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CO_2 exchange under two different pasture management systems in the Pampa Biome

Trocas de CO_2 em dois diferentes manejos de pastagens no Bioma Pampa

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ABSTRACT

Faced with the concerning scenario of increasing greenhouse gas (GHG) emissions associated with rising global temperatures, the United Nations Climate Conferences (COPs) have been discussing various strategies for countries to reduce these emissions. In Brazil, land use change — mainly through deforestation — and the agricultural sector are identified as the main sources of GHGs, primarily CO_2 and CH_4. However, studies have shown that livestock production in the natural grasslands of the Pampa biome, when practiced sustainably, can serve as an important carbon sink. In this study, different native pasture management practices in the Pampa biome were evaluated with respect to CO_2 exchange between the surface and the atmosphere: continuous conservative grazing and rotational grazing. For this purpose, one year of data collected from a flux tower on a commercial farm in Aceguá, RS, was used. The Eddy Covariance (EC) method was applied to estimate the Net Ecosystem Exchange (NEE) of CO_2. Both grazing regimes exhibited similar seasonal patterns in NEE, with pastures acting as CO_2 sinks during the spring and summer months, and as sources during autumn and winter. In terms of annual net exchange, both management systems acted as CO_2 sinks. Under rotational management, the total amount of carbon absorbed was -82.4 ± 20.4 g C m^{-2} yr^{-1}, while under continuous conservative management it was -156.8 ± 17.22 g C g C m^{-2} yr^{-1}. Therefore, cattle grazing on natural pastures in the Pampa biome can contribute to the mitigation of greenhouse gas emissions.

Keywords: Livestock; Greenhouse gases; Carbon balance

RESUMO

Diante do preocupante cenário de aumento das emissões de gases de efeito estufa (GEE) relacionado ao aumento da temperatura da Terra, a Conferência do Clima das Nações Unidas (COP's) vem discutindo diversas formas dos países reduzirem as emissões destes gases. No Brasil, a mudança do uso da terra, principalmente devido ao desmatamento, e o setor de agropecuária são apontados como as principais fontes de gases, principalmente CO_2 e CH_4. No entanto, estudos têm mostrado que a produção de pecuária realizadas em campos naturais do bioma Pampa, quando realizada de forma sustentável, pode ser um importante sumidouro de carbono. Neste trabalho, diferentes tipos de manejos das pastagens nativas no bioma Pampa foram avaliados em relação as trocas de CO_2 entre a superfície e a atmosfera: manejo contínuo conservativo e manejo rotativo. Para tanto, foi utilizado um ano de dados obtidos por torre de fluxo em uma fazenda comercial em Aceguá – RS. A metodologia de Eddy Covariance (EC) foi utilizada para estimar a troca líquida de CO_2 entre o ecossistema e a atmosfera (NEE). Ambos os manejos apresentaram uma sazonalidade no NEE muito similar, sendo que nos meses de primavera e verão as pastagens foram absorvedoras de CO_2, enquanto nos meses de outono e inverno foram fontes. No acumulado anual, ambos os manejos atuaram como sumidouros de CO_2 da atmosfera, sendo que no manejo rotativo o total absorvido foi de -82,4 ± 20,4 g C m^{-2} a^{-1} e no contínuo conservativo foi de -156,8 ± 17,22 g C m^{-2} a^{-1}. Portanto, a criação de gado em pastagem natural do bioma Pampa pode contribuir na mitigação GEE.

Palavras-chave: Pecuária; Gases de efeito estufa; Balanço de carbono

1 INTRODUCTION

The increase in atmospheric greenhouse gas (GHG) concentrations has directly contributed to climate change, affecting the planet's average temperature, especially in recent decades (IPCC, 2021). Changes in land use and agriculture have affected biogeochemical fluxes and contributed to the increase in greenhouse gas (GHG) concentrations, particularly carbon dioxide (CO_2) and methane (CH_4) (IPCC, 2019). Although some studies identify pastures used for livestock production as sources of carbon (C) (Veenendaal *et al*., 2007) or as carbon-neutral ecosystems (Prescher; Grünwald; Bernhofer, 2010), other studies have shown that these production systems can also function as important carbon sinks (Gomez-Casanovas *et al*., 2018; Gourlez De La Motte *et al*., 2018; Rutledge *et al*., 2017; Teague *et al*., 2013). In this context, native pastures need to be investigated to understand their role in mitigating total GHG emissions from livestock production system (Lal, 2004; Soussana; Tallec; Blanfort, 2010).

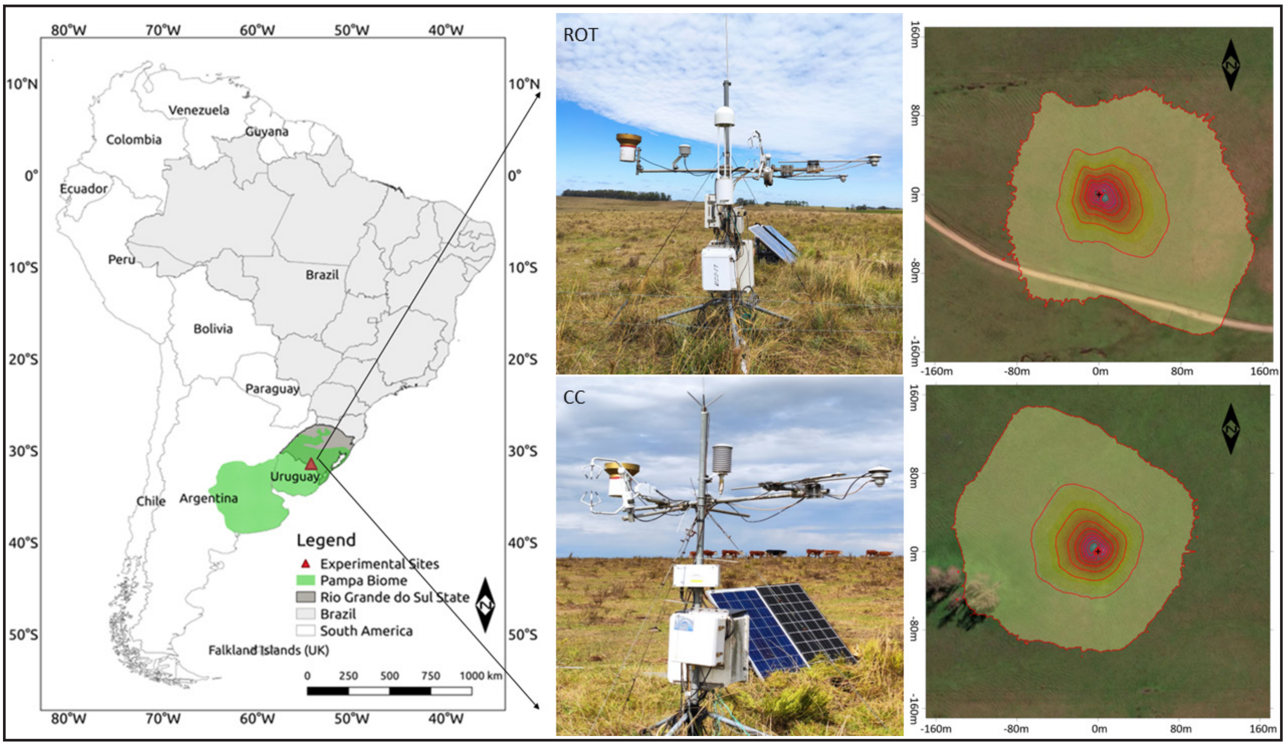
The native pastures of the Pampa biome have been used for livestock farming for centuries. The Pampa biome is located in South America, spanning Uruguay, northern Argentina, and southern Brazil, and covers a total area of approximately 750,000 km² (IBGE, 2004). This biome has great biodiversity, with natural pasture fields predominating (Pillar; Lange, 2015). These areas represent one of the most important temperate and subtropical grassland regions in the world, forming part of the Pastizales del Río de la Plata alliance (Soriano, 1992; Pallarés; Berretta; Maraschin, 2005). The predominant vegetation is photosynthetic species with C4 metabolism, coexisting with C3 species (Jaurena *et al*., 2021; Pallarés; Berretta; Maraschin, 2005). In Brazil, the Pampa biome covers 63% (174,000 km²) of the state of Rio Grande do Sul (Boldrini, 2010), where livestock production stands out as one of the main economic activities of the state. Currently, these fields are a source of forage for about 14 million animals, mainly cattle and sheep in southern Brazil (IBGE, 2020).

The introduction of beef cattle into natural pastures, when combined with appropriate management practices, can help reduce the impact of land use changes by preserving native vegetation and supporting the maintenance of the structure, physiognomy, and diversity of plant communities. (Fuhlendorf *et al*., 2009; Lezama *et al*., 2014). According to Gomez-Casanovas *et al*. (2018), adequate grazing can contribute to increased CO_2 absorption by the ecosystem. The objective of this study is to evaluate how different beef cattle management practices in natural pastures of the Brazilian Pampa biome affect CO_2 exchange between the surface and the atmosphere, specifically, whether they act as sources or sinks of CO_2. To achieve this, we used one year of CO_2 flux data collected from flux towers using the Eddy Covariance (EC) method, under two different management systems: rotational grazing and continuous conservative grazing, on a commercial farm located in the municipality of Aceguá, Rio Grande do Sul.

2 MATERIALS AND METHODS

2.1 Description of the experimental area

Figure 1 – Location and images of the flux towers under the Continuous Conservative (CC) and Rotative (ROT) management at the experimental site of Aceguá - RS with the respective area with up to 90% contribution to the fluxes measured by the sensors of each tower (footprint) obtained with the methodology described in Kljun *et al*. (2015)



Source: Authors (2025)

Legend: Legend: Map of South America, the green color represents the area of the Pampa biome, and the red color the location of the Aceguá flux towers

The experimental area is located on a private property (Estância Cinco Salsos) in the municipality of Aceguá in the state of Rio Grande do Sul, Brazil (Figure 1). The area is characterized by natural pastures of the Brazilian Pampa biome, with predominant vegetation of grasses of the type Paspalum notatum, Axonopus affinis, Mnesithea selloana, Paspalum dilatatum, Nassela sp. and Piptochaetium sp., Baccharis coridifolia, B. crispa (Baggio, 2017; Overbeck *et al*., 2007). The soil in the region is classified as Vertisols (FAO, 2015) with 17%

sand, 36% clay, and 48% silt in the top 0.05 m layer. It has a field capacity of 0,54 m^3 m^{-3} and a permanent wilting point of 0,02 m^3 m^{-3}. For more information on the soil characteristics and physical properties, see Romio *et al*. (2022) and Zimmer *et al*. (2023).

The climate of the study site is classified as humid subtropical (Cfa) according to the Köppen classification (Peel; Finlayson; Mcmahon, 2007). The seasons are well defined, with summer characterized by higher temperatures that can exceed 30 °C during the day, and winter marked by milder temperatures, with occurring frost events. Precipitation in the region is generally well distributed throughout the year but can be influenced by climatic phenomena such as El Niño and La Niña (ENSO) (Grimm; Barros; Doyle, 2000).

2.1.1 Description of pastoral management

Two flux towers were installed, one in each of the management systems analyzed: continuous conservative (CC) and rotational (ROT). The CC management system consists of a continuous 18-hectare unit without internal subdivisions, allowing unrestricted cattle access to the entire area. The site has an average slope of 3%, with a north-facing orientation. The flux tower was installed approximately in the center of this area (latitude -31.6508°, longitude -54.1737°). The stocking rate is adjusted according to the available forage supply. Young Hereford heifers owned by Estância Cinco Salsos were used, with an average annual stocking rate of 320 kg live weight (LW) per hectare, equivalent to approximately one animal per hectare or 0.7 animal units (AU), considering 1 AU = 450 kg LW.

In the ROT management system, an 18-hectare unit is divided into eight paddocks of 2.25 hectares each, where cattle are moved in a rotational grazing system. Each paddock undergoes a rest period to allow vegetation to regrow after grazing. The flux tower was installed between two central paddocks (latitude -31.6533°, longitude -54.1753°). The area has an average slope of 3%, with a south-facing orientation. To determine the rest intervals, the thermal sum of 550 degree-days was used, which corresponds to an intermediate value necessary for fast and slow developing plant species to reach their ideal development (Barbieri *et al*., 2014). The animal load was adjusted to maintain the supply of aerial biomas, varying throughout the year from 5 to 6 kg of dry matter (DM) for each kg of bovine live weight (BW) (Sollenberger *et al*., 2005). In the cold season (from March to September), the stocking rate was 3 kg of dry matter (DM) per kg of live weight (LW), and in the warm season (October to February), it ranged from 4 to 4.5 kg DM kg^{-1} LW. This resulted in an annual average of 320 kg LW ha^{-1} across the entire system, corresponding to approximately one animal per hectare, or about 0.7 animal units (AU), considering 1 AU = 450 kg LW.

2.2 Database and description of flux tower sensors

The two flux towers were equipped to measure wind components and CO_2 concentrations at high frequency (10 Hz) in order to estimate the CO_2 flux. In addition, meteorological and soil variables were recorded at 1-minute intervals. Table 1 provides a description of the sensors installed on both flux towers (rotational and continuous conservative management systems). One year of data was used in this study, covering the period from January 1 to December 31, 2020.

Table 1 – Instruments used in each flux tower in the experimental area

Variable	Sensor	Height (m)
Components of sonic wind and temperature (u, v, w and Ts)	CSAT3 – Campbell Scientific Inc., USA	2.50
Gas concentration (CO_2 and H_2O)	LI-7500 – LI-COR Inc., USA	2.50
Air temperature (Temp) and Relative Humidity (RH)	CS215-L – Campbell Scientific Inc., USA	2.50
Precipitation (Prec)	TR525USW – Texas Eletronics, Dallas, TX, USA	2.50
Solar global radiation (Rg)	CMP3 – Kipp&Zonen, Delft, The Netherlands	2.50
Soil moisture (θ_{soil})	CS 616 – Campbell Scientific Inc., USA	-0.05
Soil temperature (T_{soil})	T-108 – Campbell Scientific Inc., USA	-0.05

Source: Authors (2025)

Gaps in the meteorological variable data (air temperature, global radiation, and relative humidity) were filled using measurements from the WMO 86992 station of the Brazilian National Institute of Meteorology (INMET), located 30 km from the experimental area. Persistent gaps were filled using hourly ERA5 reanalysis data, with a spatial resolution of 0.25°, from the Copernicus Climate Change Service (C3S) Climate Data Store (CDS) (Hersbach *et al*., 2018).

2.3 Flux data processing

The net CO_2 flux between the ecosystem and the atmosphere or CO_2 net ecosystem exchange (NEE) was estimated using the correlation between fluctuations in vertical velocity and CO_2 concentration by the EC methodology, using EddyPro® software version 7.0.6 (Li-Cor, Lincoln, Nebraska) in 30-minute averages. Corrections in the flux calculation were applied following the double rotation techniques (Wilczak; Oncley; Stage, 2001), corrections for density effects (Webb; Pearman; Leuning, 1980), flux attenuation due to instrumental configuration (Gash; Culf, 1996), corrections due to high-pass (Moncrieff *et al*., 1997) and low-pass (Moncrieff *et al*., 2004) filters and high-frequency data filtering (Vickers; Mahrt, 1997).

The EddyPro® software assigns quality flags to flux data based on atmospheric stability and turbulence development criteria, according to (Foken *et al*., 2004) where flag "0" indicates good quality fluxes, "1" medium quality, and "2" low quality. In this study, fluxes flagged as "2" were discarded. The flux data were also subjected to a statistical quality control filter to remove non-physical values, following equations adapted from Béziat *et al*. (2009). Finally, periods characterized by low turbulence were identified using the friction velocity (u*) threshold, following the methodology of Papale *et al*. (2006), and data from these periods were excluded.

After data filtering, gaps in the flux data were filled using the REddyProc package (Max Planck Institute for Biogeochemistry, Germany), following the methods described by Wutzler *et al*. (2018). The REddyProc package was also used to partition the net ecosystem exchange (NEE) into gross primary production (GPP), which represents CO_2 uptake via photosynthesis, and total ecosystem respiration (Reco), which represents CO_2 emissions from ecosystem respiration (including soil microorganisms, plants, and animals), such that NEE = Reco – GPP. Partitioning was performed using the nighttime-based approach as described by Reichstein *et al*. (2005). This method is based on the response function of air temperature to nighttime NEE fluxes, which exclusively represent Reco. It is assumed that this relationship is also applicable to daytime data. From this relationship, daytime Reco is predicted based on measured air temperature. GPP is then calculated as the difference between Reco and NEE.

The annual NEE was calculated by integrating NEE values every half hour. To assess the annual NEE uncertainty, we used three sources of error according to Deshmukh *et al*. (2023): sampling error (Us), gap-filling method error (Ug), and random error of systematic determination of the threshold u* (Uu). Sampling uncertainty was calculated using EddyPro software, following Finkelstein & Sims (2001). The uncertainty of the gap-filling method was obtained by the REddyproc package. The same package also provides the uncertainty of the u* threshold estimate. The annual NEE estimate includes the total uncertainty (U_T calculated using the error propagation law ($U_T = \sqrt{Us^2 + Ug^2 + Uu^2}$).

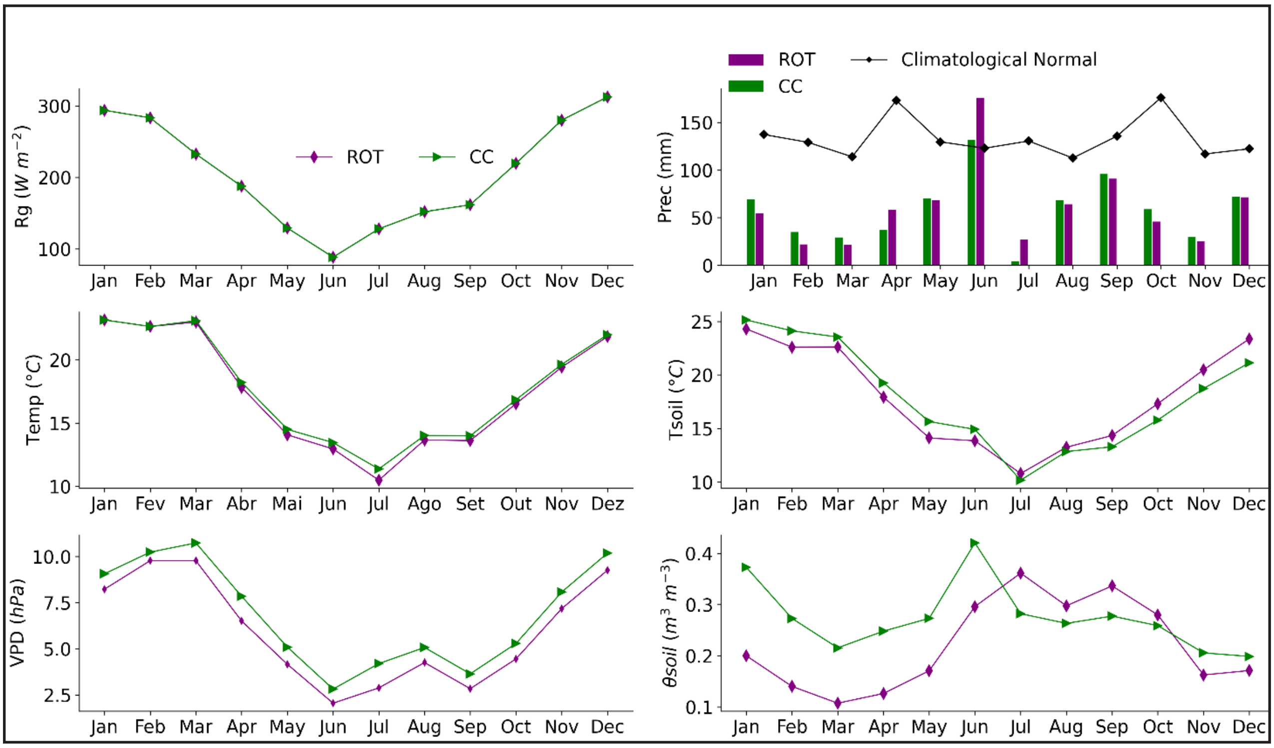
3 RESULTS AND DISCUSSION

3.1 Environmental variables

The monthly analysis of the environmental variables of global solar radiation (Rg), precipitation (Prec), air temperature (Temp), soil temperature (T_{soil}), vapor pressure deficit (VPD) and soil moisture (θ_{soil}) are presented in Figure 2. We observed that Rg, Temp, T_{soil} and VPD follow a well-defined seasonal pattern throughout the year. The values of Rg varied between 100 and 300 W m^{-2}, while Temp varied between 10 and 30 °C for the autumn/winter and spring/summer seasons, respectively. Although both managements analyzed are approximately 300 m apart, precipitation was slightly different, but distributed in the same way throughout the year. However, all months presented precipitation below the climatological normal, with the exception of June. The annual accumulated Prec was 55% below the climatological normal, that is, 2020 was a typically dry year. This fact is associated with the action of the La Niña phenomenon in the region, causing a reduction in precipitation volumes (Jones, 2022; Li *et al*., 2022).

When analyzing T_{soil} and VPD, we found that both managements presented similar behavior, however, the CC management had a slightly higher value than the ROT, except for T_{soil} from July to December. Comparing the seasonality of θ_{soil} between the two managements, we noticed that during the months of January to June, the difference in values was around 50%, with higher values for CC, inverting this relationship between July and October, which may also be related to the inversion in T_{soil}. The maximum peak of θ_{soil} was 0.41 $m^3\ m^{-3}$ in June for CC management, while in ROT management it was close to 0.36 $m^3\ m^{-3}$ in July.

Figure 2 – Monthly average of meteorological variables from the two flux towers at the Aceguá site for the year 2020

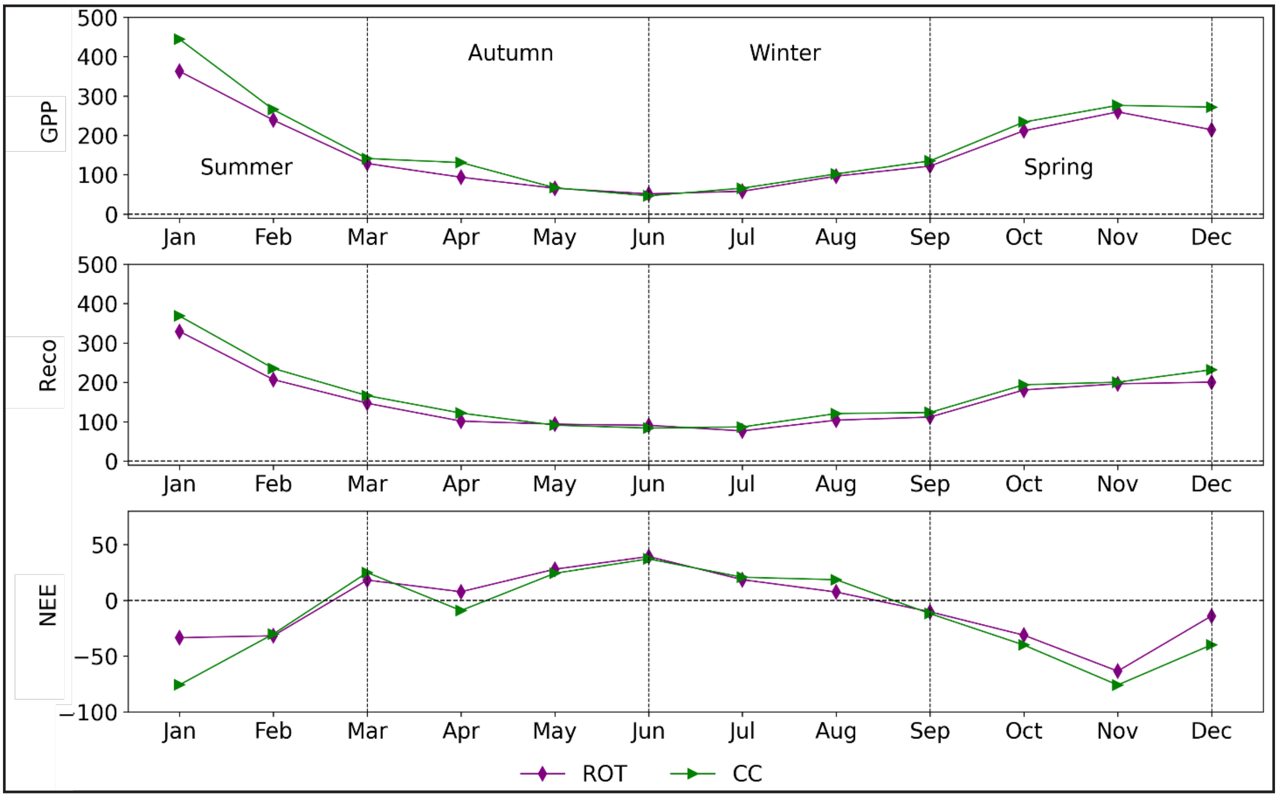


Source: Authors (2025)

3.2 CO_2 Flux

The monthly variabilities of GPP, Reco and NEE are presented in Figure 3. The seasonal variability of GPP and Reco for rotational and continuous conservation management was very similar throughout the period, with high values during the summer and lower values during the winter. This seasonal behavior is linked to the meteorological variables of Rg and Temp (Figure 2), and to the summer growth of the dominant plants in these pasture areas (Jaurena *et al*., 2021). During the spring/summer season, GPP and Reco reach values of approximately 400 g C m^{-2} month^{-1} and 350 g C m^{-2} month^{-1}, respectively. According to Hoeppner & Dukes (2012), the intensification of solar radiation, the gradual increase in temperature and regular rainfall create favorable conditions for grassland growth. From April to July, when average monthly temperatures are lower, the GPP and Reco values decrease to around 50 g C m^{-2} month^{-1} and 100 g C m^{-2} month^{-1}, respectively. This drop is associated with the autumn/winter season, where C4 type grasses, predominant in natural pastures, reduce their photosynthetic capacity (Pallarés; Berretta; Maraschin, 2005). In general, the CC management consistently showed vegetation height approximately 50% greater than that in the ROT, with an annual average of about 8.5 cm in CC and 5.5 cm in ROT.

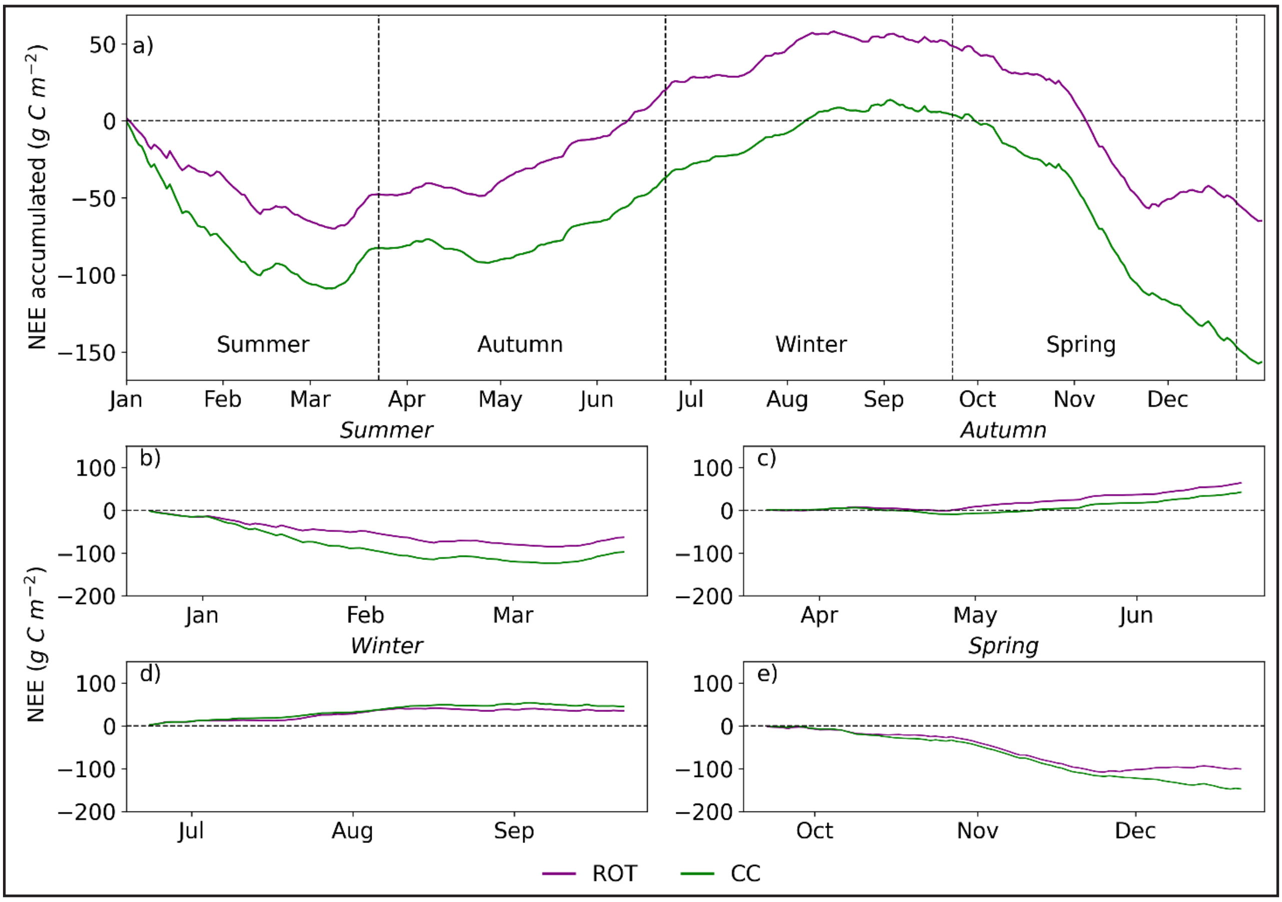
Figure 3 – Monthly values (in unit g C m^{-2} month^{-1}) of gross primary production (GPP), ecosystem respiration (Reco) and CO_2 flux (NEE) for the year 2020 for Rotational (ROT) and Continuous Conservative (CC) management



Source: Authors (2025)

Since the animal load was similar between the two management systems, the animals' respiration must have contributed similarly to the CO_2 fluxes. However, in the rotational management, this contribution must have been more intense when the animals were in the paddocks of the tower footprint. Even so, considering the annual average, this influence tends to be equivalent between the management systems.

Figure 4 – Accumulated values of annual NEE (a) and accumulated NEE for each season (b, c, d, e) for the year 2020 for Rotational (ROT) and Continuous Conservative (CC) management



Source: Authors (2025)

Differences in NEE values were observed for the spring/summer seasons between rotational and continuous conservative management, mainly in the month of January, when continuous conservative absorbed almost 50 g C m^{-2} $month^{-1}$ more than the rotational. In general, NEE was negative during spring/summer, indicating that the ecosystem absorbs significant amounts of CO_2. This result is evidenced by the accumulated NEE by seasons presented in Figure 4, where we observe that spring is the main period of atmospheric CO_2 absorption, with CC absorbing 38.64% more than ROT. On the other hand, during the months of March to August the ecosystem presents positive NEE values (Figure 3), behaving as a CO_2 emitter, except in April, in which both managements tend to be practically neutral. The accumulated NEE values for the autumn and winter seasons (Figure 4) present similar behavior for rotational and continuous conservative management, with practically zero differences in both managements.

When analyzing the annual NEE accumulation, we found that the rotational and continuous conservative management systems behave as atmospheric carbon sink systems (Figure 4), with values of -82,4 ± 20,4 g C m^{-2} yr^{-1} and -156,8 ± 17,2 g C m^{-2} yr^{-1}, respectively. Contrary to what is expected, these results indicate that continuous conservative management has greater potential for carbon sequestration, possibly because the animal load is well adjusted according to the supply of available forage and the northern orientation that should receive greater solar radiation for plant growth.

The lower CO_2 absorption by rotational management may be related to the water content available in the soil (θ_{soil}). According to Allen *et al*. (1998) and Zimmer *et al*. (2020), values below a soil moisture threshold (θ_t) characterize the soil as dry, starting a period of water deficit that hinders the development of grasses. This value of θ_t was equal to 0,23 m^3 m^{-3} for both managements, calculated according to the methodology described by Zimmer *et al*. (2020). The rotational management presented values below in the months of January to May and November to December, mainly affecting the regrowth period of the plants, reducing the potential for CO_2 absorption that is expected for this management system. Although both management areas have similar slopes, the continuous conservative management is close to a natural water drainage channel, which may provide greater accumulation of θ_{soil} in relation to the rotational management, which did not present a water deficit during the study period.

Studies using the EC methodology have shown that pasture ecosystems have behaved as CO_2 sinks: Rutledge *et al*. (2015), found average NEE of -165,3 ± 50,5 g C m^{-2} yr^{-1} in a temperate area of New Zealand with managed pasture and rotational grazing; Gourlez De La Motte *et al*. (2016) found an average NEE of -141 g C m^{-2} yr^{-1} or the period 2010-2015 in a permanent pasture region in southern Belgium; Gomez–Casanovas *et al*. (2018), found that the grazed treatment absorbed -136 ± 6 g C m^{-2} yr^{-1} in subtropical grassland regions in Florida-USA, while the ungrazed treatment emitted 83 ± 4 g C m^{-2} yr^{-1}. Therefore, the results obtained in this study, although they are for only one year of analysis, show the potential of natural pasture areas in the Pampa biome as CO_2 absorbers.

4 CONCLUSION

The results obtained in this research showed that the continuous conservative management had greater CO_2 absorption in relation to the rotational management for one year of analysis. This result was possibly influenced by the greater soil moisture in the continuous conservative system, preventing the plants from entering into water deficit. The position of the measurements on the ground may have intensified these differences in θ_{soil} and consequently in the NEE, GPP and Reco fluxes. However, these results show that raising cattle on natural pastures in the Pampa biome, under appropriate management and with adequately adjusted animal load, can contribute to the mitigation of greenhouse gases.

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