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Sustainable pasture management in the Pantanal biome for climate mitigation and adaptation in livestock systems

Abstract – The objective of this review paper was to describe management practices for natural grasslands and cultivated pastures in the Pantanal that contribute to carbon sequestration and methane emission reduction, in order to support the application of the Fazenda Pantaneira Sustentável (FPS) - sustainable Pantanal ranch - tool, used to assess pasture conservation and guide climate-smart management in ranches, used to assess pasture conservation and guide climate-smart management in cattle ranches. The used framework aligns management practices with key ecophysiological elements of pasture functions and with mitigation and resilience pathways. Carbon sequestration is enhanced by maintaining a moderate grazing pressure and through management strategies that directly conserve the existing stocks and the increase of carbon fixation. The mitigation of methane emission depends largely on the floristic composition and nutritional quality of the diet in the livestock system. This is proactively managed by using the forage value indicator to guide practices such as strategic supplementation. By aligning these target practices with the indicators and ecological thresholds of FPS, this approach enables spatially differentiated interventions that optimize nutritional balance, reduce enteric fermentation, and strengthen the resilience of the Pantanal livestock systems against climatic variability.

Index terms: carbon sequestration, Fazenda Pantaneira Sustentável tool, methane emission, native pasture.

Manejo sustentável de pastagens no bioma Pantanal para mitigação e adaptação climática em sistemas de produção

Resumo – O objetivo desta revisão foi descrever as práticas de manejo para pastagens nativas e cultivadas no Pantanal que contribuem para o sequestro de carbono e a redução da emissão de metano, para apoiar e detalhar a aplicação da ferramenta Fazenda Pantaneira Sustentável (FPS), usada para avaliar o estado de conservação da pastagem e guiar o manejo climaticamente inteligente. A estrutura utilizada alinha as práticas de manejo com os principais elementos ecofisiológicos da função da pastagem e as vias de mitigação e resiliência. O sequestro de carbono é aumentado pela manutenção da pressão de pastejo moderada e por meio de estratégias de manejo que conservam diretamente os estoques existentes e aumentam a fixação de carbono. A mitigação das emissões de metano depende da composição florística e da

Sandra Aparecida Santos (✉)
Embrapa Pecuária Sudeste, São Carlos, SP, Brazil. E-mail: sandra.santos@embrapa.br

Arnildo Pott
Universidade Federal de Mato Grosso do Sul, Campo Grande, MS, Brazil.
E-mail: arnildo.pott@gmail.com

Marcos Claudio Pinheiro Rogério
Embrapa Caprinos e Ovinos, Sobral, CE, Brazil.
E-mail: marcos.claudio@embrapa.br

Balbina Maria Araújo Soriano
Embrapa Pantanal, Corumbá, MS, Brazil.
E-mail: balbina.soriano@embrapa.br

Sérgio Raposo de Medeiros
Embrapa Pecuária Sudeste, São Carlos, SP, Brazil. E-mail: sergio.raposo@embrapa.br

✉ Corresponding author

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qualidade nutricional da dieta no sistema de produção. Isso é gerenciado de forma proativa ao se utilizar o indicador valor forrageiro para guiar práticas como suplementação estratégica. Ao alinhar essas práticas direcionadas com os indicadores e os limiares ecológicos da FPS, essa abordagem permite intervenções espacialmente diferenciadas que otimizam o balanço nutricional, reduzem a fermentação entérica e fortalecem a resiliência dos sistemas de produção do Pantanal frente às mudanças climáticas.

Termos para indexação: sequestro de carbono, ferramenta Fazenda Pantaneira Sustentável, emissão de metano, pastagem nativa.

Introduction

Brazil is the second-largest beef producer worldwide (Agethen et al., 2024), with approximately 215 million cattle heads raised on 170 million hectares of pastures, holding the world's largest commercially exploited herd (Cherubin et al., 2023). Despite ruminants playing a key role in converting grass and agricultural by-products not consumed by humans into high-quality animal protein, their production is pasture-based, requiring vast areas of land, while their overall efficiency is considered low compared with that of monogastric systems (Leiber, 2022), particularly under extensive conditions.

In recent years, Brazilian pasture-based livestock systems have faced growing international criticism due to their association with deforestation and environmental liabilities, as nearly 60% of the country's pastures exhibit some degree of degradation (Bolfe et al., 2024). In response, governmental programs have sought to improve land use efficiency by promoting sustainable management practices (Arias et al., 2017). Studies on land-use change indicate that the expansion of pasture areas peaked around 2005, followed by a stabilization period marked by the conversion of consolidated pastures to cropland (Caballero et al., 2023).

Currently, pastures are mainly located in areas less suitable for agriculture (Parente et al., 2019), such as the Pantanal biome, where there are legal and environmental restrictions for large-scale crops, coupled with a high diversity of native pastures and savannas rich in forages (Santos et al., 2017).

The region, composed of native grassland ecosystems (Santos et al., 2021b), is naturally suitable for extensive beef cattle production, particularly cow-calf systems. However, a major challenge is to enhance the productivity of cattle systems while maintaining critical ecosystem services, especially since the Pantanal presents about 50% of native grassland formations and floodable grasslands according to the mapping done by MapBiomas (2023b).

The biome, with 16% cultivated pastures, covers approximately 15 million hectares, whose total area expanded over 1.8 million hectares from 1985 to 2023, mainly (55%) in the last 23 years (MapBiomas, 2023a). The effective size of the Pantanal cattle herd was estimated at approximately 4.1 million animals, with 66.84% located in the plains of the state of Mato Grosso do Sul (Santos et al., 2023a), resulting in an annual production of about 1.0 million calves.

Despite a cattle-raising history spanning over two centuries, the productive capacity of Pantanal ranches remains constrained by the availability and resilience of natural resources. Stocking rates average around 0.3 animal unit per hectare across all landscape types, and zootechnical indicators remain low, underscoring the need for a sustainable intensification using environmentally friendly technologies (Abreu et al., 2019). Despite this, conventional Pantanal systems are still among the most renewable worldwide due to their low dependence on external inputs, mostly synthetic fertilizers, reinforcing the natural suitability of the region for a low-impact beef production (Takahashi et al., 2011).

In extensive grazing systems, a bottleneck is a high methane emission intensity (CH_4 per unit of product), largely due to a low animal productivity (Machado et al., 2022). However, the low stocking density in these systems typically results in a lower CH_4 emission per unit of land area (ha), complicating the scenario. In flood-prone biomes like the Pantanal, emissions per animal are highly dynamic and variable, often being lower in certain periods due to the availability of higher-quality pastures in seasonally flooded areas (Oliveira et al., 2016). Regardless of this trade-off and regional variability, emissions per unit of product and per unit of land area can be mitigated through a sustainable intensification, mainly by improving pasture quality through a better management (Machado et al., 2022).

The Fazenda Pantaneira Sustentável (FPS) program for sustainable ranching in the Pantanal was implemented in collaboration with various institutions to provide a support tool for pasture management decision (Santos et al., 2017). According to the same authors, the FPS program allows a comprehensive diagnosis of farm sustainability using a set of social, economic, and environmental indicators analyzed through fuzzy logic. One of its core modules focuses on pasture conservation and productivity, guiding producers toward optimal management practices. As a tool, FPS is central to greenhouse gas (GHG) mitigation efforts in the Pantanal, as it provides a diagnosis of pasture quality to inform the selection of appropriate management practices. By enabling producers to implement target management, such as optimizing stocking rates and adopting adequate grazing systems (Santos et al., 2021a) as deferred grazing, the FPS program directly improves forage quality and use. However, to refine the accuracy of the results for GHG emission within the FPS, mainly those related to CH_4 emissions from native pastures, there is a need for updated and site-specific data.

The need for a better pasture management in the Pantanal transcends the scope of mitigation alone. As an ecosystem, highly dependent on a predictable hydrological regime, cattle ranching in this biome is acutely vulnerable to climate change impacts, particularly to the increasing frequency and intensity of extreme drought and flood events (Santos et al., 2021b). In this context, the adoption of sustainable practices, such as optimizing stocking rate and improving forage quality, can reduce CH_4 emission, while simultaneously enhancing the resilience and adaptive capacity of the production system against climatic variability (Santos et al., 2021a).

This review provides a primary characterization of the relationship between environmental dynamics and beef production in the Pantanal. For this, management practices are evaluated as integrated sustainability strategies essential for the region, aiming both to reduce emissions (mitigation) and to enhance resilience and adaptive capacity (adaptation) to climate change challenges. In addition, a conceptual framework is used, aligning management practices with key ecophysiological elements of the pasture function and with the established mitigation and resilience pathways proposed by Stanley et al. (2024). The objective is to directly support the scientific basis for the FPS tool, as well as its implementation throughout the Pantanal.

Materials and Methods

The study was conducted as a comprehensive review of the literature on sustainable pasture management within the Pantanal biome, aiming to synthesize the available scientific evidence on the subject. Given the limited number of studies specifically quantifying environmental outcomes related to dynamic natural pastures in this extensive livestock system, this review prioritized the identification of management practices with a high potential for two key climate outcomes, i.e., an enhanced carbon sequestration and reduced CH_4 emissions.

The bibliographic search was conducted using a structured combination of keywords. The two cores for all searches were “Pantanal” AND/OR “extensive system pastures”. These were combined using the AND operator with terms grouped according to the following themes: livestock, native pasture, climate adaptation, stocking rate, methane emissions, and vegetation dynamic. Where applicable, the terms within each thematic group (such as “methane emissions” OR “CH_4 mitigation”) were combined using the OR operator to maximize the retrieval of relevant literature.

Subsequently, publications were selected based on their explicit focus on extensive livestock systems and pasture management practices, ensuring the relevance of the retrieved literature to the scope of this work. This resulted in the selection of 23 papers. The findings from these studies were synthesized to identify the main pasture management strategies related to soil carbon sequestration and enteric methane mitigation. The limited, yet relevant works were crucial in defining a set of best management practices suitable for the Pantanal. These practices were chosen based on their proven potential to directly reduce CH_4 emission intensity by improving pasture quality, increasing soil carbon sequestration through enhanced pasture conditions, and serving as an effective adaptation measure to increase system resilience to climatic events.

The systematization of these practices served a dual purpose: first, to support the implementation of the FPS tool (Santos et al., 2017), by providing the scientific basis for its pasture management module and guiding producers toward effective and verifiable sustainability measures; second, to provide a robust conceptual framework, by aligning practices with the key ecophysiological elements of the pasture function and with the established mitigation and resilience pathways proposed by Stanley et al. (2024). This alignment ensures that the recommended actions directly contribute to measurable climate outcomes and system resilience.

Pantanal biome: climate, pastures, and soil characteristics

The Pantanal is the world's largest continuous flooded plain, covering an area of over 160.000 km² in Brazil, precisely in the states of Mato Grosso do Sul and Mato Grosso, with smaller extensions in Paraguay and Bolivia (Figure 1). The region's low average altitude of 80 to 150 m contributes to a slow drainage, resulting in long periods of inundation (Bergier et al., 2019).

Wetland dynamic in the Pantanal are controlled by different drivers, including climate, topography, vegetation, soil type, and flood intensity and propagation. This complex interplay ensures the high biodiversity of the biome, where the seasonal

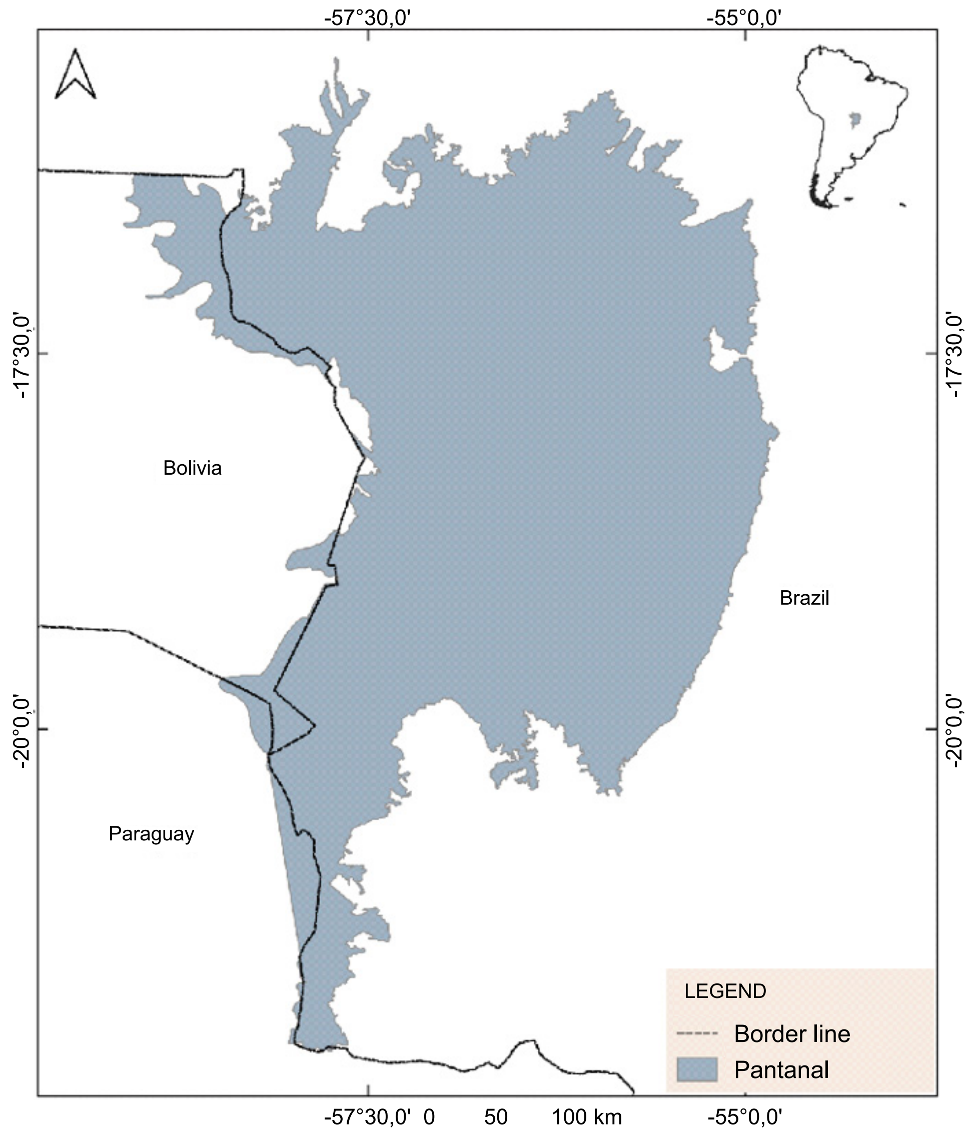

Figure 1. Location of the Pantanal region.
Source: adapted from Silva & Abdon (1998).

flood pulse is the main factor affecting vegetation, especially the availability of seasonal open grasslands (Caballero et al., 2025). In this rich biome, subtle changes in relief and hydrological conditions transform soil properties and affect the distribution of the highly diverse flora and fauna.

The wetland soils are closely related to the nature of sediments, varying with changes in erosion and deposition/sedimentation rates (Couto et al., 2023). According to Köppen, the region has an Aw climate, predominantly tropical seasonal, with a rainy summer season from October to March and a dry winter. Average annual rainfall ranges from 1,000 to 1,400 mm (Alvares et al., 2013). Notably, the conditions observed in the recent period from 2001–2021 are similar to those experienced during the previous dry period from 1965–1975 (Caballero et al., 2025), suggesting a multidecadal variability in the climate and wetland extent of the Pantanal. This historic pattern of dry and wet cycles is vital, but climate change is expected to magnify the impacts of the most recent dry period, implying an alteration in the climate and biogeochemistry of the region, with significant implications for wetlands and their ecosystems (Caballero et al., 2025).

In the Pantanal, the use efficiency of native pasture depends on an adaptive management that considers pasture dynamics, landscape configuration (proportion of forest, savanna, grassland, ponds, and floodplains), and the dominant forage species. To facilitate management under the influence of the flood pulse, Santos et al. (2020a) classified Pantanal pastures according to substrate moisture, identifying three key topographic gradients: generally dry areas, generally seasonal wet areas, and generally wet areas, with varying soil characteristics and carbon content. Freitas et al. (2024) observed that the variation in carbon stocks down to a 40 cm depth across these gradients was strongly correlated with clay content, whose physicochemical properties protect soil organic matter.

In general, wet areas dominated by grasses are characterized by C_3 species such as *Hymenachne amplexicaulis* (Rudge) Nees, *Luziola subintegra* Swallen, *Leersia hexandra* Sw., *Oryza* spp., and *Steinchisma laxum* (Sw.) Zuloaga, which exhibit high carbon stocks, especially in areas with long periods without grazing (Santos et al., 2020a). This is an indicative that grazing has reduced soil carbon in these areas, possibly due to periodic flooding and the removal of biomass by cattle that would otherwise contribute to soil organic matter. In contrast, in ungrazed pastures, vegetation can be accumulated as wildfire fuel, showing the importance of continuous grazing under a proper management to efficiently maintain or increase soil carbon, despite the commonly observed increase in soil density (Liu et al., 2023). Differently, seasonal and dry areas dominated by grasses are characterized by C_4 species as *Axonopus purpusii* Chase, *Hemarthria altissima* (Poir.) Stapf & C.E.Hubb, *Mesosetum chaseae* Luces, *Paspalum oteroi* Swallen, *Paspalum plicatulum* Pers., *Paspalum wrightii* Hitchc. & Chase, *Paspalum fasciculatum* Willd. ex Flüggé, and *Reimarochloa* spp. (Santos et al., 2021b).

These pasture categories are usually not managed in isolation, but form a functional mosaic used by cattle in a complementary manner. Therefore, the adopted grazing strategy is fundamentally adaptive and driven by the seasonal variability of the Pantanal. The cattle actively select across the mosaic to meet their nutritional needs, feeding on different pasture types based on the seasonal and annual variation in forage availability and quality (Santos et al., 2022). As to soils, those of the wet areas are typically more clayey and prone to waterlogging, whereas those of non-flooded areas are sandy, with a low nutrient content (Santos et al., 2020a). In such conditions, soil organic matter is crucial for system sustainability, especially since these areas require special attention due to the lack of fertilization, particularly in soils flooded only by rain (Freitas et al., 2024).

A native species adapted to these environments is *M. chaseae*, which maintains a stable productivity and quality year round even during extreme dry years (Santos et al., 2002), contributing significantly to herd food security. Freitas et al. (2024) concluded that *M. chaseae* accounted for the highest carbon sequestration in grazed areas, highlighting its role in a sustainable land use. These findings show the importance of on-farm management of key native forages for each pasture type, considering these species are adapted to different disturbances and enhance ecosystem resilience (Indu et al., 2022).

The FPS tool for sustainable cattle ranching in the Pantanal and management practices that enhance carbon sequestration and reduce methane emissions

The challenges faced by the extensive beef cattle system, particularly its vulnerability to climate extremes and the need for GHG mitigation, require a transition toward verifiable and integrated sustainability strategies. To address this need, the FPS is a decision support tool designed to provide a multidimensional and holistic assessment of ranch sustainability, integrating environmental, economic, and social indicators through a fuzzy logic-based system (Santos et al., 2017). Thus, the program helps producers to diagnose the status of their operations, guiding the adoption of the best management practices and validating their efforts towards sustainability, paving the way to better markets and to the integration into public policies.

One of the central modules of the FPS tool focuses on pasture conservation and productivity. However, despite its holistic approach, the FPS currently faces a key knowledge gap: the lack of site-specific and scientifically validated emission factors for different native pasture management practices within the biome. The absence of these factors hinders the program's ability to accurately quantify the specific GHG mitigation benefits of the recommended practices.

The establishment of grazing systems that contribute to enhancing carbon sequestration has become an essential strategy in pasture management (Stanley et al., 2024), being pivotal to achieve the resilience goals for the Pantanal. The same authors highlighted that well-managed native pastures are crucial in this scenario, contributing to key aspects of ecosystem resilience such as capturing atmospheric carbon, conserving biodiversity, and providing system stability against climate change impacts. As to grazing, the long-term impact on carbon sequestration depends on the five following ecophysiological elements: ground and sward cover, productivity, input allocation, forage quality, and diversity. These elements support three key pathways for soil carbon enhancement, as follows: increased carbon fixation, reduced carbon loss by a slower decomposition and reduced fire use, and improved efficiency of belowground transformations (Table 1).

The effective implementation of the FPS tool depends on the use of indicators that are scientifically supported. The FPS's environmental module assesses pasture systems based on four key indicators: forage plant cover (%), forage value (%), colonization by undesirable species (%), and grazing intensity (cm). These indicators directly align with the ecophysiological elements and carbon pathways necessary for enhancing carbon sequestration (Stanley et al., 2024).

The percentage of forage plant cover is directly related to ground and sward cover, supporting an increased carbon fixation and a reduced carbon loss, as confirmed by Santos et al. (2020c), who found that a high forage cover favors primary productivity. This is an indicative that forage value is related to forage quality, which is essential for an improved efficiency of belowground transformation due to a higher litter and efficient nutrient cycling. In this line, Indu et al. (2022) concluded that functional diversity is key for an improved efficiency of belowground transformations and overall ecosystem resilience. According to a systematic literature review, since grazing intensity acts as a proxy for productivity, a moderate intensity is vital to maintain both ground and sward cover and productivity, directly supporting an increased carbon fixation (Teague et al., 2011). Specifically for the Pantanal, moderate grazing is defined by a forage offer of approximately 8.0 kg of dry matter per animal unit per day (Santos et al., 2020b), at an intensity that should maintain pasture sward height at around 50% of the potential forage height (Santos et al., 2021a).

Based on the synthesis of the literature, the practices described below are recommended to increase soil carbon stocks in the Pantanal, in alignment with the ecological elements established by Stanley et al. (2024) and the related FPS indicators (Table 1).

In pasture management, the stocking rate should be defined by an appropriate grazing pressure (Santos et al., 2020b), which accounts for more dry matter availability (ground and sward cover and productivity), increasing carbon sequestration. Moderate grazing has been shown to enhance carbon sequestration and to increase productivity and water retention capacity (Teague et al., 2011), in addition to increasing floristic diversity in pastures (Santos et al., 2020c). It may also improve climate regulation and resilience to extreme events (Whitehead, 2020).

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Soil carbon sequestration can be promoted by the functional diversity of forage species, which allows a variety of ecological niches as root depth, nutrient acquisition strategies, and phenology. This diversity also results in richer litter, supporting soil biota that contributes to nutrient cycling (Liu et al., 2023). According to Santos et al. (2016), native forages sequester more carbon at the onset of intense rainfall periods. Therefore, strategically fencing pastures based on rainfall distribution during the early rainy season (October to November) may enhance carbon flow within the system and promote a greater forage accumulation.

Introducing exotic forage species, following legal and technical guidelines, can enhance organic matter in soils with a naturally low fertility (Santos et al., 2022), helping to increase carbon sequestration. In this line, Santos et al. (2021a) found that management practices using intercropping with legumes can capture and fix atmospheric nitrogen in the soil. In the Pantanal, cattle ranchers usually maintain pasture heterogeneity through practices such as the introduction of exotic forages to replace coarse grasses and coexist with grazed native ones, silvopastoral systems, and, mainly, prescribed burning (Santos et al., 2023a).

Recent trends indicate an increase in the frequency and severity of wildfires in the Pantanal, a phenomenon highly correlated with prolonged droughts driven by climate change (Correa et al., 2022). In this context, the management practices adopted in cattle ranching are intrinsically linked to fire dynamics, such as prescribed burning that reduces wildfires is the dominant land use in the biome (Santos et al., 2023b). Grazing, particularly in extensive continuous systems, plays a vital role in reducing the accumulation of fine

Table 1. Management practices for soil carbon sequestration in Pantanal native pastures, aligning the indicators of the Fazenda Pantaneira Sustentável (FPS) tool for maintaining sustainable ranching in the region with key ecophysiological elements[(1)] of the pasture function and with the established mitigation and resilience pathways[(2)].

Management practice	FPS indicator[(3)]	Scientific support/primary carbon pathway (V)
Adaptive grazing pressure	Grazing intensity	Replacing a fixed stocking rate with an adaptive pressure ensures an adequate regrowth, maximizes forage use, and minimizes degradation (Santos et al., 2021a). This is essential to maintain productivity (E2) and cover (E1) for an increased fixation (V1) and reduced loss (V2) of carbon.
Seasonal fencing/deferment	Forage plant cover	Strategically resting pastures (e.g. during the early rainy season) promotes biomass accumulation and root growth during the peak carbon absorption period (Santos et al., 2016). This directly increases cover (E1) for an increased carbon fixation (V1) and an improved feed efficiency (V3).
Pasture diversity management	Undesirable species & forage value	Management focused on promoting functional diversity enhances system resilience (Whitehead, 2020). Diverse root structures improve soil organic matter distribution (Liu et al., 2023), increasing forage quality (E4) and supporting efficient belowground transformations (V3).
Integrated management	Grazing intensity & forage value	Practices such as the strategic introduction of cultivated forages when legally compliant (Santos et al., 2022) and silvopastoral systems (Santos et al., 2023a) enhance forage quality and nutrient cycling (Liu et al., 2023). This increases the total organic matter input to the soil, supporting sustained carbon stocks, increased carbon fixation (V1), reduced carbon loss (V2), and improved efficiency of below ground transformations (V3).
Restoration and biodiversity promotion	Undesirable species & forage plant cover	Promoting biodiversity means managing land use to allow the full expression of native flora. This favors species intrinsically more resilient to the climate (especially to aridity) and ensures a high-quality and high-quantity input of carbon (litter and roots) to the soil, maximizing the system's long-term fixation capacity and resilience (Liu et al., 2023), while increasing carbon fixation (V1) and improving feed efficiency (V3).
Biomass management (fire control)	Grazing intensity & forage plant cover	Using grazing intensity to strategically reduce fine fuel loads prevents the massive instantaneous release of stored carbon via wildfire (Santos et al., 2023b). This practice is crucial for conserving existing carbon stocks, avoiding major pulse emissions of greenhouse gases, while reducing carbon loss (V2).

[(1)]The key ecophysiological elements (E) are: E1, ground and sward cover; E2, productivity; E4, forage quality; and E5, diversity. [(2)]The pathways (V) for greenhouse gas mitigation and resilience, adapted from Stanley et al. (2024), are: V1, increased carbon fixation (dilution of emissions per product); V2, reduced carbon loss by a slower decomposition and reduced fire use; and V3, improved efficiency of belowground transformations (via diet quality). [(3)]The FPS indicators are adapted from Santos et al. (2017).

fuel loads (Ratcliff et al., 2022; Pereira et al., 2026), lowering the risk of large and high-intensity wildfires that cause a massive and instantaneous release of stored carbon back into the atmosphere (Xu et al., 2026). However, since the effect of grazing intensity on carbon sequestration is influenced by water availability, arid areas are less tolerant to this type of disturbance (Liu et al., 2023).

In grazed and wetter pastures, a high grazing intensity can act as a natural firebreak during moderately dry years; however, when more flood-prone areas dry out, biomass accumulation increases the risk of underground fires in organic soils (floating meadows), leading to the severe loss of long-term carbon stocks (Santos et al., 2023b). Therefore, in addition to direct carbon sequestration, management practices that control aboveground biomass are strategic to protect existing soil carbon stocks. The FPS tool, by utilizing indicators as percentage of forage plant cover and grazing intensity, provides the foundation for an effective fuel management and, consequently, carbon stock conservation, showing the tool's relevance to climate resilience and adaptation.

CH_4 from enteric fermentation is the single largest source of GHG emissions in cattle ranching. Therefore, in extensive systems like the Pantanal, management strategies must also focus on enhancing forage nutritional quality and efficiency to reduce CH_4 output per unit of animal product. Santos (2023) compared key forages in the Pantanal, observing significantly lower CH_4 emissions from C_3 grasses, dominant in wet areas. The authors concluded that species such as *H. amplexicaulis* and *L. subintegra* showed a higher digestibility and energy use efficiency, resulting in significantly lower CH_4 emissions of 3.29 kg CH_4 per year per ewe when compared with those of 8.0 kg CH_4 per year per sheep obtained by Intergovernmental Panel on Climate Change (IPCC, 2006). However, the emission level of the native C_4 grass *M. chaseae* was low, reinforcing its value as a resilient low-emission forage species. These results are an indicative that the core principle for CH_4 reduction in grazing systems is improving the digestibility and energy-to-protein ratio of the animal diet.

The quality of native pastures is highly seasonal, directly affecting CH_4 emissions. Oliveira et al. (2016) observed that CH_4 emissions from cattle varied across seasons, being higher in native pastures during the rainy season and lower during the dry season. This variation is linked to the phenology of the Pantanal landscape, taking into account that, after floodwater recedes in the dry season, the highest quality pastures (located in lowlands and around water bodies) become accessible (Santos et al., 2021a). This improved quality in the animal diet during the dry season results in a faster and more efficient digestion (Santos et al., 2002), as well as in a lower CH_4 production per unit of feed (Santos, 2023). Therefore, the configuration of the landscape (a mosaic of forest, savanna, grasslands, and seasonal floodplains) allows the combination of high, medium-, and low-quality pastures that can meet the nutritional needs of breeding cows (Bergier et al., 2019; Santos et al., 2021a).

To mitigate forage seasonality, the strategic introduction of cultivated pastures is essential, mainly in non-flooded areas. Although these pastures may present a low crude protein content – ranging, for example, from 4.9 to 6.1% in *Urochloa humidicola* (Rendle) Morrone & Zuloaga (Crispim & Branco, 2002) –, their main benefits lie in increasing animal productivity and stabilizing forage supply. However, to be sustainable and contribute to GHG mitigation, this introduction must follow both the current legislation (pastures cultivated in up to 40% of the property) and technical criteria (Santos et al., 2022).

The protein:energy ratio in pastures is a limiting factor for an efficient ruminal microbial activity and, consequently, for an efficient protein supplementation. When dietary protein levels fall below maintenance thresholds of ~6%, ruminal microbial activity decreases, hindering feed efficiency (Histrov et al., 2019). Conversely, an excessive protein concentration leads to its inefficient use, meaning that excess nitrogen is excreted in feces and urine (Waldrip et al., 2015), representing a loss of nutritional resources. Crucially, this poor protein-energy synchrony causes an overall decrease in feed digestion efficiency, which increases the intensity of CH_4 emissions. The FPS can leverage systems that favor native pastures (Santos et al., 2020b) by using floristic composition indicators to estimate nutritional values, assisting producers in identifying nutritional gaps and optimizing supplementation to ensure an efficient energy use and a reduced CH_4 intensity.

One of the most effective strategies to reduce CH_4 output is managing key forage species (Table 2), such

Table 2. Management practices for methane mitigation in pasture systems in the Pantanal, aligning the indicators of the Fazenda Pantaneira Sustentável (FPS) tool for maintaining sustainable ranching in the region with key ecophysiological elements[(1)] of the pasture function and with the established mitigation and resilience pathways[(2)].

Management practice	FPS indicator[(3)]	Scientific support/primary carbon pathway (V)
Optimizing forage value and intake	Forage value	Ensuring the diet meets the minimum protein threshold of ~6% is critical for an efficient microbial activity (Histrov et al., 2019). A higher feed quality (E4) leads to a faster passage and a lower CH_4 production per unit of energy used, as evidenced by C3 grasses (Santos, 2023), also reducing carbon loss in pastures (V2).
Management and conservation of low-emission species	Undesirable species & forage value	Prioritizing native species (E5) with a low CH_4 potential emission (E4), such as C3 grasses and some C4 grasses as *Mesosetum chaseae* (Santos, 2023; Santos et al., 2020a), enhances system resilience and diet quality (V3).
Seasonal access to high-quality pastures	Grazing intensity & forage value	Using seasonal high-quality forage ensures a consistent diet (Santos et al., 2021a). Managing grazing intensity (Liu et al., 2023) controls the sustainable use of this temporary high-quality resource (E4), also enhancing system resilience and feed efficiency (V3)
Monitoring of protein-energy balance	Forage value	Using diagnostic systems favoring native pastures in FPS to guide precise supplementation prevents microbial inefficiency caused by poor protein-energy synchrony (Santos et al., 2020b). This enhanced efficiency maximizes feed use (E4), reducing CH_4 intensity and minimizing wasteful nitrogen excretion (V2).
Strategic use of cultivated pastures	Forage value & grazing intensity	The use of cultivated pastures following current legislation and technical criteria (Santos et al., 2022) increases carrying capacity and productivity (E2) per area (Crispim & Branco, 2002). This is essential for the dilution of CH_4 emissions per product (V1).

[(1)]The key ecophysiological elements (E) are: E1, ground and sward cover; E2, productivity; E4, forage quality; and E5, diversity. [(2)]The pathways (V) for greenhouse gas mitigation and resilience, adapted from Stanley et al. (2024), are: V1, increased carbon fixation (dilution of emissions per product); V2, reduced carbon loss by a slower decomposition and minimized erosion; and V3, improved efficiency of belowground transformations (via diet quality). [(3)]The FPS indicators are adapted from Santos et al. (2017).

as *Arachis* spp., *Aeschynomene* spp., and *Discolobium* spp.. Despite its modest biomass production, the species, naturally occurring in several areas, are rich in protein and capable of atmospheric nitrogen fixation, enriching the soil and supporting associated grasses (Santos et al., 2020a). This strategic inclusion of legumes improves the quality of cattle and wildlife diets (Santos et al., 2018), which is the main driver for reducing CH_4 intensity.

The FPS tool is vital for translating the theoretical knowledge on CH_4 mitigation into practical management decisions within the heterogeneous environment of the Pantanal. The tool's effectiveness lies in its capacity to diagnose the primary driver of enteric CH_4 emissions, mainly through the forage value indicator. The main management practices for CH_4 mitigation and the related FPS indicators are directly supported by the diagnostic capacity of the tool, allowing to target the primary nutritional bottlenecks (Table 2).

Concluding Remarks

The Pantanal's complexity as a dynamic ecosystem, composed of a mosaic of native and cultivated pastures, requires adaptive and context-specific management strategies. Consequently, an effective decision-making must be flexible, responding to vegetation formations, seasonal flooding, and climatic shifts, in order to ensure both ecological integrity and economic viability. The FPS tool proves to be a valuable instrument for achieving this balance, serving as an integrative framework that unifies two core climatic goals: enhancing carbon sequestration and mitigating CH_4 emissions.

A successful pasture management in the Pantanal, guided by the indicators of the FPS tool, establishes a direct synergy between production sustainability and climate goals. Carbon sequestration and conservation are ensured by maintaining a high forage cover and moderate grazing pressure. These variables are monitored via FPS indicators to prevent pasture degradation and protect the existing carbon stock. Concurrently, CH_4 mitigation is achieved by managing the composition of the animal diet. For this, the FPS leverages the forage value indicator to guide nutritional interventions that maximize ruminal efficiency, consequently reducing CH_4 emission intensity per product.

Despite the clear benefits of this FPS-guided framework, the Pantanal region still requires further site-specific studies to develop and refine management strategies that fully meet climate goals. Future research should focus on using the FPS tool to translate these on-farm management practices into verifiable climate outcomes, enabling the entry of the region in carbon markets and in frameworks for the payment of ecosystem services.

References

ABREU, U.G.P. de; CARVALHO, T.B. de; SANTOS, M.C. dos; ZEN, S. de. **Pecuária de cria no Pantanal**: análise dos sistemas modais. Corumbá: Embrapa Pantanal, 2019. 27p. (Embrapa Pantanal. Boletim de pesquisa e desenvolvimento, 140).

AGETHEN, K.; MAURICIO, R.M.; DEBLITZ, C.; IZQUIERDO, M.D.; REYES, E.; CHARÁ, J. Future perspectives of Brazilian beef production: what is the role of silvopastoral systems? **Agroforestry Systems**, v.98, p.2179-2196, 2024. DOI: https://doi.org/10.1007/s10457-024-01005-7.

ALVARES, C.A.; STAPE, J.L.; SENTELHAS, P.C.; GONÇALVES, J.L. de M.; SPAROVEK, G. Köppen's climate classification map for Brazil. **Meteorologische Zeitschrift**, v.22, p.711-728, 2013. DOI: https://doi.org/10.1127/0941-2948/2013/0507.

ARIAS, D.; VIEIRA, P.A.; CONTINI, E.; FARINELLI, B.; MORRIS, M. **Agriculture productivity growth in Brazil**: recent trends and future prospects. [Washington]: World Bank, 2017. Available at: <http://hdl.handle.net/10986/32202>. Accessed on: Mar. 29 2026.

BERGIER, I.; SILVA, A.P.S.; ABREU, U.G.P. de; OLIVEIRA, L.O.F. de; TOMAZI, M.; DIAS, F.R.T.; URBANETZ, C.; NOGUEIRA, E.; BORGES-SILVA, J.C. Could bovine livestock intensification in Pantanal be neutral regarding enteric methane emissions? **Science of the Total Environment**, v.655, p.463-472, 2019. DOI: https://doi.org/10.1016/j.scitotenv.2018.11.178.

BOLFE, É.L.; VICTORIA, D. de C.; SANO, E.E.; BAYMA, G.; MASSRUHÁ, S.M.F.S.; OLIVEIRA, A.F. de. Potential for agricultural expansion in degraded pasture lands in Brazil based on geospatial databases. **Land**, v.13, art.200, 2024. DOI: https://doi.org/10.3390/land13020200.

CABALLERO, C.B.; BIGGS, T.W.; VERGOPOLAN, N.; CAMELO, L.G.G.; ANDRADE, B.C. de; LAIPELT, L.; RUHOFF, A.L. Decadal hydroclimatic changes in the Pantanal, the world's largest tropical wetland. **Scientific Reports**, v.15, art.17675, 2025. DOI: https://doi.org/10.1038/s41598-025-01980-6.

CABALLERO, C.B.; BIGGS, T.W.; VERGOPOLAN, N.; WEST, T.A.P.; RUHOFF, A. Transformation of Brazil's biomes: the dynamics and fate of agriculture and pasture expansion into native vegetation. **Science of the Total Environment**, v.896, art.166323, 2023. DOI: https://doi.org/10.1016/j.scitotenv.2023.166323.

CHERUBIN, M.R.; MAIA, S.M.F.; DAMIAN, J.M.; CERRI, C.E.P. Matéria orgânica do solo em áreas de pastagens no Brasil. In: BETTIOL, W.; SILVA, C.A.; CERRI, C.E.P.; MARTIN NETO, L.; ANDRADE, C.A. de (Ed.). **Entendendo a matéria orgânica do solo em ambientes tropical e subtropical**. Brasília: Embrapa, 2023. p.601-625.

CORREA, D.B.; ALCÂNTARA, E.; LIBONATI, R.; MASSI, K.G.; PARK, E. Increased burned area in the Pantanal over the past two decades. **Science of the Total Environment**, v.835, art.155386, 2022. DOI: https://doi.org/10.1016/j.scitotenv.2022.155386.

COUTO, E.G.; CORRÊA, G.R.; OLIVEIRA, V.A.; NASCIMENTO, A.F. do; VIDAL-TORRADO, P.; BEIRIGO, R.; SCHAEFER, C.E.G.R. Soils of Pantanal: the largest continental wetland. In: SCHAEFER, C.E.G.R (Ed.). **The soils of Brazil**. Cham: Springer, 2023. p.239-267. (World Soils Book Series). DOI: https://doi.org/10.1007/978-3-031-19949-3_9.

CRISPIM, S.M.A.; BRANCO, O.D. **Aspectos gerais das braquiárias e suas características na sub-região da Nhecolândia, Pantanal, MS**. Corumbá: Embrapa Pantanal, 2002. 25p. (Embrapa Pantanal. Boletim de pesquisa e desenvolvimento, 33).

FREITAS, D.A.F. de; SILVA, M.L.N.; CARDOSO, E.L.; OLIVEIRA, D.M. da S.; MOITINHO, M.R.; CURI, N. Carbon and nitrogen stocks in soil under native pastures in the Pantanal Wetland Biome, Brazil. **Agronomy**, v.14, art.1994, 2024. DOI: https://doi.org/10.3390/agronomy14091994.

HISTROV, A.N.; BANNINK, A.; CROMPTON, L.A.; HUHTANEN, P.; KREUZER, M.; MCGEE, M.; OZIÈRE, P.; REYNOLDS, C.K.; BAYAT, A.R.; YÁÑEZ-REUIZ, D.R.; DIJKSTRA, J.; KEBREAD, E.; SCHAWARM, A.; SHINGFIELD, K.J.; YU, Z. Invited review: Nitrogen in ruminant nutrition: a review of measurement techniques. **Journal of Dairy Science**, v.102, p.5811-5852, 2019. DOI: https://doi.org/10.3168/jds.2018-15829.

INDU, I.; MEHTA, B.K.; SHASHIKUMARA, P.; GUPTA, G.; DIKSHIT, N.; CHAND, S.; YADAV, P.K.; AHMED, S.; SINGHAL, R.K. Forage crops: a repository of functional trait diversity for current and future climate adaptation. **Crop & Pasture Science**, v.74, p.961-977, 2022. DOI: https://doi.org/10.1071/CP22200.

LEIBER, F. Let them graze! Potentials of ruminant production outside the feed-food competition. In: EL-HAGE SCIALABBA, N. (Ed.). **Managing healthy livestock production and consumption**. London: Academic Press Elsevier, 2022. p.137-148. DOI: https://doi.org/10.1016/b978-0-12-823019-0.00009-x.

LIU, L.; SAYER, E.J.; DENG, M.; LI, P.; LIU, W.; WANG, X.; YANG, S.; HUANG, J.; LUO, J.; SU, Y.; GRÜNZWEIG, J.M.; JIANG, L.; HU, S.; PIAO, S. The grassland carbon cycle: mechanisms, responses to global changes, and potential contribution to carbon neutrality. **Fundamental Research**, v.3, p.209-218, 2023. DOI: https://doi.org/10.1016/j.fmre.2022.09.028.

MACHADO, J.M.; MOTTA, E.A.M. da; BARBOSA, M.R.; WEILER, R.L.; MILLS, A.; ONGARATTO, F.; MAIDANA, F.M.; MONTAGNER, P.; RODRIGUES, D.P.A.; SILVEIRA, D.C. Strategies to mitigate the emission of methane in pastures: enteric methane: a review. **Australian Journal of Crop Science**, v.16, p.682-690, 2022. DOI: https://doi.org/10.21475/ajcs.22.16.06.p3457.

MAPBIOMAS. **Coleção 8 da série anual de Mapas de Cobertura e Uso da Terra do Brasil**. 2023a. Available at: <https://brasil.mapbiomas.org/>. Accessed on: Dec. 18 2025.

MAPBIOMAS. **Coleção 9 da série anual de Mapas de Cobertura e Uso da Terra do Brasil**. 2023b. Available at: <https://brasil.mapbiomas.org/termos-de-uso/>. Accessed on: Apr. 16 2025.

OLIVEIRA, L.O.F.; FERNANDES, A.H.B.M.; FERNANDES, F.A.; SANTOS, S.A.; ABREU, U.G.P.; CRISPIM, S.M.A.; GARCIA, J.B.; SANTOS, R. Comparison of methane emissions by cattle pastures in the Pantanal, between two seasons of the year. In: INTERNATIONAL SYMPOSIUM ON GREENHOUSE GASES IN AGRICULTURE, 2., 2016, Campo Grande. **Proceedings**. Brasília: Embrapa, 2016. p.73-74.

PARENTE, L.; MESQUITA, V.; MIZIARA, F.; BAUMANN, L.; FERREIRA, L. Assessing the pasturelands and livestock dynamics in Brazil, from 1985 to 2017: a novel approach based on high spatial resolution imagery and Google Earth Engine cloud computing. **Remote Sensing of Environment**, v.232, art.111301, 2019. DOI: https://doi.org/10.1016/j.rse.2019.111301.

PEREIRA, A. de M.M.; BAO, F.; SOUZA, E.B. de; OLIVEIRA, M. da R.; ESCOBAR, A.C. de S.; SILVA, R.H. da; CARVALHO, S.S. de; POTT, A.; POTT, V.J.; CORREIA, S.A.C.; DAMASCENO-JÚNIOR, G.A. Fire, flooding, and herbivory: interactive drivers of taxonomic and functional diversity in a tropical wetland. **Wetlands Ecology and Management**, v.34, art.35, 2026. DOI: https://doi.org/10.1007/s11273-026-10134-y.

RATCLIFF, F.; RAO, D.; BARRY, S.; DEWEES, S.; MACAULAY, L.; LARSEN, R.; SHAPERO, M.; PETERSON, R.; MORITZ, M.; FORERO, L. Cattle grazing reduces fuel and leads to more manageable fire behavior. **California Agriculture**, v.76, p.60-69, 2022. DOI: https://doi.org/10.3733/ca.2022a0011.

SANTOS, J. de S. **Eficiência energética e produção de gases de efeito estufa em borregas alimentadas com fenos de gramíneas nativas**. 2023. 56p. Dissertação (Mestrado) – Universidade Estadual Vale do Acaraú, Sobral.

SANTOS, L.D. dos; VIEIRA, J.M.R.; RIGUETTI, A.L.; PADOVANI, C.R. **Estimativa da população de bovinos no Pantanal por meio da Pesquisa da Pecuária Municipal 2021**. 2023a. 10p. Corumbá: Embrapa Pantanal (Embrapa Pantanal. Comunicado técnico, 122).

SANTOS, S.A.; CARDOSO, E.L.; BRASIL, M.; GARCIA, J.B.; BERSELII, C. Estilosantes Campo Grande como Alternativa para Recuperação e Enriquecimento de Pastagens Nativas Degradadas do Pantanal. **Cadernos de Agroecologia**, v.13, p.1-5, 2018.

SANTOS, S.A.; CARDOSO, E.L.; PAULA, J.B. de; ARAÚJO, F.A.S. Manejo de pastagem. In: SANTOS, C.C.; ARAÚJO, F.A.S. (Org.). **Guia de melhores práticas pecuárias da planície pantaneira**. Brasília: Fundo Mundial para a Natureza, 2021a.

SANTOS, S.A.; CARDOSO, E.L.; VALLS, J.F.M.; POTT, A. Natural pastures of the Pantanal: diversity, productive potential and dynamics. In: DAMASCENO-JUNIOR, G.A.; POTT, A. (Ed.). **Flora and vegetation of the Pantanal Wetland**. Cham: Springer, 2021b. chapter 10, p.471-489. (Plant and vegetation, v.18). DOI: https://doi.org/10.1007/978-3-030-83375-6_10.

SANTOS, S.A.; COSTA, C.; SOUZA, G. da S. e; POTT, A.; ALVAREZ, J.M.; MACHADO, S.R. Composição botânica da dieta de bovinos em pastagem nativa na sub-região da Nhecolândia, Pantanal. **Revista Brasileira de Zootecnia**, v.31, p.1648-1662, 2002. DOI: https://doi.org/10.1590/S1516-35982002000700007.

SANTOS, S.A.; CRISPIM, S.M.A.; OLIVEIRA, L.O.F. de; GARCIA, J.B.; FERNANDES, A.H.B.M.; CARDOSO, E.L.; BUENO SOBRINHO, A.A.; BERSELLI, C. Managing Pantanal rangelands for optimizing carbon flow: effects of growing season and pasture type on dry mass accumulation. In: INTERNATIONAL SYMPOSIUM ON GREENHOUSE GASES IN AGRICULTURE, 2., 2016, Campo Grande. **Proceedings**. Brasília: Embrapa, 2016. p.295-298. (Embrapa Gado de Corte. Documentos, 216).

SANTOS, S.A.; LIMA, H.P. de; MASSRUHÁ, S.M.F.S.; ABREU, U.G.P. de; TOMÁS, W.M.; SALIS, S.M.; CARDOSO, E.L.; OLIVEIRA, M.D. de; SOARES, M.T.S.; SANTOS JR, A. dos; OLIVEIRA, L.O.F. de; CALHEIROS, D.F.; CRISPIM, S.M.A.; SORIANO, B.M.A.; AMANCIO, C.O.G.; NUNES, A.P.; PELLEGRIN, L.A. A fuzzy logic-based tool to assess beef cattle ranching sustainability in complex environmental systems. **Journal of Environmental Management**, v.198, p.95-106, 2017. DOI: https://doi.org/10.1016/j.jenvman.2017.04.076.

SANTOS, S.A.; POTT, A.; CARDOSO, E.L.; SALIS, S.M.; VALLS, J.F.M.; GARCIA, J.B. **Guia para identificação das pastagens nativas do Pantanal**. Brasília: Embrapa, 2020a.

SANTOS, S.A.; POTT, A.; GARCIA, L.C.; PEREIRA, A. de M.M.; EL SEHER, F.E.; DAMASCENO JUNIOR, G.A. Fogo como ferramenta de manejo em pastagens nativas. In: SANTOS, M.V.F. dos (Ed.). **Pastagens tropicais**: dos fundamentos ao uso sustentável. Visconde do Rio Branco: Suprema, 2023b. p.387-408.

SANTOS, S.A.; SALIS, S.M.; URBANETZ, C.; DELBEN, A.; FRANCO, J.L.; COMASTRI FILHO, J.A.; SANTOS, P.M. **Recomendações técnicas para o planejamento da introdução de forrageiras exóticas de forma sustentável no Pantanal**. Corumbá: Embrapa Pantanal, 2022. (Embrapa Pantanal. Documentos, 176).

SANTOS, S.A.; SOUZA, G.S.; TOMICH, T.R.; MORAIS, M. da G.; FRANCO, G.; ABREU, U.G.P. Protein-energy supplementation for different categories of animals in beef cattle on natural and cultivated pastures of the Brazilian Pantanal. **Annals of Agricultural & Crop Sciences**, v.5, art.1059, 2020b.

SANTOS, S.A.; TAKAHASHI, F.; CARDOSO, E.L.; FLORES, C.; OLIVEIRA, L.O.F. de; SOUZA, G. da S. e; GOMES, E.G.; ORTEGA, E. An emergy-based approach to assess and valuate ecosystem services of tropical wetland pastures in Brazil. **Open Journal of Ecology**, v.10, p.303-319, 2020c. DOI: https://doi.org/10.4236/oje.2020.105019.

SILVA, J. dos S.V. da; ABDON, M. de M. Delimitação do Pantanal Brasileiro e suas sub-regiões. **Pesquisa Agropecuária Brasileira**, v.33, p.1703-1711, 1998.

STANLEY, P.S.; WILSON, C.; PATTERSON, E.; MACHMULLER, M.B.; COTRUFO, M.F. Ruminating on soil carbon: applying current understanding to inform grazing management. **Global Change Biology**, v.30, e17223, 2024. DOI: https://doi.org/10.1111/gcb.17223.

TAKAHASHI, F.; SANTOS, S.; ABREU, U.; ORTEGA, E. Emergy evaluation of an extensive cattle ranching system in Pantanal watershed, Brazil. In: BROWN, M.T.; SWEENEY, S.; CAMPBELL, D.E.; HUANG, S.-L.; ORTEGA, E.; RYDBERG, T.; TILLEY, D.; ULGIATI, S. (Ed.). **Emergy Synthesis 6**: theory and applications of the emergy methodology: Proceedings from the Sixth Biennial Emergy Conference, 2010. Gainesville: The Center for Environmental Policy, 2011. chapter 30, p.337-346. DOI: https://doi.org/10.13140/2.1.3854.1763.

TEAGUE, W.R.; DOWHOWER, S.L.; BAKER, S.A.; HAILE, N.; DELAUNE, P.B.; CONOVER, D. Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie. **Agriculture, Ecosystems and Environment**, v.141, p.310-322, 2011. DOI: https://doi.org/10.1016/j.agee.2011.03.009.

WALDRIP, H.M.; COLE, N.A.; PAS; TODD, R.W. Review: Nitrogen sustainability and beef cattle feedyards: II. Ammonia emissions. **The Professional Animal Scientist**, v.31, p.395-411, 2015. DOI: https://doi.org/10.15232/pas.2015-01395.

WHITEHEAD, D. Management of Grazed Landscapes to Increase Soil Carbon Stocks in Temperate, Dryland Grasslands. **Frontiers in Sustainable Food Systems**, v.4, art.585913, 2020. DOI: https://doi.org/10.3389/fsufs.2020.585913.

XU, S.; ZHU, X.; REN, H.; YAN, X.; FANG, X.; AHMED, S.; WANG, Q. How can grazing mitigate wildfires? A review of fuel management, ecological trade-offs, and adaptive frameworks. **Sustainability**, v.18, art.718, 2026. DOI: https://doi.org/10.3390/su18020718.

Author contributions

Sandra Santos: investigation (equal) methodology (equal) writing - original draft (lead) writing - review & editing (equal); **Arnildo Pott**: writing - review & editing (equal); **Marcos Claúdio Pinheiro Rogério**: conceptualization; **Balbina Maria Soriano**: methodology (equal) writing - original draft (Equal); **Sérgio Raposo Medeiros**: writing - review & editing (equal).

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Data availability statement

The data supporting the findings of this study are available in the article. Should any raw data be needed, they will be provided by the corresponding author upon reasonable request.

Declaration of use of AI technologies

During the preparation of this work, the authors used Gemini and NotebookLM in order to improve English language clarity, correct grammar, and assist with document structuring. After this use, the authors reviewed and edited the content as needed and takes full responsibility for it.

Conflict of interest statement

The authors declare no conflicts of interest.

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