sustainability

Article

Sustainability in Natural Grassland in the Brazilian Pampa Biome: Livestock Production with CO_2 Absorption

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Abstract: The Brazilian Pampa biome has natural pastures that have been used for centuries for cattle grazing. This is considered a sustainable system because it combines the conservation of natural vegetation and high-quality meat production, protecting the biome from commercial agriculture's advances. However, whether it is a source or a sink of carbon dioxide (CO_2) has yet to be evaluated. Hence, this study aimed to quantify the net ecosystem exchange (NEE) of the CO_2 of a natural pasture of the Pampa biome used for livestock production. The experimental area is located in a subtropical region of southern Brazil, where eddy covariance (EC) measurements were conducted from 2015 to 2021 in a rotational cattle grazing system. The seven months of the warm season (September to March) were characterized as CO_2 absorbers, while the five months of the cold season (April to August) were CO_2 emitters. Throughout the six years and with complete data, the ecosystem was an absorber of atmospheric CO_2, with an average value of -207.6 g C m^{-2} year^{-1}. However, the significant interannual variability in NEE was observed, with cumulative values ranging from -82.0 to -385.3 g C m^{-2} year^{-1}. The results suggest the coupling of climatic conditions to pasture management can be the factor that modulated the NEE interannual variability. The cattle raising system on the natural pastures of the Pampa absorbs CO_2, which is further evidence of its sustainability and need for conservation.

Keywords: eddy covariance; net CO_2 exchange; natural pasture; cattle production; sustainable food system

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1. Introduction

The Brazilian Pampa biome covers an area of roughly 174,000 km^2 and is entirely situated in Rio Grande do Sul state (southern Brazil), corresponding to 63% of the state [1]. Biomes are characterized by its unique vegetation, soil, climate, and wildlife. The Pampa biome is located inside the Pastizales del Rio de la Plata, which span over 700,000 km^2, covering southern Brazil, Uruguay, and northern Argentina (28° S to 38° S, 50° W to 61° W). This Pastizales is one of the world's most important temperate and subtropical natural grasslands due to their vast areas and the fact that they harbor a plethora of endemic plant and animal species.

The natural landscape of the Brazilian Pampa biome is characterized by gently undulating relief and vegetation consisting of herbaceous plants, with a predominance of summer-growing grasses [2]. Trees are only found near water bodies in most areas. Due to these characteristics, the Pampa has been used for extensive cattle grazing. This economic activity originated with the Spanish Jesuit priests who colonized the region at the end of the seventeenth century [3]. In Brazil, the Pampa is a source of forage for roughly 5.5 million beef cattle. By preserving the natural vegetation, this ecosystem is home to rich biodiversity and formed by about 3000 species of plants, 100 species of mammals, and 500 species of birds [1,4].

Recent evidence has shown that almost 30% of the natural vegetation in the Brazilian Pampa has been lost in the last two decades, mainly due to agriculture and forestry [5]. Large areas of natural pasture have been converted into soybean fields and eucalyptus afforestation [6]. For example, the annual loss of natural vegetation in the Brazilian Pampa increased from 500 hectares in 2019 to 3000 hectares in 2022 [7], consequently leading to soil degradation and biodiversity loss since these soils have predominantly sandy textures, making them susceptible to water and wind erosion [8].

Society has made great efforts to reduce the loss of natural pastures in the Pampa biome, and one of the alternatives is increasing the economic profitability of the traditional activity of raising animals [3,9–12]; this is conducted by improving pasture and cattle management, increasing animal production per area [13]. Another alternative is acknowledging the value of meat produced in the Pampa biome through marketing since traditional production takes place with European beef breeds that produce high-quality meat (e.g., Hereford, Devon, Angus, etc.) and in natural pastures with high plant diversity, thereby contributing to a regional terroir. Additionally, environmental marketing can be employed if such production is neutral or sequesters C, since sustainability is an increasing concern for consumers willing to pay more for eco-friendly products [14]. However, the natural pastures in the Pampa biome have not yet been evaluated to assess whether they are a source of carbon or a carbon sink.

Proper pasture management in cattle grazing can lead to carbon sequestration and mitigate greenhouse gas emissions from livestock [15]. Although pasture C exchange can be determined by changes in soil organic carbon stocks, this technique requires long assessment periods and cannot assess C dynamics at seasonal, annual, and interannual scales [16,17]. Nevertheless, these limitations are overcome by employing the eddy covariance method (EC), which allows one to evaluate C dynamics in shorter periods [18]. This method measures the C fluxes (CO_2 and CH_4) occurring between the ecosystem and atmosphere at the hectare scale by the covariance between continuous measurements of vertical wind speeds and gas concentrations. The CO_2 flux represents the net exchange due to the respiration of soil, plants, and animals and assimilation by photosynthesis, while the CH_4 flux is due to the enteric emission of cattle and generation/assimilation by soil microorganisms. Therefore, the EC enables one to evaluate the impact of management practices or specific climatic conditions on these fluxes [19–21].

Given the above, this study aimed to answer, qualitatively and quantitatively, if the natural pastures in the Pampa biome used for livestock are a carbon source or sink. The predominance of summer-growing grass species results in higher forage production in warmer periods and lower production in colder periods. Hence, this study hypothesizes that (i) the CO_2 net ecosystem exchange (NEE) throughout the year presents a strong seasonality, and (ii) the performance of this system in the annual CO_2 balance depends on the interrelationships between management and climatic conditions. In this sense, this study provides the first continuous measurements with the EC method on a seven-year basis to measure the CO_2 sequestration/emission capacity of a natural pasture used for cattle ranching in the Pampa biome, contributing to efforts to improving this traditional livestock production system, which combines quality meat production and natural vegetation conservation.

2. Materials and Methods

2.1. Site Description

The experimental site comprises 40 hectares of natural pasture used for beef cattle production within the Federal University of Santa Maria campus in Santa Maria (Rio Grande do Sul State, Brazil; Figure 1), located in an experimental area that has been subject to research on different management systems for bovine production since 1995. The predominant climate is classified as humid subtropical Cfa according to the Köppen classification [22], with an average annual temperature of 19.4 °C, characterized by having well-defined seasons with hot summers (maximum above 35 °C) and cold winters (minimum below 5 °C), subject to frost, and with regular precipitation between seasons (annual average of 1778 mm) (climatological normal from 1991 to 2020).

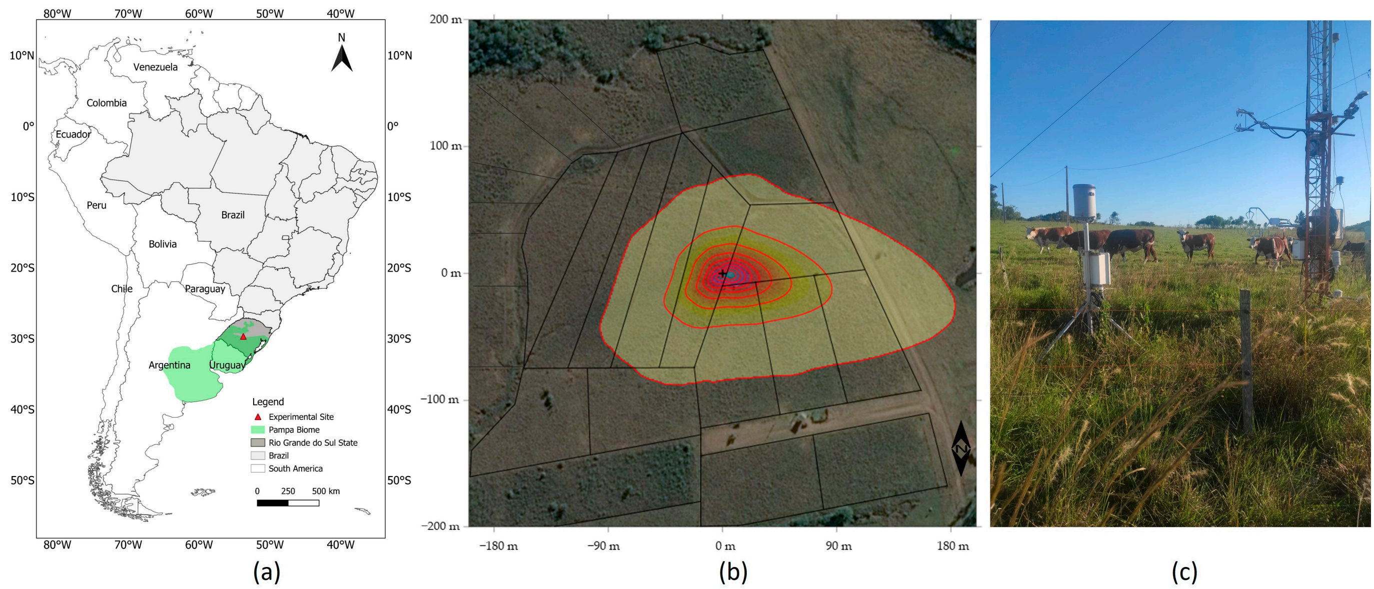

Figure 1. Extension of the Pastizales del Rio de la Plata (Pampa biome) with the location of the experimental area in the triangle in red (**a**), the footprint of the flux tower with the plots marked (**b**), and an overview of the study area (**c**).

The soil is classified as Ultisol [23], with the following characteristics at 0.10 m depth: soil organic carbon (Walkley and Black) 10 g dm^{-3}, pH (H_2O) 4.5, phosphorous (Mehlich) 5.0 mg dm^{-3}, exchangeable K 60.0 mg dm^{-3}, exchangeable Ca 1.2 cmolc dm^{-3}, exchangeable Mg 0.7 cmolc dm^{-3}, exchangeable Al 1.3 cmolc dm^{-3}, field capacity (θ_{FC}) 0.31 m^3 m^{-3}, permanent wilting point (θ_{WP}) 0.11 m^3 m^{-3}, soil porosity (θ_s) 0.45 m^3 m^{-3}, and soil bulk density (ρ_s) 1397 kg m^{-3}, as described by Rubert et al. [24]. The vegetation is classified as Mesic Pampa grassland subtype 5b [25]; the most abundant species are the C4 grasses *Axonopus affinis*, *Paspalum notatum*, *Andropogon lateralis*, and *Aristida laevis*, which are uniformly distributed [26].

2.2. Pasture Management

A rotational grazing management system was conducted in 0.5 hectare plots, where the Braford heifers, aged between 8 and 20 months, with live weights between 160 and 290 kg, had free access to water and salt. The stocking density was, on average, 4.4 cattle per hectare in the warm season (spring and summer, from October to March) and 3.3 cattle per hectare in the cold season (autumn and winter, from April to September) (Table 1). The start and end date of the warm season was determined by pasture growth (height), which was a consequence of the climatic conditions of each year. The resting period of the pasture, in a rotation of 8 plots, was calculated by the accumulated thermal sum of 750-degree days (DD, sum across days of the average between the maximum and minimum daily temperatures), which is the period required to elongate 1.5 leaves per tiller (*Aristida laevis* grass). The cattle grazed each plot for approximately 5 days in the warm season and 7 days in the cold season; in the winters of 2020 and 2021, the cattle grazed freely in the plots. A complete description of the rotational management in this area was described by [27].

Animal production was evaluated between 2015 and 2020 in the warm season. The animals were weighed about every 28 days, and the weight gain was obtained by the mean weight difference between weighings. The total forage dry mass was estimated by visually comparing standards and calibrated using the double sampling technique of Haydock and Shaw [28]. The total forage dry mass was estimated by a visual comparison of standards, with 30 visual estimates and 10 cuts at ground level using a 0.25 m^2 metal frame for subsequent drying in a forced ventilation oven at 65 °C until a constant mass was achieved. For each frame, three canopy heights were defined and classified according to the structure (prostrate or clump) to estimate the average height of the pasture. The leaf percentage was estimated by separating the leaf blades from the cut samples to calibrate the visual estimates.

2.3. Instrumentation and Data Processing

A flux tower was installed between the rotational plots at 53°45′36.097″ W and 29°43′27.502″ S, 88 m above sea level (Figure 1). The evaluation period of the flux tower data was from 1 January 2015 to 31 December 2021. The high frequency (10 Hz) sensor array, installed 3 m above ground, included a 3D sonic anemometer (Wind Master Pro; Gill Instruments, Hampshire, UK) to measure wind components and air temperature and an open-path gas analyzer (LI7500, LI-COR Inc., Lincoln, NE, USA) to determine CO_2/H_2O concentrations until 15 June 2016. Afterward, the gas analyzer and anemometer were replaced with the integrated open-path CO_2/H_2O gas analyzer and 3D sonic anemometer (IRGASON, Campbell Scientific Inc., Logan, UT, USA). No data were collected from 15 June to 15 September 2021 due to technical problems.

Low frequency (1 Hz) atmospheric variables were measured with the following sensors placed at a 3 m height: air temperature (T_a, °C) and relative humidity (RH, %) with a thermo-hygrometer (HMP155, Vaisala, Finland) until 15 June 2016, and then with a new thermo-hygrometer (CS215-L, Campbell Scientific Inc, Logan, UT, USA), incoming shortwave radiation (R_g, W m^{-2}) and net radiation (R_n, W m^{-2}) calculated from incoming longwave, outcoming longwave, incoming shortwave, and outcoming shortwave solar radiation, collected with a net radiometer (CNR4, Kipp & Zonen, Delft, the Netherlands). Precipitation (Prec, mm) was measured by a rain gauge (TR525USW, Texas Electronics, Dallas, TX, USA) at a 1.7 m height. Soil heat flux (G, Wm^{-2}) was measured with soil heat plates (HFP01, Hukseflux Thermal Sensors BV, Delft, the Netherlands) placed at a 0.10 m depth. Soil temperature (T_s, °C) was evaluated with a temperature probe (T108, Campbell Scientific Inc., Logan, UT, USA) at a depth of 0.05 m. Soil water content (SWC, m^3 m^{-3}) was measured using a water content reflectometer (CS616, Campbell Scientific Inc., Logan, UT, USA) at a depth of 0.10 m. The data collection system was initially set up with a CR1000 datalogger (CR1000, Campbell Scientific Inc., Logan, UT, USA) to collect the high- and low-frequency data. After 5 December 2019, the atmospheric high- and low-frequency data were collected with a CR6 datalogger (CR6, Campbell Scientific Inc., Logan, UT, USA) and the soil data by a CR1000. The low-frequency data were grouped into 30 min averages. From November 2019 through March 2020, no data were collected from the soil sensors.

There were occasional power outages or malfunctioning sensors, which caused failures in data collection and generated gaps. To complete the missing data for the meteorological variables of air temperature (18.9% gaps), relative humidity (18.8% gaps), and solar radiation (10.4% gaps), we utilized data from the official INMET weather station (National Institute of Meteorology; code OMM 86977), which is 3.7 km from the flux tower (29.72° W, 53.72° S, 103 m above sea level). The remaining gaps of 1.2, 4.1, and 2.7% for air temperature, solar radiation, and relative humidity, respectively, were filled using reanalysis data obtained from ERA5 hourly data on pressure levels from 1979 to the present Copernicus

Climate Change Service (C3S) Climate Data Store (CDS) [29]. The precipitation and soil moisture data were compared with the data from the INMET station to identify and close possible gaps. The INMET station database was also used to obtain climatological data (30-year average, 1981–2010).

High-frequency data processing was performed using the eddy covariance (EC) technique with EddyPro software (version 7.0.9; LI-COR Inc., Lincoln, NE, USA) to estimate NEE (CO_2 net exchange ecosystem), latent heat flux (LE), and sensitive heat flux (H) in a half-hourly frequency. For the flux estimation, the following corrections were applied: double rotation [30], corrections for density effects [31], flux attenuation due to the instrumental setup [32], corrections due to high-pass and low-pass filtering [33,34], and high-frequency data filtering [35].

To conduct a quality control in the flux data, we used the EddyPro software, which calculates different indicators based on well-developed steady-state and turbulence tests: indicator "0" for high-quality fluxes, "1" for intermediate-quality fluxes, and "2" for low-quality fluxes [36]. We removed fluxes when the indicator was "2". Fluxes were discarded in precipitation events and the subsequent half hour (for instrument drying). The physical threshold filter for LE and H were defined by Rubert et al. [24] for the same site, being 650 W m^{-2} < LE < −40 W m^{-2} and 300 W m^{-2} < H < −60 W m^{-2}. For the NEE, this filter was considered when ∣NEE∣ > 50 µmol m^{-2} s^{-1}. Statistical control was used according to Béziat et al. [37]: data outside a standard deviation range of ±2.5 of the moving window of 200 data points (separately for daytime and nighttime data) were identified as remaining outliers and removed. The NEE was filtered to remove observations made under low-turbulence conditions based on the u_*-threshold criterion [38].

The footprint of the flux tower was estimated using the model developed by Kljun et al. [39] through online data processing (Flux Footprint Prediction; http://footprint.kljun.net, accessed on 20 January 2023) and is shown in Figure 1. Because plots within the EC footprint were not always grazed at the same time, different plots had different pasture covers at any given time. The distance at which the contribution to the flux measurements was 90% was approximately 180 m in the predominant wind direction (east). No flux data were discarded by footprint analysis.

The raw flux data had 30.8, 29.1, and 18.2% failures for NEE, LE, and H, respectively, due to technical problems in the measurement instruments. After applying all filters and processing quality controls, 57.6, 58.7, and 64.6% remained for the NEE, LE, and H data, respectively. These amounts of failures corroborate the literature on the EC technique [38]. The gaps in NEE, H, and LE flux data were filled using the REddyproc package (Max Planck Institute for Biogeochemistry, Germany) using the marginal distribution sampling method that combines the lookup table and mean diurnal course methods described by Wutzler et al. [40]. The gap due to the maintenance of the gas analyzer from 15 June to 15 September 2021 was not filled.

The NEE was partitioned between gross primary production (GPP) and total ecosystem respiration (Reco) by the nighttime method described by Reichstein et al. [41] using the REddyproc package. Negative NEE values denote CO_2 assimilation or absorption by the ecosystem, while positive NEE values indicate CO_2 net emissions to the atmosphere.

2.4. Estimates of Uncertainty in NEE

The uncertainty in NEE caused by random errors and errors associated with data gaps was estimated based on the method of Richardson et al. [42] and Richardson and Hollinger [42–44]. This method follows the standard rules of error propagation based on random error estimation and the long gap-filling procedure. The random uncertainty was estimated based on the approach of successive days with similar environmental conditions [45]: 30% random gaps were inserted into the data set without gaps, and artificial noise based on the double exponential distribution was added to the remaining data. These gaps were filled by applying the gap-filling algorithm (ReddyProc package) and the calculated cumulative NEE sum. The process was repeated 100 times, and the random uncertainty was calculated as the standard deviation of all generated cumulative fluxes. Artificial random gaps were introduced into the gap-free data and refilled as conducted in Richardson and Hollinger [44] for long gap uncertainty. The random and long gap uncertainties were added in quadrature to calculate the total NEE uncertainty, assuming the two types of errors were independent [44].

2.5. Energy Balance Closure

The relationship between available energy ($R_n - G$) and turbulent fluxes (H + LE) is often used as an indicator of the accuracy of estimates by the eddy covariance method [46]. Failure to close the energy balance is widely documented in the literature, and values of up to 30% are considered reliable [47]. This study used H and LE fluxes with high-quality (0 and 1 indicators) and unfilled gaps to calculate energy balance closure only when all four components (H, LE, R_n, and G) were available. The slope of the linear regression between ($R_n - G$) and (H + LE) for the evaluated period was 0.75 (y = 0.75x + 19, R^2 = 0.88), meaning the non-closure of the energy balance was roughly 25%, as analyzed and discussed by Rubert et al. [24] for the same experimental site.

3. Results

3.1. Pasture Management

The cattle grazed rotationally in the plots within the flux tower footprint throughout the experimental period, except in the autumn and winter of 2020 and 2021, when they grazed freely. Animal performance and pasture structural variables were assessed annually in the spring/summer, which we defined as the warm season with greater pasture growth (Table 1). In response to interannual climate variability, the total dry mass of the pasture in the plots ranged from 2858.6 (2019/2020) to 4951.1 kg ha^{-1} (2016/2017). As a result of this availability, animal stocking ranged from 822.7 (2019–2020) to 1262.4 kg LW ha^{-1} (2017–2018) (LW = live weight of cattle). Pasture management was performed correctly as the average pasture height was similar between years, ranging between 29 and 33 cm, except in the first warm season (2015/2016), when the value was 22.7 cm. Throughout the experimental period, the average weight gain of the cattle in the warm season was 130.6 kg LW ha^{-1}, with the highest gain in 2018/2019 (154.8 kg LW ha^{-1}) and the lowest in 2019/2020 (95.9 kg LW ha^{-1}).

Table 1. Parameters of natural pasture growth, stocking, and weight gain of cattle grazing on the experimental site in the Brazilian Pampa biome during the warm season.

Warm Season	No. of Days	Pasture			Cattle	
		Average Height (cm)	Total Dry Mass (kg ha^{-1})	Leaves (%)	Average Occupancy (kg LW ha^{-1})	Weight Gain (kg LW ha^{-1})
23/10/2015–22/03/2016	152	22.7	4197.2	40	885.9	136.8
29/09/2016–30/03/2017	183	33.2	4951.1	40	923.4	146.4
25/10/2017–22/03/2018	149	30.4	4777.0	35	1262.4	119.2
29/09/2018–19/03/2019	172	29.2	3428.8	55	826.3	154.8
06/11/2019–21/03/2020	137	29.2	2858.6	45	822.7	95.9

3.2. Climate and Soil Conditions

Monthly averages of meteorological variables and the climatological normal for the experimental site are presented in Figure 2. Incoming solar radiation, Rg, showed the expected seasonality for this subtropical region, with monthly mean values in December (~300 W m^{-2}) being almost three times higher than those in June (~100 W m^{-2}) (Figure 2a). The maximum hourly peaks of R_g at noon on clear days reached approximately 1200 W m^{-2} in summer and 550 W m^{-2} in winter. The highest air temperatures were recorded between December and March, with an hourly maximum of 39.5 °C. The lowest temperatures were recorded between July and September, with an hourly minimum of −2.8 °C, with frequent frost occurrences. May through September had an average temperature below the climatological annual mean, while in the other months, the temperature was higher (Figure 2b). The average monthly temperature in spring and summer remained above the climatological normal, especially in March, which registered ~3.5 °C above the average. In autumn and winter, the climatic variability was greater than in spring and summer; in June 2019, the temperature was 5.7 °C higher than the climatological average, while in June 2016, the temperature was 2.5 °C below the climatological average. Frost events also varied between the years, with only 4 events recorded in 2017 but 18 events in 2019, although this year was not the one with the lowest average air temperature (Table 2). The monthly average soil temperature at 0.05 m depth was generally up to 1 °C lower than the air temperature (Figure 2d).

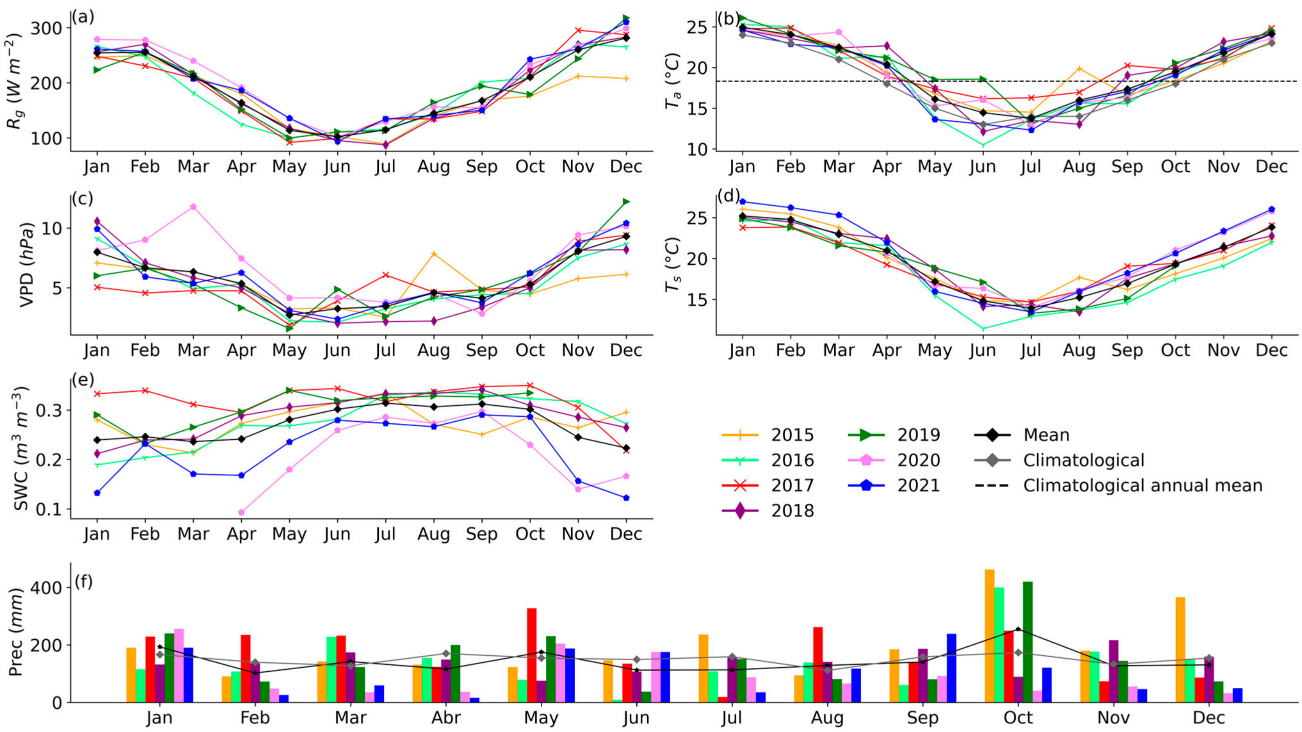

Figure 2. Monthly averages of incoming solar radiation (R_g) (**a**), air temperature (T_a) (**b**), vapor pressure deficit (VPD) (**c**), soil temperature at 0.05 m (T_s) (**d**), volumetric soil water content (SWC) (**e**), and total monthly precipitation (Prec) (**f**) from 2015 to 2021 in a natural pasture of the Brazilian Pampa biome grazed by cattle.

The annual climatological precipitation for the study region is 1797 mm. The year 2015 recorded the highest precipitation, with 551 mm (31%) above the climatological value, while 2020 recorded 702 mm (39%) below the climatological average (Table 1). The Figure 2f shows that precipitation is well distributed throughout the year without characterizing a dry or wet season.

In 2020 and 2021, the La Niña phenomenon occurred, which explains the low precipitation in the study area [48]. The vapor pressure deficit (VPD) significantly varied between the months and years, with higher values in the summer and lower ones in the winter (Figure 2c). The precipitation variability affected the soil water content (SWC), with extremes of 0.10 and 0.35 $m^3\ m^{-3}$ throughout the study period (Figure 2e). Zimmer et al. [49] estimated that SWC below 0.19 $m^3\ m^{-3}$ represents the dry soil condition at this experimental site. In all years, the period from May to October was considered wet except for May 2020. Although most of the summer months were also considered wet, 2020 and 2021 had periods of dry soil when the monthly average soil temperature was higher than the air temperature, especially in 2021.

Table 2. Periods, number of days, incoming solar radiation (R_g), air temperature (T_a), precipitation (Prec), net ecosystem exchange (NEE), gross primary productivity (GPP), and ecosystem respiration (Reco) of a subtropical natural pasture of the Pampa biome grazed by cattle. The averages of R_g, T_a, and the accumulated Prec, NEE, GPP, and Reco were performed annually in the warm and cold seasons (according to the evaluation periods of cattle grazing in the area). EC uncertainty is included in the annual NEE.

Periods	No. of Days	R_g (W m^{-2})	T_a (°C) [No. of Frost]	Prec (mm)	NEE (g C m^{-2})	GPP (g C m^{-2})	Reco (g C m^{-2})
Warm season							
23/10/2015–22/03/2016	152	224.5	23.1	933.8	−164.5	1664.9	1500.4
29/09/2016–30/03/2017	183	238.6	22.7	1420.8	−209.9	2245.3	2035.4
25/10/2017–22/03/2018	149	270.0	23.3	560.0	−220.5	1922.2	1701.7
29/09/2018–19/03/2019	172	245.1	23.5	941.4	−290.8	2267.0	1976.2
06/11/2019–21/03/2020	137	280.0	24.0	495.2	−220.3	1867.4	1647.1
29/09/2020–21/03/2021	174	259.7	22.5	409.6	−348.8	2049.9	1701.1
Cold season							
12/03/2015–22/10/2015	225	142.6	17.5 [12]	1434.0	−58.3	1354.0	1295.7
23/03/2016–28/09/2016	190	132.6	15.3 [11]	663.4	13.3	834.4	847.7
31/03/2017–24/10/2017	208	135.9	17.9 [4]	1210.4	−49.5	1333.1	1283.5
23/03/2018–30/09/2018	192	126.4	16.5 [16]	904.6	189.5	989.4	1178.9
20/03/2019–05/11/2019	231	148.8	17.9 [18]	1259.2	9.3	1425.5	1434.9
22/03/2020–28/09/2020	191	147.8	16.3 [15]	654.8	128.5	828.3	956.8
22/03/2021–22/09/2021	185	139.2	15.6 [7]	722.6	NA	NA	NA
Annual							
2015	365	174.6	19.6	2347.8	−385.3 ± 19	2838.5	2453.2
2016	366	186.0	18.9	1722.8	−120.7 ± 7	2902.7	2781.9
2017	365	186.3	20.3	2114.6	−280.2 ± 31	3418.4	3138.3
2018	365	188.7	19.6	1721.6	−122.5 ± 8	3236.9	3114.4
2019	365	188.8	20.2	1853.6	−82.0 ± 5	3314.7	3232.7
2020	366	205.2	19.4	1130.4	−254.7 ± 14	2853.5	2598.7

NA—not available.

3.3. CO_2 Flux Dynamics

The half-hourly NEE values for each month throughout the study period and their average monthly cycle are shown in Figure 3. The largest hourly variabilities in the NEE occurred in the spring and summer. The peak of the NEE absorbed in the daytime was approximately −44 µmol CO_2 m^{-2} s^{-1}, occurring in February. In the monthly mean cycle, February showed the highest mean values of the diurnal absorption peak (approximately −21.6 µmol CO_2 m^{-2} s^{-1}) and the highest mean values of the nocturnal emission (approximately 10 µmol CO_2 m^{-2} s^{-1}). June showed the lowest monthly mean values of peak diurnal absorption (approximately −7.0 µmol CO_2 m^{-2} s^{-1}) and the lowest monthly mean values of nocturnal emission (approximately 4.0 µmol CO_2 m^{-2} s^{-1}), which are similar to the July diurnal mean.

In the monthly averages, GPP and Reco showed strong seasonal variability. The monthly mean values of GPP and Reco were around 3.6 and 2.5 times higher in the summer (January: GPP = 420 g C m^{-2} month^{-1} and Reco = 376 g C m^{-2} month^{-1}) than in winter (July: GPP = 117 g C m^{-2} month^{-1} and Reco = 149 g C m^{-2} month^{-1}), respectively (Figure 4). The most significant variabilities among the values for a given month occurred in the summer; for instance, in January, the GPP ranged from 312 g C m^{-2} month^{-1} in 2021 to 487 g C m^{-2} month^{-1} in 2018, and Reco ranged from 256 g C m^{-2} month^{-1} in 2021 to 460 g C m^{-2} month^{-1} in 2018. The lowest variabilities occurred in the cooler months, for example, in June, with GPP between 94 g C m^{-2} month^{-1} in 2018 and 141 g C m^{-2} month^{-1} in 2015 and Reco between 115 g C m^{-2} month^{-1} in 2018 and 144 g C m^{-2} month^{-1} in 2015 and 2017. In general, in the spring and summer, the GPP was greater than the Reco, resulting in a Reco/GPP ratio = 0.88; between autumn and winter, Reco was greater than the GPP, resulting in Reco/GPP = 1.03. The annual average of Reco/GPP was 0.93, showing that 93% of what was absorbed via photosynthesis was emitted in the form of ecosystem respiration. In absolute values, the largest differences between the GPP and Reco occurred in the spring and summer months.

The seasonality of GPP and Reco resulted, on average and throughout the seven years analyzed, in CO_2 absorption for seven months (September to March), represented by negative NEE. In contrast, the system was a CO_2 emitter in the remaining five months (April to August), as represented by positive NEE. However, April and August were, on average, nearly neutral, with greater variability in April (70 g C m^{-2} $month^{-1}$ in 2018 and -20 g C m^{-2} $month^{-1}$ in 2021) (Figure 4). Only July was an emitter in all years, while the months between September and January were all absorbers, except November 2019. On average, November was the month with the highest CO_2 absorption, with a daily average of -2.08 g C m^{-2} d^{-1}, and June was the month with the highest emission, with a daily average of 1.08 g C m^{-2} d^{-1}.

Although the dynamics of CO_2 were repeated in all the years evaluated, there were exceptions, which were likely due to the climatic variations in this subtropical region and/or the management of the animals. For example, in all the years assessed, the NEE became positive starting in May, except in 2016 (Figure 4c), which was positive in March and April, although it became negative in May and positive again from July to August. Between 17 April and 8 May, a strong cold front swept the region, decreasing the mean daily temperature by ~20 °C for about 10 days and sharply reducing Reco; nonetheless, the GPP was not significantly affected, and the NEE became negative in May 2016 (Figure 4). Unlike the other years analyzed, an atypical NEE value was observed in November 2019, which was very close to neutral (Figure 4). This may have been related to the higher ecosystem respiration (around 130 g C m^{-2} $month^{-1}$ above the mean value for November), as the GPP was similar to the mean values for this month in the other years. In January 2021, GPP and Reco were lower than in the other years, although this did not lead to any differences in the NEE, which was close to the average value of the other years. This behavior may be related to low soil moisture since, in this month, the SWC was the lowest of all the months of January analyzed in the series.

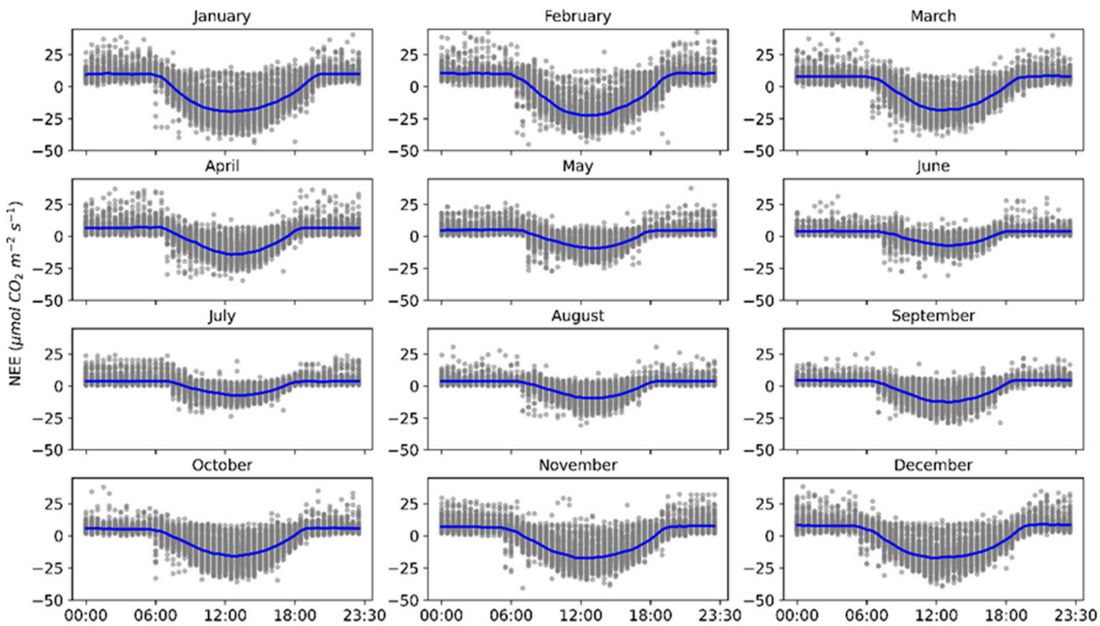

Figure 3. Net CO_2 exchange (NEE) of the natural pasture of the Pampa biome grazed with cattle quantified every half hour (gray points) from 2015 to 2021. The blue line represents the average monthly cycle.

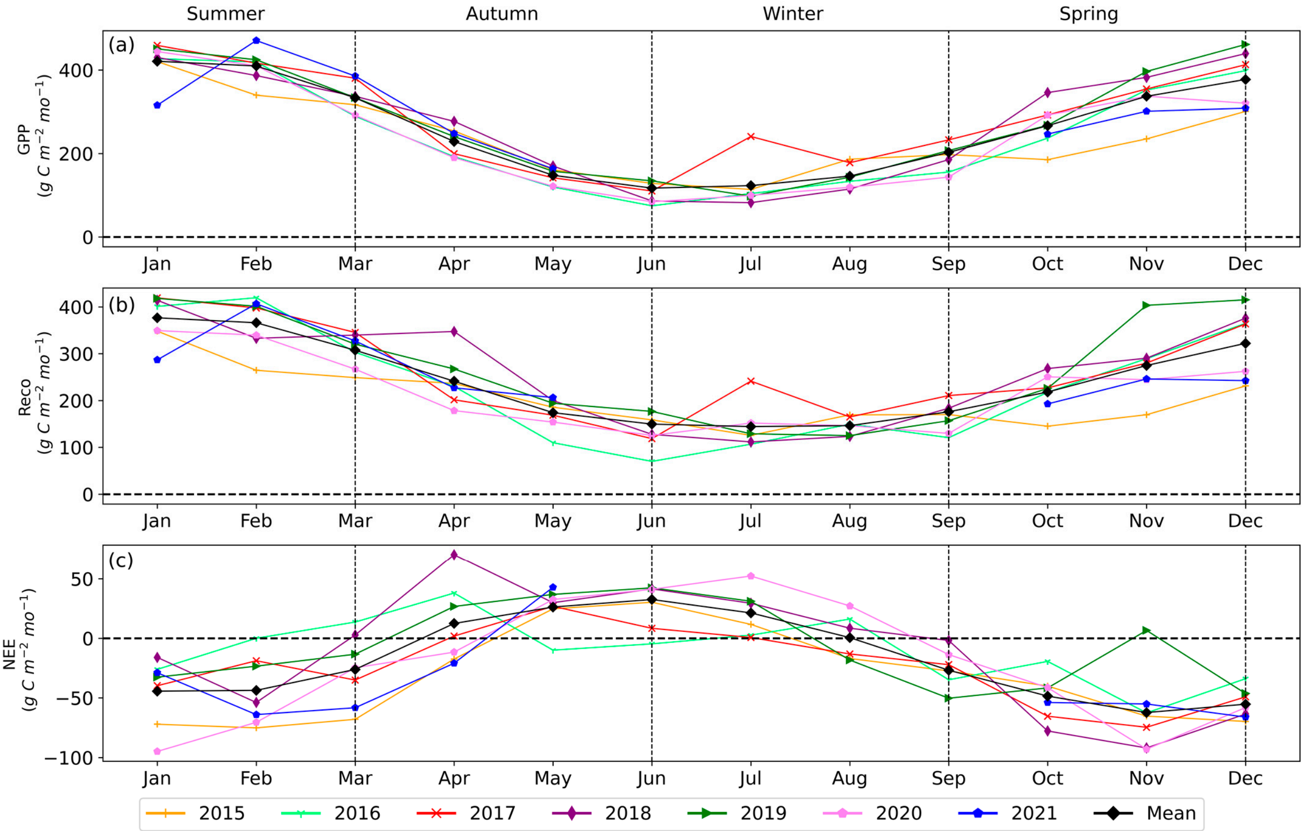

Figure 4. Monthly cumulative values (in g C m^{-2} month^{-1}) of gross primary productivity (GPP) (**a**), ecosystem respiration (Reco) (**b**), and net ecosystem exchange (NEE) (**c**) in a natural pasture of the Pampa biome grazed with cattle from 2015 to 2021.

3.4. Cumulative NEE

The ecosystem behaved as a carbon sink with, on average, −207.6 g C m^{-2} year^{-1} between 2015 and 2020, which were the 6 years of complete data analyzed, with higher absorption in 2015 and lower absorption in 2019 (Table 2). By analyzing the periods according to cattle management, one can observe that all warm seasons were CO_2 sinks, with an average value of −242.5 g C m^{-2}. In contrast, the cold seasons were CO_2 sources, with an average of 38.8 g C m^{-2}, except for the cold seasons of 2015 and 2017, which were sinks (Table 2).

Figure 5a shows the accumulated NEE for each year and climate season. All years were sinks in the annual calculation, but a large variability in the accumulation pattern between years was noted. The smallest annual sink was in 2019, characterized by being the smallest in spring and one of the largest sources in autumn. The largest annual sink was in 2015, driven by autumn and winter neutral and large summer absorption. By analyzing the accumulated NEE in each season from the respective days of the solstices (summer and winter) and equinoxes (spring and autumn) in the Southern Hemisphere, we can observe that the slope pattern of the curve is quite similar in the springs, whereas these patterns showed variability in the summer, autumn, and winter (Figure 5b–e). The system was always a sink in the springs and summers and a source in the autumns and winters, except for the autumns and winters of 2015 and 2017, which were sinks or nearly neutral.

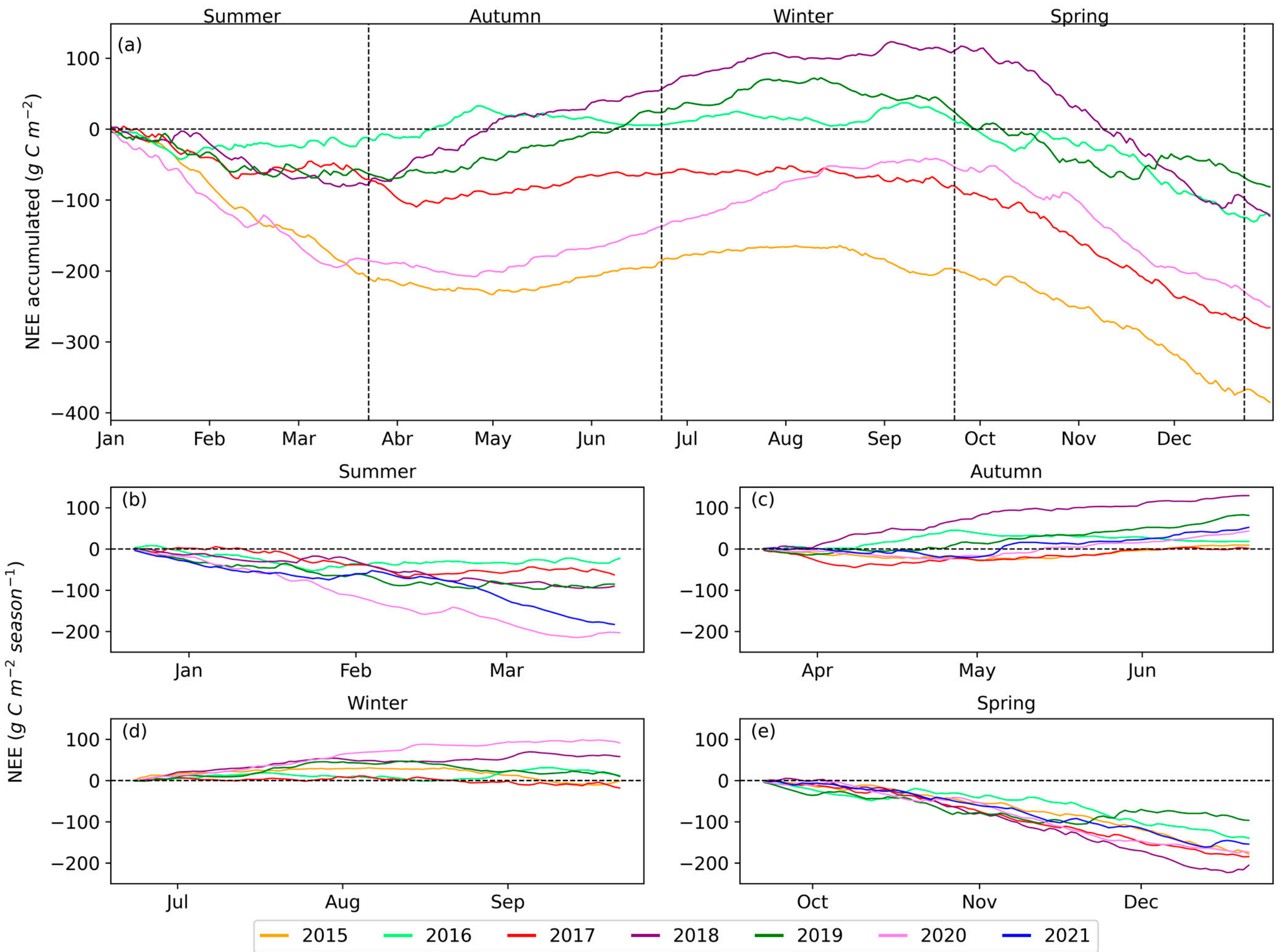

Figure 5. Cumulative annual and seasonal net ecosystem exchange (NEE) from 2015 to 2021 in a subtropical natural grassland of the Pampa biome grazed with cattle. (**a**) Annual; (**b**) Summer; (**c**) Autumn; (**d**) Winter; (**e**) Spring.

3.5. Environmental Controls of NEP, GPP, and Reco

The statistical relationships between the NEE and meteorological, soil, and management variables are presented in Table 3. The NEE correlates strongly negatively with R_g (R = −0.8) on the monthly scale, followed by T_a and VPD (R = −0.6). The SWC and Prec show weak correlations with NEE, likely due to the soil being classified as wet for most of the period and precipitation not showing seasonality. On the annual scale, NEE shows moderate correlations with T_s and Prec and weak correlations with R_g, T_a, VPD, and SWC (R < 0.3). For the meteorological seasons, correlations are significant in summer and spring, with only T_s strongly negatively correlated with the NEE in spring. For autumn and winter, the correlations with T_a, VPD, T_s and SWC are not significant, while R_g and Prec present significant but weak correlations, except for Prec in autumn, which also moderately correlates with the NEE. Similar behavior is observed in the two management seasons, where only Prec correlates significantly with the NEE (R = −0.6) in the cold season, while in the warm season, all variables are weakly correlated but significant. Therefore, no single variable can explain the interannual and interseasonal variability in the NEE. The pasture height variable moderately correlates (R = −0.6) with the NEE in the warm season (Figure S1). The anomalies of the NEE in relation to the monthly average were analyzed comparatively against the behavior of environmental variables, seeking to identify possible causes of interseasonal variability. Once again, no strong correlations were found between these anomalies (R < 0.2), as illustrated in Figure S2.

Table 3. Pearson's correlation coefficient (R) between NEE and meteorological, soil, and management variables (Table 1) for different scales in a natural pasture of the Brazilian Pampa biome grazed with cattle from 2015 to 2021 for p-value < 0.001 and (ns) for p-value > 0.05.

Variables	Monthly Scale	Annual Scale	Meteorological Seasons				Management Seasons	
			Spring	Summer	Autumn	Winter	Warm	Cold
R_g	−0.8	0.3	0.2	−0.1	0.2	−0.2	−0.3	−0.3 (ns)
T_a	−0.6	−0.1	−0.1	−0.4	0.6 (ns)	−0.7 (ns)	−0.4	−0.5 (ns)
VPD	−0.6	−0.2	0.5	−0.3	−0.2 (ns)	−0.6 (ns)	0.0	−0.5 (ns)
T_s	−0.5	−0.6	−0.8	0.4	0.8 (ns)	−0.1 (ns)	0.0	−0.1 (ns)
SWC	0.2	0.2	0.4	−0.5	0.1 (ns)	−0.4 (ns)	−0.3	−0.3 (ns)
Prec	−0.1	−0.4	0.1	0.2	−0.5	−0.2	−0.1	−0.6
Pasture height		-	-	-	-	-	−0.6	-
Total dry mass		-	-	-	-	-	0.4	-
Weight gain		-	-	-	-	-	−0.3	-

4. Discussion

No chemical or organic fertilizers are applied in the natural pasture area of this study, only manure and urine from grazing animals. No sowing or forage cutting is performed with machines, and the cattle in the grazing area did not receive supplementation during the study period. Therefore, the carbon input into the ecosystem is only through carbon uptake by plants or autotrophic microorganisms. This pasture represents the traditional cattle production system in the Brazilian Pampa biome, which covers roughly 6.5 million hectares of land, with an estimated herd of 5.5 million cattle. Another characteristic of this biome is that it is located in a subtropical region and therefore subject to significant meteorological variations on seasonal and yearly scales. During the data collection period, the climatic phenomena El Niño/La Niña occurred, which are responsible for higher/lower precipitation in this region, respectively. According to the ENSO classification, 2015 and 2016 were marked by the moderate action of the El Niño phenomenon, providing above-average precipitation. In 2020 and 2021, the La Niña phenomenon occurred, which explains the low precipitation in the study area [48]. Therefore, the data presented in this work reflect these climatic variations and the consequent adjustments of animal stocking rates in the area, resulting from the influence of climatic variations in pasture growth.

The CO_2 dynamics of this pasture show marked seasonality, with higher GPP and Reco values in the spring–summer and lower in the autumn–winter (Figure 4). This behavior results from the seasonal variation in solar radiation and air temperature variation in this subtropical region. The dominant herbaceous plants in the natural pasture of the Brazilian Pampa biome are of summer growth [2]. In the autumn–winter seasons, they decrease their photosynthetic rate and accumulate senescent material. During autumn, the GPP and Reco values gradually decrease in all the analyzed years, reaching minimum values in June and July, with the lowest incidence of solar radiation and lower air temperature; this period is also marked by frost (Table 2). At the end of winter, solar radiation intensifies, gradually increasing the temperature, which is associated with regular precipitation, and increases the plant growth rate [50]. At the end of winter, GPP and Reco values increase, and the ecosystem begins to absorb CO_2 (i.e., NEE negative in Figure 4c).

In the six years evaluated, the pasture in the rotational system behaved as a CO_2 sink, with an average NEE of -207.6 g C m^{-2} y^{-1} $\pm$ 118.0 g C m^{-2} $year^{-1}$. These data have a high degree of reliability since the total uncertainty on the EC NEE data was below 10%, with a maximum of 31 g C m^{-2} y^{-1}, thereby corroborating [37,44,51]. Other studies with the EC method have shown that grassland ecosystems have mostly behaved as CO_2 sinks. Plant growth is also stimulated as the animals remove part of the leaves on the soil surface, leading to a more significant GPP increase than Reco [15]. Rutledge et al. [52] found an average NEE of -165.3 ± 50.5 g C m^{-2} y^{-1} (2008–2011) in an intensively managed pasture with fertilizer addition and year-round rotational grazing in a temperate climate region of New Zealand. Gourlez de la Motte et al. [51] reported an average NEE of

-141 g C m^{-2} y^{-1} over five years (2010–2015) in a permanent pasture in southern Belgium, which was managed with fertilizer application and high stocking rates. Gomez-Casanovas et al. [19] investigated the effect of grazing on C fluxes in subtropical Florida (US) grasslands and found that in the grazed area, a sink of -136 ± 6 g C m^{-2} y^{-1} occurred, while the ungrazed area had an emission of 83 ± 4 g C m^{-2} y^{-1}. Feigenwinter et al. [53] analyzed an intensively managed, permanent grassland in Switzerland for over 16 years, finding an average NEE of -284 ± 115 g C m^{-2}y^{-1}. By analyzing various ecosystems based on 554 site years of data, Baldocchi et al. [54] revealed that the mean NEE was -200 g C m^{-2} y^{-1} with a standard deviation of 163 g C m^{-2} y^{-1}. Our findings, with 6 years of uninterrupted data, despite the variations, demonstrated that the absorptions of pasture in the Brazilian Pampa biome might be higher than those observed elsewhere, thereby highlighting the potential of this natural ecosystem as an important CO_2 sink while preserving the original vegetation and producing high-quality meat.

Baldocchi et al. [54] identified that grasslands and evergreens (humid conifer forests) are functional types where year-to-year changes in Reco were greater than in GPP. The vulnerability of grassland ecosystems to transition from being carbon sources to sinks could increase due to additional disturbances in carbon fluxes resulting from factors such as climate and environmental changes. Our findings showed a slope of these changes very close to 1, although dGPPdt > dReco/dt (slope = 0.98, Figure 6). The average of the NEE anomalies between the years was positive, being 26.12 g C m^{-2} y^{-1} (Table 2), indicating that the ecosystem is decreasing its ability to absorb carbon. It appears that climatic anomalies have influenced respiration more than photosynthesis, which has modulated annual NEE variations. Our results are the first obtained in the Brazilian Pampa biome by the EC method and need to be complemented with further studies; nonetheless, our findings indicate that this ecosystem may be susceptible to climate change since we detected a very close relationship between respiration and photosynthesis processes in CO_2 exchange. Notably, these evaluations occurred in years of El Niño and La Niña phenomena, showing that the variations found in this work represent the different climatic conditions. However, ecosystem adaptations to climate change can occur naturally and in relation to management, reinforcing the need to increase flux tower measurements over the years.

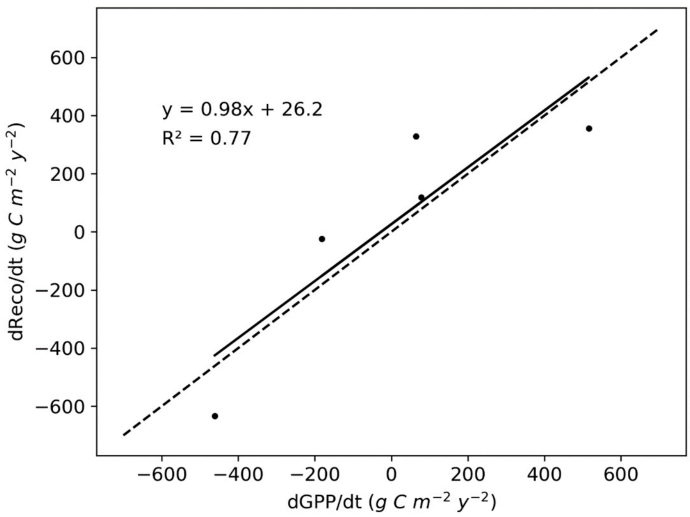

Figure 6. Relation between year-to-year changes in GPP (dGPP/dt) and Reco (dReco/dt). Solid line represents the linear fit of the data. For reference, the dashed black line represents 1:1 relation.

Grazing management was performed at intervals of 750 DD. This association between pasture management and weather conditions makes it difficult to distinguish their isolate impact on the NEE. For instance, if there are high temperatures and greater precipitation in a certain period of the year, the more significant plant growth is compensated by more intense grazing due to the pasture's improved nutritional quality. The opposite occurs in periods of low pasture growth when grazing is less intense, and for this reason, no relationships between interannual variability in NEE and weather and animal management variables were found in our analysis (Figure S2). This coupling between weather conditions and management could also partly explain the low NEE interannual variability in the main animal production period (warm season, Tables 1 and 2) [53].

Nevertheless, this seems to be a typical characteristic of grasslands [55,56]. Gourlez de la Motte et al. [51] analyzed the carbon balance of permanent grasslands in Belgium and reported not finding any correlation between weather variables anomalies and NEE anomalies. Our study also found no relationship between animal productivity and NEE, although the relationships between pasture height and NEE, GPP, and Reco are linear (Figure S1). The periods of the highest CO_2 uptake occurred when the pasture was the highest (i.e., 28–35 cm; Tables 1 and 2). Other researchers have indicated that these grazing heights increased animal production and the mitigation of the environmental impact of ranching in the subtropical region of Brazil [57]. However, Carnevalli et al. [58] related higher pasture heights with lower photosynthetic rates due to an increased percentage of older leaves and a more significant accumulation of stems and dead material. In this situation, Reco remains high while GPP decreases. In our study, Reco and GPP increased as pasture height increased, although GPP showed greater increases than Reco (Figure S2). This demonstrates that the cattle management was correct, allowing the pasture to grow and preventing its senescence. Therefore, grazing should not be performed at heights above those indicated as it will also reduce the animals' weight gain due to the pasture's lower nutritional quality [57]. A good-quality pasture provides an adequate cattle nutrition and greater weight gain.

In this study, the adequate adjustment of the animal load provided a weight gain of 130.6 kg LW ha^{-1} in the average of the warm seasons of the 5 years evaluated (Table 1). This result is 87% higher than the average of Rio Grande do Sul State, which is 70 kg LW ha^{-1} [2]. The average stocking rate of animals in the experimental area during the warm season was 944.1 kg LW ha^{-1}, corresponding to 2.1 AU ha^{-1} (1 AU, animal unit, is equivalent to 450 kg LW). This stocking rate is more than double the one used in cattle production systems on native pastures in the Pampa biome, which is approximately 1 AU [2]. This indicates that rural producers can improve pasture management in the Pampa biome to increase the animal load and meat production per area without degrading the pasture.

Our findings demonstrate that the Pampa Biome's natural pastures are vital in absorbing CO_2 from the atmosphere when well managed. Evidence has also shown that grazing can mitigate CH_4 emissions from ruminants if combined with appropriate pasture management practices [59–61]. Due to equipment deficiency, unfortunately, we did not assess CH_4 emissions from this ecosystem. Nevertheless, Cezimbra et al. [59] estimated the emission of 151 g CH_4 $animal^{-1}$ day^{-1} (beef cattle) in a natural pasture ecosystem of the Brazilian Pampa biome, 300 km away from our site, under very similar climate, soil, vegetation, and animal conditions. Thus, we estimated an average annual CH_4 emission in our system considering the average number of animals in each season (warm or cold) and the number of days of each season (Table 2), resulting in 208.1 kg CH_4 y^{-1} ha^{-1} (151 g CH_4 $animal^{-1}$ day^{-1} $\times$ 4.4 animal ha^{-1} $\times$ 158 days + 151 g CH_4 $animal^{-1}$ day^{-1} $\times$ 3.3 animal ha^{-1} $\times$ 207 days). Converting the CH_4 into CO_2-eq (1 g CH_4 = 28 g CO_2-eq, 100 years' time horizon not considering the climate–carbon feedbacks, as per IPCC, 2013), cattle were responsible for emitting 5826.8 kg CO_2-eq ha^{-1}. With this methane emission rate, the global warming potential (GWP) of our study (GWP = NEE_{CO2} + $CH_{4CO2\text{-}eq}$) can be estimated, and converting NEE into CO_2 (-207.6 g C m^{-2} $year^{-1}$) results in -7612.0 kg CO_2 ha^{-1}. Thus, the GWP of the system was -1785.2 kg CO_2-eq ha^{-1}.

These data imply that adequate management of the natural pastures of the Pampa biome would offset the methane emissions by cattle grazing, resulting in an absorption balance of roughly 1800 kg CO_2-eq ha^{-1} y^{-1}, which represents 1.8 carbon credits. The carbon credit is a new "currency" used to offset emissions by productive sectors, and the credits generated by beef production in the Pampa biome could be used as a form of financial compensation for environmental services and the environmental marketing of the meat produced in this system, which would help preserve the original vegetation of this biome.

The results of this study represent a counterpoint to the common sense that Brazilian meat production comes from pastures in deforested areas. In the Amazon, located in northern Brazil, numerous studies have shown that converting forests into cultivated pastures produces CO_2 emissions [62,63]. However, in the Pampa biome in southernmost Brazil, meat production occurs in natural pastures with European breeds and can absorb CO_2 when the pasture is well managed. The value of the secular activity of raising cattle in the Pampa should be properly acknowledged and not confused with other farming systems in Brazil as it is one of the few beef production systems in the world that has the potential to absorb C.

5. Conclusions

Cattle ranching on natural pastures in the Pampa biome under rotational management is a sink of CO_2 from the atmosphere, ranging from -82.0 ± 5 to -385.3 ± 19 g C m^{-2} year^{-1} in the six years evaluated by the eddy covariance method. Strong seasonal variability was identified and mainly related to incoming solar radiation. The ecosystem was a CO_2 sink in the spring/summer and a source of CO_2 in the autumn/winter. As the grazing rotation of the animals in the area respected a 750 DD interval, the weather conditions were coupled to the pasture management, making it difficult to distinguish the impact of both weather and grazing in NEE interannual variability, suggesting this coupling can be responsible for NEE variability. Therefore, with proper management, beef cattle production in the Pampa biome's natural pasture is a sustainable food production system, combining the conservation of natural vegetation, high-quality meat production and CO2 sequestration.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16093672/s1, Figure S1: Relationship between pasture height and net ecosystem exchange (NEE) (a), gross primary productivity (GPP) (b), and total ecosystem respiration (Reco) (c) during warm season periods in a natural pasture of the Brazilian Pampa biome grazed by cattle; Figure S2: Correlation between anomalies in monthly NEE and anomalies in monthly incoming solar radiation (R_g) (a), air temperature (T_a) (b), vapor pressure deficit (VPD) (c), soil temperature at 0.05 m (T_s) (d), volumetric soil water content (SWC) (e), and precipitation (Prec) (f) in a natural pasture of the Brazilian Pampa biome grazed by cattle; Figure S3: Annual correlation between gross primary productivity (GPP) and weight gain of cattle in the warm season in a natural pasture of the Brazilian Pampa biome in the warm season periods.

Author Contributions: A.M., R.A.G., G.P.V. and T.B. collected, processed, and analyzed the eddy covariance data. L.M. collected the management variables. D.R.R., A.M. and R.J.S.J. wrote the manuscript. D.R.R. and F.L.F.d.Q. conceived and designed the experiments. D.R.R. supervised and advised all the research work that led to this paper. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

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