avoid inferring successional dynamics. Further research incorporating additional areas, different savanna vegetation types, variations in cattle management practices, and explicit assessments of fire regimes will be essential to understand these interacting disturbances better.

Implications for vegetation conservation

In Brazil, rural properties in the Cerrado must designate 20% of their area as a Legal Reserve, totaling approximately 89.7 million hectares within this biome (Guidotti et al., 2017). Currently, Legal Reserves are a point of conflict between social and private interests. Farmers often perceive the costs of conserving these reserves as burdensome, mainly due to the opportunity costs and income losses associated with setting aside large portions of their land (Sant'Anna 2011). Consequently, there is a deficit of 3.7 million hectares of Legal Reserves across rural properties in the Cerrado (Soares-Filho et al. 2014). Therefore, it is essential to make the conservation of Legal Reserves more appealing to landowners by integrating sustainable economic uses. For instance, Legal Reserves in the Cerrado can yield valuable non-timber forest products, especially native fruits (e.g., pequi/*Caryocar brasiliense*, mangaba/*Hancornia speciosa*, araticum/*Annona crassiflora*, and cagaita/*Eugenia dysenterica* – Brazilian vernacular names/scientific names), nuts like baru/*Dipteryx alata* (Bailão et al. 2015), and seeds to restore native vegetation (Schmidt et al. 2019). Furthermore, using managed cattle grazing to prevent fires and to supply fodder during the resting periods of cultivated pastures presents a promising alternative for cattle farms.

Conclusion

Our study demonstrated that a long-term grazed savanna in the Cerrado had lower species richness and altered plant composition compared with an adjacent ungrazed savanna. However, grazing impacts in this Cerrado ecosystem appear manageable and reversible. Grazing does not appear to drive the savanna across irreversible thresholds; rather, reducing or removing grazing pressure, such as through temporary cattle exclusion or rotational systems, allows the vegetation structure and composition to recover. Furthermore, integrating such managed grazing practices adds value by providing intermittent forage and reducing biomass fuel loads, which may help limit the risk of high-intensity wildfires that are otherwise associated with further losses of species richness and compositional shifts.

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Declarations

Competing interests The authors declare no competing interests.

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