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Alecsander Mergen

VARIABILIDADE INTERANUAL DOS FLUXOS DE CO_2 EM UMA PASTAGEM NATURAL NO BIOMA PAMPA BRASILEIRO

Santa Maria, RS
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Dissertação de Mestrado apresentada ao Programa de Pós-Graduação em Física da Universidade Federal de Santa Maria (UFSM, RS), como requisito parcial para a obtenção do título de **Mestre em Física**.

Orientador: Dra. Débora Regina Roberti

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RESUMO

VARIABILIDADE INTERANUAL DOS FLUXOS DE CO_2 EM UMA PASTAGEM NATURAL NO BIOMA PAMPA BRASILEIRO

AUTOR: Alecsander Mergen
ORIENTADORA: Dra Débora Regina Roberti

O Pampa é um bioma da América do Sul, localizado na região sul do Brasil, Uruguai e parte da Argentina, sua vegetação é composta principalmente por gramíneas intercaladas por pequenas matas de galeria e mata ciliar. A complexidade deste bioma se deve a vegetação diversificada, composta em sua maioria por gramíneas do tipo C4 em coexistência com o tipo C3. A utilização dos campos nativos do bioma Pampa para pecuária vem ocorrendo desde o século XVII, com a introdução dos bovinos pelos Jesuítas, e é visto hoje como a principal forma de conservação da paisagem deste bioma. Estudos realizados sugerem que as pastagens naturais podem atuar como importantes sumidouros de dióxido de carbono (CO_2) atmosférico, mas do ponto de vista econômico, a produtividade pecuária dos campos deve ser melhorada. Neste sentido, têm se buscado maximizar a produtividade pecuária, reduzindo os impactos ambientais ao Pampa nativo. Um manejo que tem mostrado aumento na produtividade é o manejo rotativo, que consiste em dividir a área total em pequenas subdivisões pelas quais o rebanho será direcionado uma após a outra, de modo a manter uma quantidade de biomassa que conserve a diversidade florística dos campos com uma carga animal adequada. Neste trabalho analisamos as trocas liquidas do ecossistema de CO_2 (NEE) em uma área de pecuária com manejo rotativo no bioma Pampa no sul do Brasil. Para isso, usamos seis anos de dados obtidos através do método Eddy Covariance (EC) em uma área experimental de manejo rotativo. O ecossistema atuou como sumidouro de CO_2 atmosférico, com acumulados anuais no período de estudo variando de -101.0 ± 5 gC m^{-2} ano^{-1} a -381.2 ± 5 gC m^{-2} ano^{-1}, com valor médio nos 6 anos de -227.1 gC m^{-2} ano^{-1}. A variabilidade interanual do NEE não apresentou relação com anomalias nas variáveis climáticas ou com a produção de gado, provavelmente por este sistema de manejo depender das condições de produção de forragem, que por sua vez está interrelacionada com as condições climáticas. Esses resultados são importantes para entender a dinâmica de troca de CO_2 e mostrar que o bioma Pampa pode ser um importante sumidouro de CO_2 atmosférico, produzindo proteína animal de qualidade e preservando a fauna e flora local.

Palavras-chave: Bioma Pampa. Sistema rotativo. Troca liquida de CO_2. Respiração do ecossistema. Produção primária bruta.

ABSTRACT

INTERANNUAL VARIABILITY OF CO_2 FLUXES IN A NATURAL PASTURE IN THE SOUTHERN BRAZILIAN PAMPA BIOME

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The Pampa is a biome in South America, located in the southern region of Brazil, Uruguay and part of Argentina, its vegetation is mainly composed of grass interspersed with small gallery forests and riparian forests. The complexity of this bio is due to grass diversity, mostly by C4 species coexisting with the C3 type. The use of native fields of the Pampa biome for livestock has been taking place since the 17th century, with the introduction of cattle by the Jesuits, and is seen today as the main form of conservation of the landscape of this biome. Studies carried out suggest that natural pastures can act as important sinks of atmospheric carbon dioxide (CO_2), from an economic point of view, livestock productivity in the fields must be improved. In this sense, efforts have been made to maximize livestock productivity, reducing environmental impacts on the native Pampa. A management that has shown an increase in productivity is rotational management, which consists of dividing the total area into small subdivisions through which the herd will be directed one after the other, in order to maintain an amount of biomass that conserves the floristic diversity of the fields with an adequate animal load.

In this work we analyze the net exchange of CO_2 ecosystem (NEE) in a livestock area with rotational management in the Pampa biome in southern Brazil. For this, we used six years of data obtained through the Eddy Covariance (EC) method in an experimental area of rotational management. The ecosystem acted as a sink of atmospheric CO_2, with annual accumulations in the study period ranging from -101.0 ± 5 gC m^{-2} ano^{-1} a -381.2 ± 5 gC m^{-2} ano^{-1}, with an average value over 6 years of -227.1 gC m^{-2} $year^{-1}$. The interannual variability of NEE was not related to anomalies in climatic variables or to livestock production, probably because this management system depends on forage production conditions, which in turn are interrelated with climatic conditions. These results are important to understand the dynamics of CO_2 exchange and show that the Pampa biome can be an important atmospheric CO_2 sink, producing quality animal protein and preserving the local fauna and flora.

Keywords: Pampa biome. Rotating system. Net CO_2 exchange. Ecosystem respiration. Gross primary production.

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LISTA DE ABREVIATURAS E SIGLAS

CLA	Camada Limite atmosférica
GHG	Gases do efeito estufa
GEE	Gases do efeito estufa
EC	Covariância dos Vórtices
NEE	Fluxo líquido de CO_2
Reco	Respiração do ecossistema
GPP	Assimilação bruta de CO_2
CO_2	Dióxido de Carbono
C	Carbono
H_2O	Água
CH_4	Metano
N_2O	Óxido nitroso
LE	Fluxo de calor sensível
H	Fluxo de calor latente
G	Fluxo de calor no solo
Rn	Saldo de radiação
u_*	Velocidade de fricção
B	Razão de Bowen
Rg	Radiação solar incidente
PAR	Radiação fotossinteticamente ativa
VPD	Déficit de vapor de pressão
T	Temperatura do Ar
u, v, w	Componentes da velocidade do vento
K ↓	Onda curta incidente
K ↑	Onda curta refletida
L ↓	Onda longa incidente
L ↑	Onda longa refletida
MDV	Mean Diurnal Variation
MDS	Marginal distribution sampling
LUT	Look-up table
NLR	Non-linear regression
MDC	Mean diurnal course

K	Kelvin

SUMÁRIO

1 INTRODUÇÃO GERAL

O efeito estufa é um fenômeno natural responsável pela manutenção da temperatura no planeta. Os gases do efeito estufa (GEE), tais como o CO_2, CH_4 e N_2O, são responsáveis por interagir com a radiação de onda longa, na faixa do infravermelho, que é emitida da superfície 0da terra para a atmosfera, e reemitida novamente para a superfície terrestre, impedindo a perda de calor e aumentando a temperatura (Liou, 2002). O CO_2 é um dos principais gases do efeito estufa (Wu et al., 2018) e a taxa de aumento na sua concentração teve acréscimo significativo desde a revolução industrial, atingindo cerca de 400 ppm na última década (Knutti et al., 2013). Assim, o aumento da concentração de CO_2 na atmosfera pode intensificar o aquecimento do planeta como mostrado em diversos estudos (Kandel, 1981; Kuhn and Kasting, 1983; Sohn et al., 2019). De uma perspectiva global, as emissões de CO_2 antropogênicas, especialmente consumo de energia baseado em combustíveis fósseis, tornaram-se o principal fator humano que impulsiona o aquecimento global (Meinshausen et al., 2009; Sari & Soytas, 2009).

O solo e a biosfera são um grande reservatório de carbono, emitindo e absorvendo CO_2 através de diversos processos biogeoquímicos. Em contraponto, manejo inadequado e mudanças de uso de cobertura do solo através do desmatamento, lavragem e queimadas para uso com agricultura ou pecuária tem contribuído para diminuição do estoque de C do solo, modificando os ecossistemas naturais (Singer & Munns, 2006; Williams & Jackson, 2007; McSherry & Ritchie, 2013; Conant et al., 2017; Abdalla et al., 2018; Whitehead et al., 2018; Wilson et al., 2018).

Neste sentido, estudos mostram que ecossistemas de pastagens naturais prestam relevante papel ambiental, fornecendo serviços de regulação climática e sequestro de carbono, além de serem utilizadas principalmente para produção de proteína animal (Nabinger et al., 2009). O Pampa é um bioma caracterizado por pastagens naturais localizado entre o sul do Brasil, Uruguai e norte da Argentina, utilizado principalmente para produção de pecuária desde a colonização por Jesuítas no século XVII (Boldrini, 2010). No Brasil, este bioma aparece apenas no sul do estado do Rio Grande do Sul (RS), onde atualmente estes campos são uma fonte de forragem para cerca de 14 milhões de animais, principalmente bovinos e ovinos (IBGE, 2020). Práticas inadequadas no manejo das pastagens podem causar degradação do solo e baixo rendimento econômico, o que, tem impulsionado a conversão de muitas áreas originalmente usadas para a produção pecuária em outros usos, como silvicultura e agricultura extensiva (Overbeck et al., 2007; Pillar et al., 2009; Maraschin, 2009). Estudos mostram que o pastejo é um importante mecanismo de manutenção da vegetação de pastagem do bioma Pampa e pode mitigar as emissões de GEE se combinado com práticas de manejo adequadas (Neely et al., 2009; Vasconcelos et al., 2018; de Souza Filho et al., 2019). Neste contexto, diferentes tipos de manejo pastoril dos animais em pastagens têm buscado encontrar equilíbrio entre a manutenção da biodiversidade vegetal e maior produtividade animal.

O sistema de manejo rotativo, utilizado na área de estudo, no qual a área é ocupada pelos animais em períodos alternados de ocupação e descanso tem mostrado produtividade acima da média do estado do RS (Barbieri et al., 2014, 2015; Kuinchtner et al., 2018). No entanto, o método de pastoreio contínuo com lotação fixa ainda é o mais utilizado nas pastagens naturais do bioma Pampa (Nabinger et al., 2009). Uma característica importante da vegetação das pastagens naturais do bioma Pampa é a coexistência com espécies de metabolismo fotossintético C3 de crescimento hibernal e C4 crescimento estival, com predominância das espécies C4 (Nabinger et al., 2000). Isto proporciona oferta de forragem em taxas maiores nos períodos quentes, e diminuição da oferta de forragem nas estações frias. O manejo pastoril, em geral é adaptado a estas condições de clima e vegetação para evitar uma degradação da pastagem nas estações frias. Como a capacidade fotossintética do ecossistema nas estações do ano varia, as trocas de CO_2 entre a superfície e a atmosfera devido a essa diversidade vegetal pode variar, e o potencial de absorção de CO_2 do ecossistema pode depender de uma interpelação entre as condições climáticas e de pastoreio. Estudos da dinâmica das trocas de CO_2 entre as pastagens do bioma Pampa e a atmosfera são necessários para contribuir aos esforços regionais de preservação e conservação da vegetação nativa, aliadas a produção animal. Conhecer o quanto este sistema emite ou absorve de CO_2, ou ainda quando ele é mais efetivo em um ou outro processo, é fundamental pra que se possam criar estratégias a serem adotadas para orientar as melhores práticas e políticas públicas, possibilidade de investimento e financiamento para produzirmos com menor impacto no ecossistema natural, e até mitigar as emissões de gases do efeito estufa do setor pecuário.

Neste contexto, um desafio técnico ainda existente é a correta estimativa das trocas de CO_2 por um determinado ecossistema. Isso ocorre pois os estudos são feitos de forma independente. Inúmeras metodologias têm sido utilizadas, dentre elas estimativas de carbono orgânico no solo, estimativa das emissões do solo com coleta de amostras de ar com câmaras próximo do solo e medidas de emissão do CH4 com equipamentos acoplados diretamente aos animais (Johnson & Johnson, 1995; Teague et al., 2016). Especificamente para as medidas ambientais das trocas de CO_2 e outros gases do efeito estufa, como um todo, o estado da arte é o método micrometeorológico de covariância dos vórtices turbulentos ou ‘Eddy Covariance’. Este método integra as trocas de CO_2 totais de um ecossistema, quantificando a absorção e a emissão pelo conjunto de organismos nele existentes. Embora o método Eddy Covariance – (EC) exija equipamentos muito sensíveis e de alto custo, ele tem a significativa vantagem de permitir medidas contínuas ao longo do tempo, sem modificação das propriedades físicas do ecossistema (solo, comportamento dos animais), que possibilitam inúmeras correlações com outras variáveis ambientais e manejo das pastagens.

Nesta dissertação medidas das trocas de CO_2 utilizando a metodologia EC em uma área de pecuária do bioma Pampa sob sistema rotativo serão utilizadas para investigar a relação entre o clima e o manejo na dinâmica do CO_2. Este trabalho, trata-se de uma continuação do estudo realizado por Acosta 2019, que analisou as trocas de CO_2 em pastagem natural do bioma Pampa, do ponto de vista climatológico, sem levar em consideração as interações do manejo pecuário empregado na área de estudo.

1.1 OBJETIVOS

1.1.1 Objetivo Geral

- Determinar a dinâmica dos fluxos de CO_2 em pastagem nativa do Pampa.
- Investigar a relação do manejo pecuário na dinâmica das trocas de CO_2.

1.1.2 Objetivos Específicos

i) caracterizar os padrões de variabilidade temporal das variáveis ambientais às quais os ecossistemas estiveram submetidos durante o período de estudo;

ii) mensurar e compreender as relações biosfera-atmosfera no que diz respeito as trocas de CO_2 entre o ecossistema e atmosfera e;

iii) estabelecer relação entre a produção animal e padrões de variação do fluxo de CO_2.

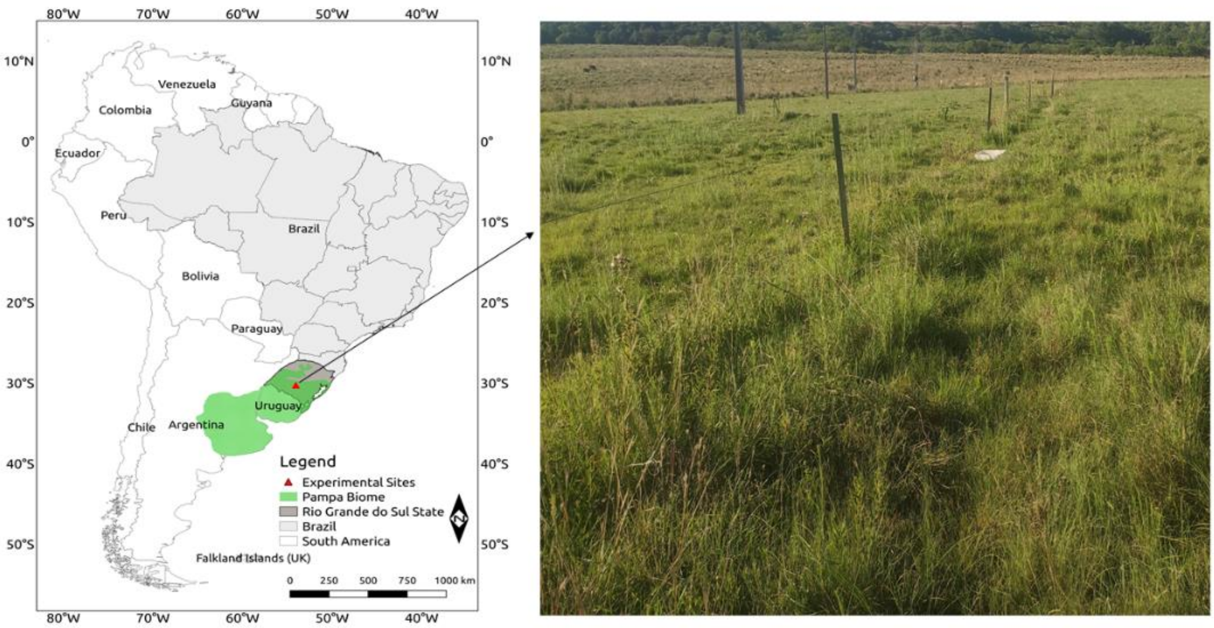
2 FUNDAMENTAÇÃO TEÓRICA

2.1 PASTAGENS E MÉTODOS DE PASTOREIO

O bioma Pampa apresenta uma vasta biodiversidade, onde seus ecossistemas destacam-se por sua multifuncionalidade e contam com 3 mil espécies de plantas, 102 espécies de mamíferos e 500 espécies de aves (Boldrini, 2009; Bencke, 2009). Somente nas pastagens naturais do sul do Brasil são encontradas cerca de 520 espécies de gramíneas e 250 espécies de leguminosas (Boldrini, 2006, 2010). Uma característica comum das pastagens desta região é a associação de espécies de crescimento estival, em especial rota metabólica C4, com espécies de crescimento hibernal C3 (Nabinger et al., 2000). Esta característica permite a criação de gado desde a colonização dos Jesuítas no século XVII. Alguns fatores são considerados os principais responsáveis por moldar a fisionomia dos campos do bioma Pampa: fatores climáticos, fatores de solo e relevo, e fatores de manejo (Boldrini, 2009).

Devido a sua vegetação predominante de campos de pastagem natural, o bioma pampa foi empregado na produção pecuária, uma das principais atividades econômicas da região (Nabinger, 2000; Overbeck et al., 2007; Nabinger, 2000). Atualmente estes campos são uma fonte de forragem para cerca de 14 milhões de animais principalmente bovinos e ovinos no sul do Brasil (IBGE, 2020). Segundo Carvalho et al. (2009), a pastagem natural é essencial para a exploração pecuária no RS e representa a principal fonte alimentar dos rebanhos de bovinos e ovinos, sendo responsável pela maior parte da alimentação destes animais. Além de sua importância econômica, as pastagens do Pampa também constituem um patrimônio genético de ampla diversidade, importante para a produção animal, sendo que possibilita uma dieta variada aos ruminantes, agregando características particulares ao produto animal proveniente desta alimentação (Nabinger, 2006). Entretanto, o pastejo realizado por esses animais, pode exercer influência na riqueza de espécies, influenciando a dinâmica da vegetação desse ecossistema (Nabinger et al., 2009).

Figura 1 – Extensão do bioma Pampa na América do Sul e exemplo pastagem natural sob manejo rotativo.



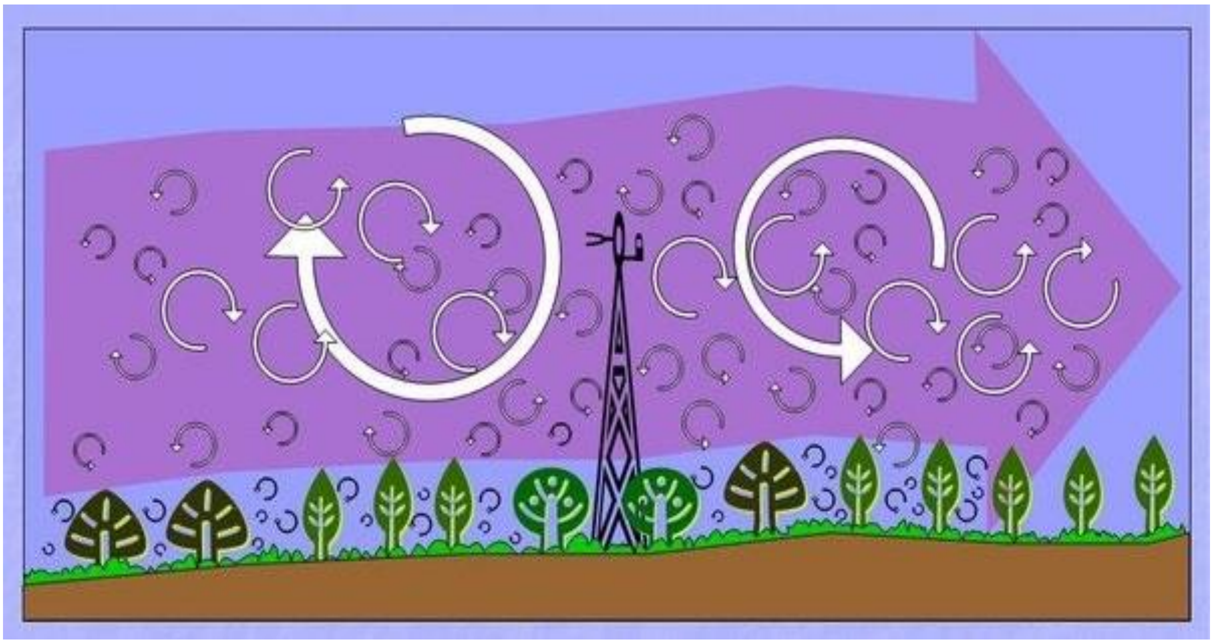
Fonte: (Autor)

2.2 ESTIMATIVA DOS FLUXOS DE CO_2

A estimativa dos fluxos de gases entre a superfície do solo e a atmosfera pode ser realizada através de uma covariância estatística entre as flutuações temporais da velocidade vertical do vento com as flutuações temporais da concentração de gases. A turbulência é o processo físico responsável por estes fluxos na atmosfera, denominado transporte turbulento e estudado principalmente na área de micrometeorologia.

O transporte turbulento de escalares na atmosfera ocorre através de movimentos circulares irregulares chamados vórtices (do inglês eddies), como ilustrado na figura 2. A turbulência é um processo que envolve vórtices sobrepostos de diferentes tamanhos. O tamanho dos vórtices pode variar de alguns milímetros até aproximadamente 3 km de diâmetro (Stull, 1988). Durante o dia a turbulência é gerada pelos forçantes térmicos e mecânicos. Nas horas mais quentes do dia a camada limite planetária (CLP) pode chegar a cerca de 2 km de altura. Já durante a noite com a formação da camada de inversão térmica provocada pelo resfriamento da superfície, caracterizada pela estabilidade com turbulência esporádica ou contínua. Essa camada atua suprimindo a turbulência, de modo que a camada limite atinge algumas centenas de metros, dependendo da intensidade dos forçantes térmicos e mecânicos.

Figura 2 – Representação dos vórtices sobre a superfície.



Fonte: Adaptado de Burba e Anderson (2010).

2.3 COVARIÂNCIA DOS VÓRTICES TURBULENTOS: TÉCNICA EDDY COVARIANCE (EC)

O monitoramento da concentração de determinado gás na atmosfera depende principalmente da quantificação dos processos de emissão e absorção destes pela superfície. Dessa forma, quantificar as emissões e absorções de um determinado gás é fundamental para compreender suas variações de concentração na atmosfera. A turbulência é o principal mecanismo de transporte na CLP, próximo da superfície. Nos últimos anos, uma técnica utilizada frequentemente para estimar esses fluxos turbulentos é a covariância dos vórtices (Eddy Covariance). Por meio dessa técnica, são estimados os fluxos verticais de gases como dióxido de carbono (CO_2), metano (CH_4), óxido nitroso (N_2O), vapor d'água (H_2O), fluxo de momentum, calor sensível e calor latente (evapotranspiração) entre a superfície e a atmosfera (Burba, 2013).

O método EC consiste no fluxo cinemático (F) de qualquer escalar (X) e é determinado pela covariância entre as flutuações turbulentas da velocidade vertical do vento (w) e esse escalar (Aubinet et al., 1999). Desta forma, o fluxo de uma certa quantidade é dado por:

$$F = \overline{\rho_a w X}, \tag{1}$$

onde que é a razão de mistura do escalar X, ρ_Q a densidade do escalar X, ρ_a é a densidade do ar e w é a velocidade vertical do vento. Usando as médias de Reynolds separamos os valores instantâneos em uma componente média e uma componente turbulenta.

$$\rho_a = \overline{\rho_a} + \rho'_a, \tag{2}$$

$$w = \overline{w} + w', \tag{3}$$

$$X = \bar{X} + X'. \tag{4}$$

As barras horizontais representam médias temporais e os apóstrofos as perturbações em relação ao valor médio. Substituindo as equações (2, 3 e 4) na equação (1), tem-se:

$$F = \overline{(\overline{\rho_a} + \rho'_a)(\overline{w} + w')(\bar{X} + X')}, \tag{5}$$

ou ainda, abrindo os termos do lado direito da equação:

$$F = \frac{\overline{(\overline{\rho_a}\overline{w}\bar{X}) + (\overline{\rho_a}\overline{w}X') + (\overline{\rho_a}w'\bar{X}) + (\overline{\rho_a}w'X') + (\rho'_a\overline{w}\bar{X}) + (\rho'_a\overline{w}X') +}}{+\overline{(\rho'_a w'\bar{X}) + (\rho'_a w'X')}} \tag{6}$$

Das propriedades das médias de Reynolds, sabemos que as médias das componentes turbulentas é zero, desta forma a equação (6) pode ser escrita como:

$$F = \overline{(\overline{\rho_a}\overline{w}\bar{X}) + (\overline{\rho_a}w'X') + (\rho'_a\overline{w}X') + (\rho'_a w'\bar{X}) + (\rho'_a w'X')} \tag{7}$$

Assumindo que as flutuações na densidade do ar podem ser desconsideradas, logo:

$$F = \overline{(\overline{\rho_a}\bar{w}\bar{X}) + (\overline{\rho_a}w'X')} \quad (8)$$

ou ainda, considerando um terreno plano, em que a média da velocidade vertical é zero, desta forma a equação é reduzida para:

$$F = \overline{(\overline{\rho_a}w'X')} \quad (9)$$

A equação (9) representa o fluxo turbulento para um escalar em um terreno plano e homogêneo, portanto um fluxo turbulento é dado pela covariância entre as flutuações turbulentas da velocidade vertical do vento e um escalar de interesse “X”. Desta forma, é possível estimar um fluxo de um escalar turbulento. Atualmente apenas os gases CO_2, CH_4, N_2O e H_2O são possíveis de serem medidos em alta frequência. Como neste trabalho não abordaremos a estimativa de CH_4, vamos expor apenas a equação para o fluxo de CO_2, calor sensível e fluxo de calor latente que podem ser escritos como:

$$Fluxo_{CO2} = \rho_a \, \overline{w'c'} \quad (10)$$

$$H = \rho_a C_p \overline{w'\theta'} \quad (11)$$

$$LE = \rho_a \lambda \, \overline{w'q'} \quad (12)$$

onde, C_p é a capacidade calorífica a pressão constante, θ' é a flutuação de temperatura virtual, λ é o calor latente de vaporização, q' e c' são as flutuações das concentrações de vapor d’água e CO_2, respectivamente (Launiainen et al., 2005).

2.4 SOFTWARE DE PROCESSAMENTO E ESTIMATIVA DOS FLUXOS

As estimativas dos fluxos através da técnica Eddy Covariance, podem ser realizadas utilizando o software EddyPro® (LI-COR Biosciences, Lincoln, Nebraska, EUA). Neste software são inseridos os dados de alta frequência obtidos pela torre de fluxo, definindo quais os sensores utilizados na coleta dos referidos dados assim como dados de apontamento destes sensores, localização da torre de fluxo e dados de altura da vegetação local.

O EddyPro® permite a determinação do intervalo de tempo das estimativas de fluxo, sendo adotada a média em bloco de 30 minutos. Além disso, algumas correções e filtros podem ser inseridas no momento das estimativas de fluxo, como: rotação dupla, que visa correções da influência da inclinação do anemômetro sônico, sendo aplicada para determinar os ângulos necessários para colocar o anemômetro sônico em um sistema de coordenadas no sentido do fluxo envolvendo uma série de duas rotações, aplicadas ao final de cada período de média turbulenta (Wilczak et al., 2001). Correções para efeitos de densidade, que consiste em transformar a medida nativa do analisador de gás em uma medida de razão de mistura. Para isso é utilizada a densidade do ar que por sua vez flutua devido às flutuações de temperatura e pressão e depende das flutuações no conteúdo de gases residuais, principalmente vapor de água. Essas flutuações precisam ser compensadas para obter uma medição de proporção de mistura adequada. Assim, uma correção apropriada deve ser adicionada (Webb et al., 1980). Correções devido a filtros de passa baixa, usando o método de (Moncrieff et al., 1997) referido como puramente analítico, faz uso de formulações matemáticas para modelar propriedades espectrais de fluxo e descrever atenuações de fluxo devido à configuração do instrumento e passa alta seguindo (Moncrieff et al., 2004), onde os espectros são expressos em função da frequência natural e dependendo principalmente do fluxo considerado (momento, calor sensível ou fluxo de gás), da estratificação atmosférica, da velocidade do vento e da altura de medição sobre o dossel. Por esta razão, os co-espectros devem ser recalculados para cada período médio. O software EddyPro calcula diferentes sinalizadores com base em testes de estado estacionário e de turbulência bem desenvolvidos (Foken et al., 2004): sinalizando valores “0” para fluxos de alta qualidade, “1” para fluxos de qualidade intermediária e “2” para baixa qualidade fluxos.

2.5 PREENCHIMENTO DE FALHAS

Lacunas nos dados de fluxo são geralmente originadas por problemas, como: falta de energia nos instrumentos, remoção devido a critérios do controle de qualidade, e ocorrência de precipitação. Para calcular com precisão os valores anuais de NEE, é necessário o preenchimento destas lacunas. Os métodos comumente usados para preencher dados ausentes incluem mean diurnal variation (MDV) (Falge et al., 2001), look-up table (LUT) (Falge et al., 2001), regressão não linear (NLR) (Falge et al., 2001; Noormets et al., 2007), marginal distribution sampling (MDS) (Reichstein et al., 2005), modelo de imputação múltipla (Hui et al., 2004) e rede neural artificial (Braswell et al., 2005; Schmidt et al., 2008).

Neste trabalho foi utilizado o pacote ReddyProc (Wutzler et al., 2018), que possui algumas destas metodologias implementadas para o preenchimento das lacunas nos dados. São utilizados dados meteorológicos como temperatura, radiação e déficit de pressão de vapor, para auxiliarem no preenchimento dos fluxos. Através de uma combinação de look-up table (LUT), mean diurnal course (MDC) e marginal distribution sampling (MDS) métodos descritos em (Wutzler et al., 2018), o pacote identifica os dados faltantes nos fluxos e realiza uma busca por valores de fluxo em horários com dados meteorológicos semelhantes, em janelas de tempo definidas (Reichstein et al., 2005; Wutzler et al., 2018).

2.6 BALANÇO DE ENERGIA

O balanço de energia mostra a relação entre a energia disponível dada pela soma do saldo de radiação (Rn) e fluxo de calor no solo (G) e os fluxos turbulentos de calor sensível (H) e latente (LE):

$$H + LE = Rn - G \tag{13}$$

$$Rn = (K \downarrow - K \uparrow) + (L \downarrow - L \uparrow) \tag{14}$$

onde $K\downarrow$ é a radiação de onda curta incidente, $K\uparrow$ é a radiação de onda curta refletida, $L\downarrow$ é a radiação de onda longa reemitida pela atmosfera e $L\uparrow$ é a radiação de onda longa emitida pela superfície da terra. A equação (13) representa o balanço de energia, que é dado pela relação dos fluxos turbulentos de energia (lado esquerdo) com a energia disponível (lado direito da igualdade).

Este balanço é frequentemente utilizado como indicador da acurácia das estimativas pelo método de EC (Wilson et al., 2001; Culf et al., 2004; Leuning et al., 2005; Foken, 2008a). No entanto, no método Eddy Covariance esse balanço não apresenta fechamento exato. Segundo (Foken et al., 2012), o fenômeno do não fechamento do balanço de energia na superfície não é um problema técnico do método de EC, e depende de características do sítio, como por exemplo a declinação do terreno e escoamentos superficiais. Este fenômeno é amplamente documentado na literatura e são considerados de boa confiabilidade dados com até 30% de não fechamento (Barr et al., 2012; Sánchez et al., 2010).

Uma técnica amplamente utilizada para realizar o fechamento consiste na distribuição do resíduo do balanço de energia entre o H e o LE (Twine et al., 2000; Foken, 2008b). Esta distribuição é feita utilizando a razão de Bowen (B) (Bowen, 1926) na escala horária, assumindo a condição de similaridade ente fluxos.

$$B = \frac{H}{LE} \quad (15)$$

Usando a equação (15), isolando os termos (H ou LE) substituindo na equação (13), desta forma encontramos as relações corrigidas paras os fluxos de calor sensível (H*) e latente (LE*):

$$H^* = \frac{B\,(Rn - Fg)}{1 + B} \quad (16)$$

$$LE^* = \frac{(Rn - Fg)}{1 + B} \quad (17)$$

2.7 DIÓXIDO DE CARBONO - CO_2

Uma molécula de CO_2 é uma molécula linear triatômica apresentando quatro modos normais de vibração denominados: estiramento simétrico (7,5 μm), estiramento assimétrico (4,2 μm) e dois modos de deformação angular (15 μm). A molécula de CO_2 absorve a radiação eletromagnética de comprimentos de onda respectivos a seus modos de vibração. Além disso, durante a vibração ocorre uma mudança no momento de dipolo da molécula, sendo que este momento de dipolo interage com os campos elétricos e magnéticos da radiação infravermelha, aumentando a absorção (Banwell, 1972; Smith, 1998). Desta forma, como a faixa de comprimentos de onda da radiação infravermelha que a Terra emite para a atmosfera estão na faixa de 1 μm a 50 μm, tendo seu pico de emissão em torno de 10 μm, conforme a lei de Wien para uma temperatura média acerca de 15 °C (288 K), todos os modos de vibração do CO_2 recebem energia, sendo que a absorção de radiação de 15 μm é particularmente intensa (Liou, 2002).

O CO_2 atmosférico faz parte do ciclo natural do carbono (C) que engloba a absorção de CO_2 pelas plantas, incorporação de C no solo, emissão de CO_2 através da decomposição de matéria orgânica por bactérias decompositoras e a respiração de todos os animais, plantas e microrganismos. As plantas são capazes de absorver esse gás através do processo de fotossíntese, removendo uma quantidade de CO_2 da atmosfera. Para realização do processo de fotossíntese pelas plantas é necessário energia, na forma de radiação, proveniente do Sol. As plantas respiram a todo momento, durante o dia e a noite, realizando processos de troca de CO_2, que durante período diurno é regido pela fotossíntese com maior absorção de carbono da atmosfera e durante o período noturno é marcado pela respiração dos seres vivos do ecossistema, emitindo CO_2 para a atmosfera.

2.8 PARTICIONAMENTO DO FLUXO DE NEE

O método Eddy Covariance é capaz de estimar de forma precisa as trocas de carbono entre a superfície e a atmosfera, definindo a troca liquida de carbono do ecossistema (NEE). O fluxo de NEE corresponde a toda troca de CO_2 entre a superfície e a atmosfera, considerando as emissões de CO_2 pela respiração do ecossistema (Reco), que engloba a respiração das plantas, demais seres vivos e demais formas de emissão de CO_2 na área, e a absorção de CO_2 pelas plantas através da fotossíntese, chamada de Produção Primaria Bruta, do inglês Gross Primary Prodution (GPP). Assim o NEE pode ser escrito como:

$$NEE = Reco + GPP \tag{18}$$

Para identificar a contribuição de cada parcela, metodologias de particionamento do fluxo de NEE foram desenvolvidas. Uma abordagem usada para estimar a Reco é utilizando o modelo empírico de Arrhenius. Proposta por (Reichstein et al., 2005) utiliza o modelo de regressão exponencial (Lloyd and Taylor, 1994):

$$\text{Reco} = rb\ e^{E_0\left(\frac{1}{T_{ref}-T_0} - \frac{1}{T-T_0}\right)}, \tag{19}$$

considerando que a Reco é o NEE noturno (unidades de μmol CO_2 m^{-2} s^{-1}), onde rb (μmol CO_2 m^{-2} s^{-1}) é a respiração na temperatura de referência T_{ref} (aqui 15 °C); E_0 (°C) é um parâmetro que caracteriza a sensibilidade da respiração à temperatura; T_0 é um parâmetro de escala de temperatura mantido constante em -46,02 °C (Lloyd e Taylor, 1994), e T é a temperatura do ar. Esta relação é usada para estimar o Reco a partir da temperatura do ar tanto para o período noturno quanto para o dia. O GPP é calculado subtraindo o NEE da Reco pela equação (3.8.1).

Existem outras metodologias para o particionamento do fluxo de NEE, como o método proposto por (Lasslop et al., 2010). No entanto, neste trabalho utilizamos o método proposto por (Reichstein et al., 2005).

3 ARTIGO 1*: INTERANNUAL VARIABILITY OF CO2 FLUXES IN A NATURAL PASTURE IN THE SOUTHERN BRAZILIAN PAMPA BIOME

ABSTRACT

The Pampa is a biome located between southern Brazil, Uruguay, and northern Argentina, with vegetation composed mainly of grasses interspersed with riparian forests. The native grasslands of the Pampa biome have been used for ranching for centuries and are seen today as the main tool to combat environmental degradation, keeping the local flora and fauna protected from the advance of commercial agriculture. Nevertheless, the livestock productivity of these fields must be improved from an economic point of view. In this sense, studies have been conducted to maximize the productivity of cattle ranching, reducing the environmental impacts on the fields of the Pampa biome. One system that has shown increased productivity is rotational management, which consists of dividing the total area into small plots through which the herd will be directed to maintain an amount of biomass that preserves the floristic diversity of the fields with an adequate stocking rate. In this system, natural grasslands are expected to act as important atmospheric carbon dioxide (CO_2) sinks. Given this scenario, we aimed to analyze six years of net ecosystem exchange (NEE) of CO_2 using Eddy Covariance (EC) measurements in a cattle ranching area with rotational management in the Pampa biome of southern Brazil. On average, the months from September to March (seven months) were characterized as absorbing CO_2, while from April to August (five months), the system was characterized as emitting. This monthly variability is related to the climatic variability of the region, whose climate, according to the Köppen classification, belongs to the Cfa zone (humid temperate with hot summers and cold and mild winters) and is susceptible to drought and frost events. The ecosystem was an atmospheric CO_2 sink with annual cumulative values for 2015, 2016, 2017, 2018, 2019, and 2020 of 381.2 ± 19, 116.8 ± 7, 340.2 ± 31, 141.1 ± 8, 101.0 ± 5, and 282.3 ± 14 g C m^{-2} $year^{-1}$, respectively. The NEE interannual variability showed no relationship with anomalies in climate variables or cattle production, and this is likely because this management system depends on forage production conditions, which in turn is interrelated with climatic conditions. These findings are important for understanding the dynamics of CO_2 exchange and show that the Pampa biome can be an important sink for atmospheric CO_2, producing quality animal protein and preserving the local fauna and flora.

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Keywords: Pampa biome, Rotation system, Net CO_2 exchange, Ecosystem respiration, Gross primary productivity.

1. INTRODUCTION

Carbon sequestration potential in grasslands can play a critical role in mitigating total greenhouse gas emissions from livestock production systems (Lal, 2004; Soussana et al., 2010). Nevertheless, the pasture carbon balance is still not well understood (Mudge et al., 2011; Soussana et al., 2010), as studies have presented varying findings, reporting sites as carbon sinks (Allard et al., 2007; Byrne et al., 2007), carbon sources (Veenendaal et al., 2007), or carbon neutral (Prescher et al., 2010). Although pasture carbon exchange can be directly determined by measuring changes in soil organic carbon stocks, they do not allow investigations of carbon dynamics on seasonal, annual, and interannual (<5 - 10 years) scales. (Smith et al., 2004; Rees et al., 2005; Lettens et al., 2005; Goidts and van Wesemael, 2007; Meersmans et al., 2009; Meersmans et al., 2011). These carbon dynamics can be assessed by combining measurements of CO_2 fluxes between the ecosystem and the atmosphere using the Eddy Covariance (EC) method aided by carbon input and output measurements, including fertilizer use and carbon converted to meat, which allows users to obtain soil integrated carbon. In this way, it is possible to analyze the impacts of specific management practices or climatic conditions in shorter time intervals (Suyker et al., 2003; Ciais et al., 2005; Harper et al., 2005; Jaksic et al., 2006; Allard et al., 2007; Ammann et al., 2007; Aires et al., 2008; Heimann and Reichstein, 2008; Hussain, 2011; Teuling et al., 2010; Jongen et al., 2011; Klumpp et al., 2011; Peichl et al., 2012)

The Pampa biome represents one of the most important temperate and subtropical grasslands in the world, located in South America between 34° and 30° latitude and 57° and 63° west latitude, comprising southern Brazil, Uruguay, and northern Argentina. The Pampa is an exuberant landscape with a cultural heritage associated with biodiversity, where pastures predominate, with sparse shrub and tree formations, woodlands, riparian forests, and wetlands (Berretta, 2001). The ecosystems stand out for their multifunctionality, with 3000 plant species, 102 mammal species, and 500 bird species (Boldrini, 2009; Bencke, 2009). The Brazilian portion of the Pampa biome is located in southernmost Brazil and occupies an area of 63% (174,000 km²) of Rio Grande do Sul State (Cordeiro and Hasenack, 2009). The vegetation of the natural grasslands of the Pampa biome is covered by photosynthetic species with C4 metabolism that co-exist with C3 species, which is one of the distinct characteristics of the southern Brazilian grasslands. Because of the natural grasslands, the natural aptitude of these ecosystems is cattle production, being one of the primary economic activities of the region likely since the Jesuits came to this region in the 17th century (Bilenca & Miñarro, 2004). Currently, these fields are a source of forage for about 14 million animals, mainly cattle and sheep (IBGE, 2020).

Most of the soil in the Brazilian Pampa region has an extremely sandy texture due to its origin in sedimentary rock (Boldrini, 2010; Suertegaray and Pires, 2009). The geological material makes the soils fragile and highly sensitive to water and wind erosion; the natural fragility of the soil and inappropriate human activities, especially the conversion of extensive areas of grasslands into monoculture tree plantations and the change in soil use with the incursion of the agricultural frontier, associated with the increase in grain production, have significantly changed the natural landscape of the Pampa biome (Overbeck et al., 2007; Pillar et al., 2009). What is more, the loss of natural pastures in the Pampa biome can be avoided by adopting alternative management strategies that allow native vegetation to be preserved, albeit with higher cattle production and better net income for farmers and low investments (Confortin et al., 2017).

Globally, grasslands must produce adequate food in the form of animal protein for global population growth, although this must be done sustainably. In general, grazing contributes to maintaining plant communities' structure, physiognomy, and diversity and increases ecosystem CO_2 uptake (Fuhlendorf et al., 2009; Lezama et al., 2014; Gomez-Casanovas et al., 2018). Nonetheless, even though high stocking rates momentarily increase cattle productivity, it can cause degradation of the plant community, leading to soil erosion and water pollution. Thus, pasture quality can decrease as the stocking rate increases because animals do not move and feed randomly but instead prefer selected areas, including those near water and available salt and minerals, along with easily accessible areas (Holecheck and Galt, 2000). Pastures are never grazed evenly within a given time, and the impact of the spatial distribution of animals is rarely uniform. One alternative is the rotational management system, in which pastures are divided into plots, interspersing the animals' grazing in recovery intervals before a new grazing (Broadbent et al., 2019). Plant recovery time under rotational grazing conditions depends on the type of vegetation and environmental conditions. Several studies have been conducted in a rotational system in the grasslands of the Pampa biome and showed that cattle production increases while conserving the diversity of native vegetation (Cruz et al., 2010; Barbieri et al., 2014, 2015; Confortin et al., 2017). Nevertheless, the dynamics of CO_2 exchange in this management system have yet to be investigated.

Given this scenario, this study aimed to evaluate the CO_2 exchanges between the surface and atmosphere in native pastures of the Pampa biome used for beef cattle raising in a rotational system. The predominance of summer-growing C4 grasses in this region must maintain high forage production during hotter periods, reducing during colder periods. Therefore, this work hypothesizes that the CO_2 exchanges throughout the year present a strong seasonality, and the performance of this system in the annual CO_2 balance should depend on the interrelationships between management and climatic conditions. In this sense, this study will provide the first continuous measurements based on over six years of data using the EC method to measure CO_2 sequestration/emission capacity to contribute to regional efforts to preserve and conserve native vegetation in the Pampa biome, combined with cattle production.

2. MATERIALS AND METHODS

2.1. SITE DESCRIPTION

The experimental site has 12 ha of native pasture of the Pampa biome used for beef cattle production and is located within the Federal University of Santa Maria, municipality of Santa Maria (Rio Grande do Sul State, southern Brazil). The predominant climate is humid subtropical type Cfa according to the Köppen classification (Kottek et al., 2006), characterized by having well-defined seasons, reaching elevated temperatures in summer (>35 °C) and mild winters subject to frost phenomena with regular rainfall between months. The soils of the experimental area are classified as Ultisol soil type (Streck et al., 2008).

The natural grassland vegetation found in the experimental area is used as pasture for beef cattle. It has a predominance of grasses in the forage mass, with the most abundant species being the following C4 cycle grasses: *Axonopus affinis* and *Paspalum notatum* (prostrate species) and *Andropogon lateralis* and *Aristida laevis* (clump-forming species), which are uniformly distributed in the study area (Barbieri et al., 2014, 2015; Confortin et al., 2017; Kuinchtner et al., 2018).

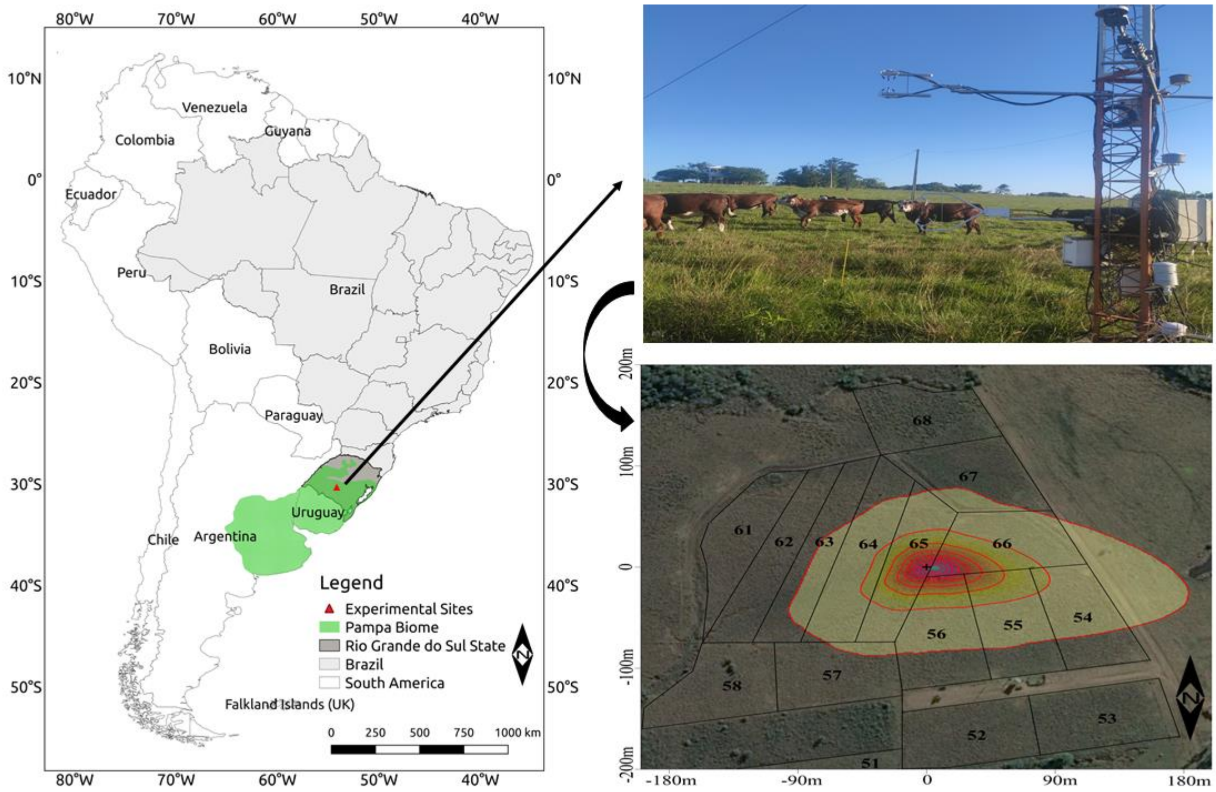
2.2. LIVESTOCK MANAGEMENT

A rotational grazing management system was adopted in the experimental area. To define the resting intervals, the accumulated thermal sum of 750 degree days (DD) was used in order to reach the average duration of grass leaf elongation in the resource conservation functional group (Cruz et al., 2010). This treatment was distributed in three replicated areas that comprised eight 0.5-ha subdivisions and represented by the 40's, 50's, and 60's. Thus, the use of grazing plots follows the occupation criterion of which the animals change plots at each accumulated thermal sum of ~107 DD, returning to the first plot when at 750 DD.

The calculation of instantaneous animal stocking in each plot is done in such a way as to allow for the disappearance of approximately 70% of the foliar lamina of the grasses, whether by animal consumption or trampling. For this, a proportional disappearance of 4.5% of the live weight of the animals is estimated (Heringer and Carvalho, 2002). The cattle of the analyzed period were of Braford breed aged between 8 and 20 months with average live weights ranging from 160 to 290 kg. A complete description of the rotational management in this area is found in Barbieri et al. (2014, 2015) and Confortin et al. (2016).

A flux tower was installed between two replications of the rotational treatment (namely 50's and 60's; Figure 1). In this study, we evaluated the period from January 01, 2015, to December 31, 2021; in this period, the animal production in the plots under the footprint of the flux tower was evaluated in the hot season, which was defined as late September to late March, comprising the spring-summer season. In the cold season, defined between April and September, comprising the fall-winter season, we did not evaluate animal production, although the animals followed the rotation between the plots, except in 2020 and 2021 when the cattle grazed freely between the plots.

Figure 1. Extension of the Pampa biome, localization of the experimental site, flux tower, and footprint flux tower.



The average animal stocking rate was obtained by multiplying the number of animals by the average body weight allocated to each sample unit, divided by the total area of each experimental unit in each treatment. The animals were weighed periodically with an average interval of 28 days. The average daily gain (ADG) was obtained by the test animals' weight difference between weighing divided by the number of days between weighing. The body weight gain per hectare (BWG; kg ha^{-1}) was obtained by dividing the average animal stocking rate (ASR) by the average weight of the animals in each sample unit and multiplied by the BWG of the animals and the number of days of the experiment.

Forage mass (FM) was estimated by visual comparison of standards and calibrated using the double sampling technique of (Haydock and Shaw, 1975) with 30 visual estimates and 10 cuts at ground level using a 0.25-m² metal frame. In each of the frames of the 30 estimates, three canopy heights were taken using a ruler graduated in cm and classified according to structure (clump or lower stratum) to estimate the average height of the pasture. The percentage of leaves was estimated by separating the leaf blades from the cut samples to calibrate the visual estimates. Leaf forage mass was estimated by multiplying the FM by leaf percentage.

2.3. INSTRUMENTATION AND DATA PROCESSING

A flux tower was installed between plots 56, 65, and 66 (53°45'36.097"W and 29°43'27.502"S, 88 m above sea level; Figure 1). The high frequency (10 Hz) sensor set included a 3D sonic anemometer (Wind Master Pro; Gill Instruments, Hampshire, UK) to measure wind and air temperature components and an open-path gas analyzer (LI7500, LI-COR Inc., Lincoln, NE, USA) measuring the CO_2/H_2O concentration at a 3-m height and sampled at a 10-Hz frequency until June 15, 2016. After this period, the gas analyzer and anemometer were replaced by the Integrated CO_2/H_2O Open-Path Gas Analyzer sensor and a 3D Sonic Anemometer (Irgason, Campbell Scientific Inc., Logan, UT, USA). Unfortunately, from June 15, 2021, to September 15, 2021, no data were collected from the gas analyzer due to technical issues.

Low frequency (1 Hz) variables were measured with the following sensors placed at a 3-m height: air temperature and relative humidity (RH) with a thermo-hygrometer (HMP155, Vaisala, Finland) until June 15, 2016, and after with a humidity probe (CS215-L, Campbell Scientific Inc., Logan, UT, USA); global radiation and net radiation were determined with a net radiometer (CNR4, Kipp & Zonen, Delft, The Netherlands). The precipitation was measured with a rainfall sensor (TR525USW, Texas Electronics, Dallas, TX, USA) at 1.7-m height. The soil heat flux was measured with soil heat plates (HFP01, Hukseflux Thermal Sensors BV, Delft, The Netherlands) placed at 0.10-m depth, soil temperature with a temperature probe (T108, Campbell Scientific Inc., Logan, UT, USA) at 0.05-m depth and soil water content was measured using water content reflectometers (CS616, Campbell Scientific Inc., Logan, UT, USA) at a 0.10-m depth.

The data collection system was set up with two CR1000 dataloggers (CR1000, Campbell Scientific Inc., Logan, UT, USA) to collect high- and low-frequency data. After December 05, 2019, the high and low-frequency data were collected with a CR6 datalogger (Campbell Scientific Inc., Logan, UT, USA) and the soil data with a CR1000 datalogger. The low-frequency data were grouped into 30-min averages. Unfortunately, from November 2019 to March 2020, no data were collected from the soil sensors.

Problems due to power failure or malfunction of the sensors may eventually cause failures in data collections and generate gaps. To complete the missing data for the meteorological variables of air temperature (18.9% of gaps), relative humidity (18.8% of gaps), and solar radiation (10.4% of gaps), we used data from the Santa Maria INMET weather station (National Institute of Meteorology; WMO A803, World Meteorological Organization), which is roughly 4 km from the flux tower (29.72ºW, 53.72ºS, elevation 103 m). The remaining gaps of 1.2, 4.1, 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 using the Copernicus Climate Change Service (C3S) Climate Data Store (CDS) (Hersbach et al., 2018). The precipitation data and soil moisture were also compared with the INMET station data to identify possible gaps and closures with the Santa Maria INMET precipitation. The Santa Maria INMET dataset was used for climatological data (30-year average, 1981-2010).

The high-frequency data processing was performed using the EC technique and EddyPro software (v 7.0.6; LI-COR Biosciences, Lincoln, Nebraska, USA) to estimate the CO_2 surface fluxes (CO_2 net ecosystem exchange, NEE) and heat fluxes (latent, LE, and sensible, H, heat fluxes). To calculate the fluxes, the 30-min block average was adopted and the following corrections were applied: double rotation (Wilczak et al., 2001); corrections for density effects (Webb et al., 1980); flux attenuation due to instrumental configuration (Gash and Culf, 1996); corrections due to high-pass (Moncrieff et al., 1997); low-pass (Moncrieff et al., 2004) filters; filtering of high-frequency data (Vickers and Mahrt, 1997).

The EddyPro software calculates different flags based on steady-state and well-developed turbulence tests (Foken et al., 2004): flag "0" for high quality fluxes, "1" for intermediate quality fluxes, and "2" for poor quality fluxes. In this study, we removed fluxes when the flag was "2." The fluxes were discarded in precipitation events plus a half-hour after (for instrument drying). The physical threshold filter for spikes of LE and H and NEE was defined by (Rubert et al., 2019) 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 NEE, a statistical control was used according to (Béziat et al., 2009), which consisted of data outside a ± 2.5 standard deviation range from 200 data point moving window (separately for day- and night-time data) were identified as remaining outliers and removed. The NEE was filtered to remove observations made under low-turbulence conditions based on u∗-threshold criteria (Papale et al., 2006).

The fetch and footprint of the flux tower were conducted using the model of (Kljun et al., 2015) through Flux Footprint Prediction (FFP) online data processing (http://footprint.kljun.net) and are illustrated in Figure 1. The distance at which the contribution to the flux measurements was 90% was approximately 180 m in the predominant wind direction (east direction). No flux data was removed by footprint analysis. Figure 1 numbers the plots within the tower's footprint for flux estimations.

The raw flux data presented gaps of 25.9, 29.9, and 17.7% for NEE, LE, and H, respectively, due to technical problems in the measurement instruments. After applying all filters and processing quality controls, there remained 49.2, 54.3, and 65.4% for NEE, LE, and H data, respectively. These amounts of gaps corroborate the literature on the EC technique (Papale et al., 2006). The gaps in NEE, H, and LE flux data were filled using the Reddyproc package (Max Planck Institute for Biogeochemistry, Germany) and the marginal distribution sampling method, which combines the look-up table (LUT) and mean diurnal course (MDC) methods described by (Wutzler et al., 2018). Due to the maintenance of the integrated gas analyzer (6/15/2021 to 9/15/2021), the gap was not filled.

2.4. NEE PARTITION

The NEE was partitioned between gross primary productivity (GPP) and total ecosystem respiration (R_{eco}) by the method described by (Reichstein et al., 2005) using the Reddyproc package (Max Planck Institute for Biogeochemistry, Germany). The flux partitioning method is based on the regression model of (Lloyd and Taylor, 1994), which uses the relationship between night-time NEE and air temperature to determine the sensitivity of R_{eco} to temperature, according to the equation:

$$\mathrm{Reco} = rb\, e^{E_0\left(\frac{1}{T_{ref}-T_0} - \frac{1}{T-T_0}\right)}, \tag{1}$$

where R_{eco} is the night-time NEE (units of µmol CO_2 m^{-2} s^{-1}), *rb* (µmol CO_2 m^{-2} s^{-1}) is the respiration at the reference temperature T_{ref} (15 °C), E_0 (°C) is a parameter characterizing the respiration sensitivity to temperature, T_0 is a temperature scale parameter kept constant at -46.02 °C (Lloyd and Taylor, 1994), and T is the air temperature. This relationship is used to estimate R_{eco} from the measured air temperature for night- and day-time periods. The GPP is calculated by subtracting the NEE from the R_{eco} obtained by Eq. (1). The negative NEE values denote CO_2 assimilation or uptake by the ecosystem, while positive NEE indicates net CO_2 emissions into the atmosphere.

2.5 ESTIMATES OF THE TOTAL UNCERTAINTY IN NEE

The uncertainty in the NEE caused by random errors and errors associated with data gaps was estimated based on the method of (Hollinger and Richardson, 2005; Richardson and Hollinger, 2007, 2005). This method follows the standard error propagation rules based on the random error estimation and long gap-filling procedure. The random uncertainty was estimated based on the successive days approach with similar environmental conditions (Zeri and Sá, 2010): 30% of random gaps were inserted in the gap-free dataset, 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 cumulative NEE sum calculated. The process was repeated 100 times, and the random uncertainty was calculated as the standard deviation of all cumulative fluxes generated. Random artificial gaps were introduced into the gap-free data and re-filled as (Richardson and Hollinger, 2007) detailed for long gap uncertainty. The random and long gap uncertainty were added in quadrature to calculate the total NEE uncertainty, assuming that the two types of errors are independent (Richardson & Hollinger, 2007).

3. RESULTS

3.1. WEATHER AND SOIL CONDITIONS

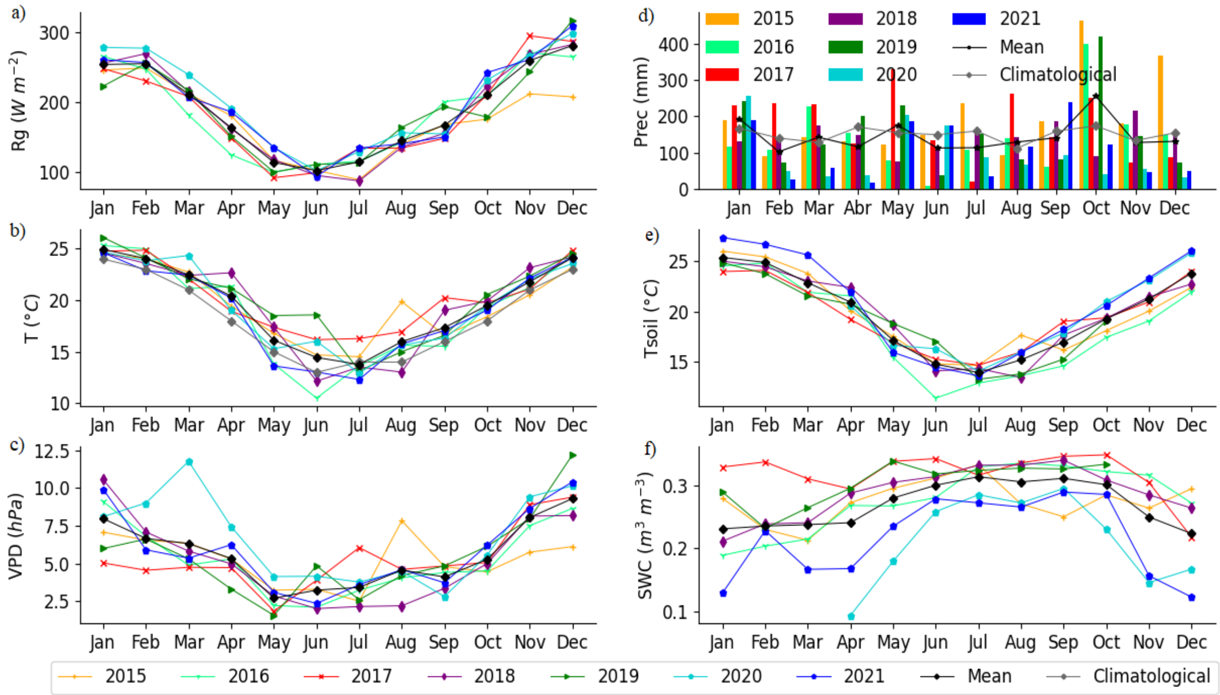
The monthly averages of meteorological variables and climatological normal for the Santa Maria experimental site are shown in Figure 2; the global radiation showed the expected seasonality for the region. The maximum hourly peaks of global radiation (Rg) at noon on clear days reached 1100 W m^{-2} in the summer and 500 W m^{-2} in the winter. The highest air temperatures were recorded between December and March, with a maximum of 39.5 °C; the lowest temperatures were recorded between July and September, with a minimum of -2.77 °C and the occurrence of frost. The average monthly temperature in the spring and summer period remained above the climatological normal, with emphasis on March 2020, in which the average temperature was around 3.5 °C above the climatological average. In autumn and winter, the climatic variability was greater than in spring-summer, and in June 2019, the temperature was 5.7 °C higher than the climatological normal, while in June 2016, the temperature was 2.5 °C below the climatological normal. Frost events were also quite variable between the years, with 2017 having only four frost events and 2019 having 18 events, albeit this was not the year with the lowest average temperature (Table 1). The vapor pressure deficit (VPD) shows significant variability between months and years, with higher values in the summer and lower ones in the winter.

The climatological normal of annual rainfall for the study region is 1797 mm. The year 2015 recorded the highest precipitation, 551 mm above the climatological normal, while 2020 recorded 702 mm below the climatological normal (Table 1). Although precipitation is usually well distributed throughout the year, according to Figure 2d, without being characterized as a dry and rainy season, the seasonal variability of precipitation may be related to the occurrence of climatic phenomena such as El Niño/La Niña that are responsible for the increase/decrease of precipitation in this region (Grimm et al., 2000). According to the ENSO classification (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php), 2015 and 2016 were marked by the moderate effects of the El Niño phenomenon, providing above-average rainfall, and 2020 and 2021 by the La Niña phenomenon, explaining the low rainfall volume recorded in the study area (Grimm et al., 2000).

In general, soil temperature at 0.05 cm depth was up to 1 °C lower than the air temperature on a monthly average. The soil water content (SWC) followed the precipitation variability, ranging from 0.10 to 0.35 $m^3\ m^{-3}$ over the study period. (Zimmer et al., 2020) analyzed soil physical parameters for this experimental site and estimated that SWC below 0.19 $m^3\ m^{-3}$ represents dry soil. All months between May and October were considered wet except for May 2020. Although most summer months were also considered wet, 2020 and 2021 showed dry soil. Precipitation in December 2019 and between February and March 2020 was lower than the climatic normal by approximately 100 mm each month; however, there is no SWC data in this period due to sensor maintenance. In the dry soil periods, the monthly average soil temperature was higher than the air temperature, especially in 2021.

Figure 2. Monthly means of (a) global radiation (Rg), (b) air temperature (T), (c) vapor pressure deficit (VPD), (d) monthly totals precipitation (Prec), (e) monthly means of soil temperature,

and (f) volumetric soil water content (SWC) from 2015 to 2021 for the SMA site in Pampa Biome. The mean value for the period is represented by the black lines and the climatic values, when available, in grey lines.



3.2 MANAGEMENT PRACTICES

In the experimental area, cattle were rotationally grazing between pastures throughout the year, except in the fall and winter of 2020 and 2021; nonetheless, evaluations of animal performance and structural variables of the pasture were performed only between spring and summer (i.e., the hot season); this is because the dominant species have their growing season concentrated in this season. Table 1 shows the dates of entry and exit of the animals in the rotational system that encompasses the tower footprint (Figure 1), the average height of the pasture in the plots, total forage mass, leaf percentage, leaf forage mass, average stocking rate, and total weight gain of the animals. The dates of entry and exit from each specific plot were not controlled. The start of cattle grazing for system evaluation varied between late september and early november, depending on the availability of forage mass and the availability of animals for the area. The average total forage mass in the plots ranged from 2713.5 (at the end of 2019) to 5140.1 kg ha^{-1} (at the end of 2016), and the stocking rate ranged from 822.7 (2019-2020) to

1262.4 kg ha^{-1} (2017-2018). Mean pasture height among the replications was similar among the years, between 29 and 33 cm (ranging from 2 to 4 cm), except in 2016 when the value was 22.7 cm. Leaf percentage was similar between the years, varying between 0.35 and 0.45 except in 2018/2019, which was 0.55. Cattle removal occurred between March 19 and March 30 in all years evaluated. The average weight gain from 2015 to 2020 was 125.3 kg ha^{-1}, with the highest weight gain occurring between 2018/2019 and the lowest between 2019/2020.

Table 1: Data from the management and animal production analysis at the experimental site.

Inbound - Outbound	No. days	Avg height (cm)	Forage mass (kg ha^{-1})	Leaves (%)	Leaf forage mass (kg ha^{-1})	Avg number of animals (kg ha^{-1})	Weight gain (kg ha^{-1})	NEE (g C m^{-2})	GPP (g C m^{-2})	R_{eco} (g C m^{-2})	Rg (W m^{-2})	T_{air} (°C) [n. frost]	Prec (mm)
Hot season													
23/10/2015 - 22/03/2016	152	22.7	4197.2	0.40	1709.4	885.9	110.0	-147.33	1680.77	1533.44	224.45	23.05	933.8
29/09/2016 - 30/03/2017	183	33.2	4951.1	0.40	1980.5	923.4	146.4	-272.46	2235.30	1962.83	238.62	22.69	1420.8
25/10/2017 - 22/03/2018	149	30.4	4777.0	0.35	1671.9	1262.4	119.2	-242.64	1946.93	1704.28	269.98	23.27	560.0
29/09/2018 - 19/03/2019	172	29.2	3428.8	0.55	1885.8	826.3	154.8	-331.11	2256.80	1925.68	245.10	23.46	941.4
06/11/2019 - 21/03/2020	137	29.2	2858.6	0.45	1286.4	822.7	95.9	-243.49	1815.37	1571.88	280.03	24.00	464.4
29/09/2020 - 21/03/2021		NA	NA	NA	NA	NA	NA	-375.24	1881.96	1506.72	259.68	22.51	409.5
Cold season													
12/03/2015* - 22/09/2015		NA	NA	NA	NA	NA	NA						
23/03/2016- 28/09/2016		NA	NA	NA	NA	NA	NA	54.26	855.29	909.55	132.58	15.30 [11]	663.4

31/03/2017-24/10/2017	-	NA	NA	NA	NA	NA	NA	-53.41	1220.49	1167.07	135.85	17.88 [4]	1210.4
23/03/2018-30/09/2018	-	NA	NA	NA	NA	NA	NA	180.55	1042.64	1223.19	126.43	16.54 [16]	904.6
20/03/2019-05/11/2019	-	NA	NA	NA	NA	NA	NA	39.87	1442.12	1481.99	148.84	17.86 [18]	1259.2
22/03/2020-28/09/2020								102.34	781.06	883.40	147.83	16.29 [15]	650.2
22/03/2021 - 22/09/2021								-2.57	615.59	823.12	139.21	15.59[7]	722.6
Annual													
2015	-	-	-	-	-	-	-	-381.2 ± 19	2695.33	2249.88	174.57	19.60	2348
2016	-	-	-	-	-	-	-	-116.8 ± 7	2875.10	2742.90	186.02	18.90	1723
2017	-	-	-	-	-	-	-	-340.2 ± 31	3215.97	2942.80	186.33	20.26	2115
2018	-	-	-	-	-	-	-	-141.1 ± 8	3252.21	3084.71	188.68	19.61	1722
2019	-	-	-	-	-	-	-	-101.0 ± 5	3208.15	3068.10	188.77	20.20	1854
2020	-	-	-	-	-	-	-	-282.3 ± 14	2817.62	2569.03	205.17	19.42	1130

*There were cattle in the hot season until March 11, 2015; NA - not available

3.3. ENERGY BALANCE CLOSURE

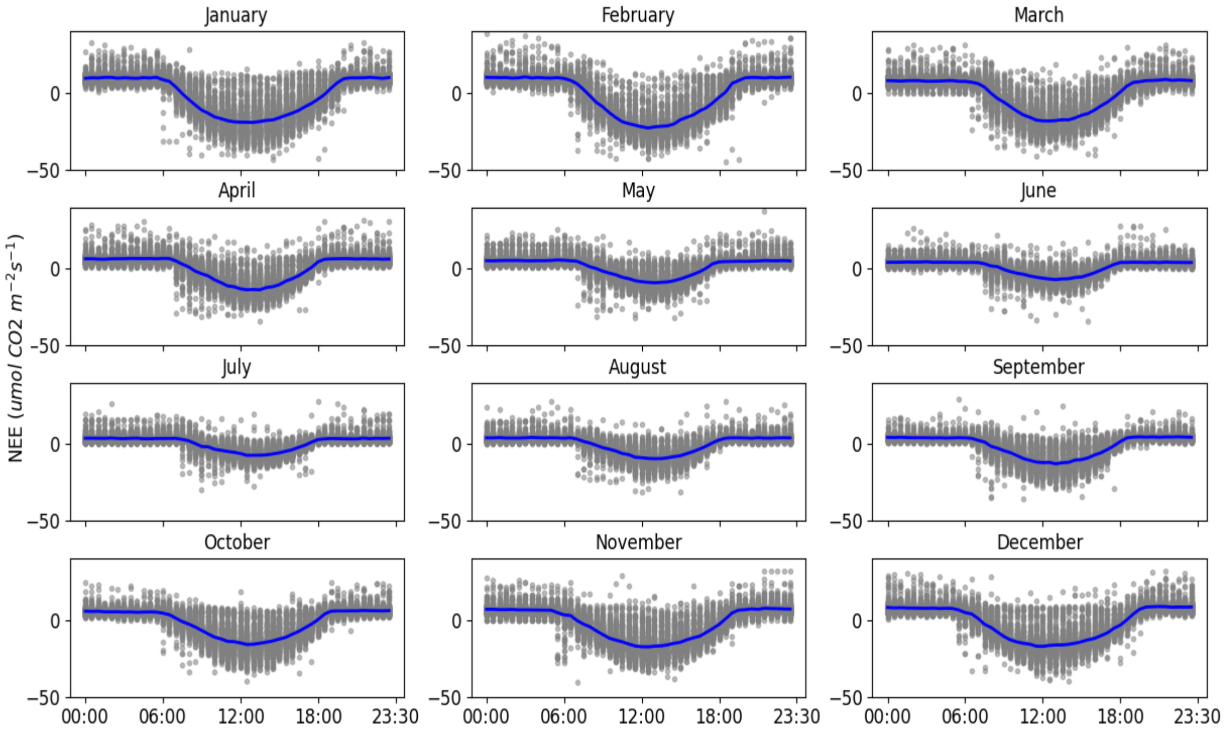
The relationship between available energy (Rn - G) and turbulent fluxes (H + LE) is often used as an indicator of the accuracy of estimations by the eddy covariance method (Wilson et al., 2001; Leuning et al., 2005; Culf et al., 2004; Foken, 2008). High-quality (0 and 1 flags) and non-gap-filled fluxes of H and LE were used to calculate energy balance closure only when all four components (H, LE, Rn, and G) were available. The slope of the linear regression between (Rn - G) and (H + LE) for the period evaluated was 0.75 (Figure S1), i.e., the energy balance closure is violated by approximately 25%, as analyzed and discussed by (Rubert et al., 2019) for the same experimental site. This non-closure energy balance is widely documented in the literature, and values up to 30% are considered of good reliability (Sánchez et al., 2010; Barr et al., 2012).

3.4. SEASONAL AND INTERANNUAL CO_2 DYNAMICS

The half-hourly NEE values during the study period, along with the half-hourly mean pattern for each month, are illustrated in Figure 3. Positive NEE values mark the monthly daily mean cycles during the night and starting at sunrise, the sign of NEE reverses, becoming negative. The most significant hourly variability in NEE occurred in the spring and summer months. The peak NEE absorbed during the day was approximately -44 µmol CO_2 m^{-2} s^{-1}, and the peak night-time emission was + 28 µmol CO_2 m^{-2} s^{-1}, both occurring in February.

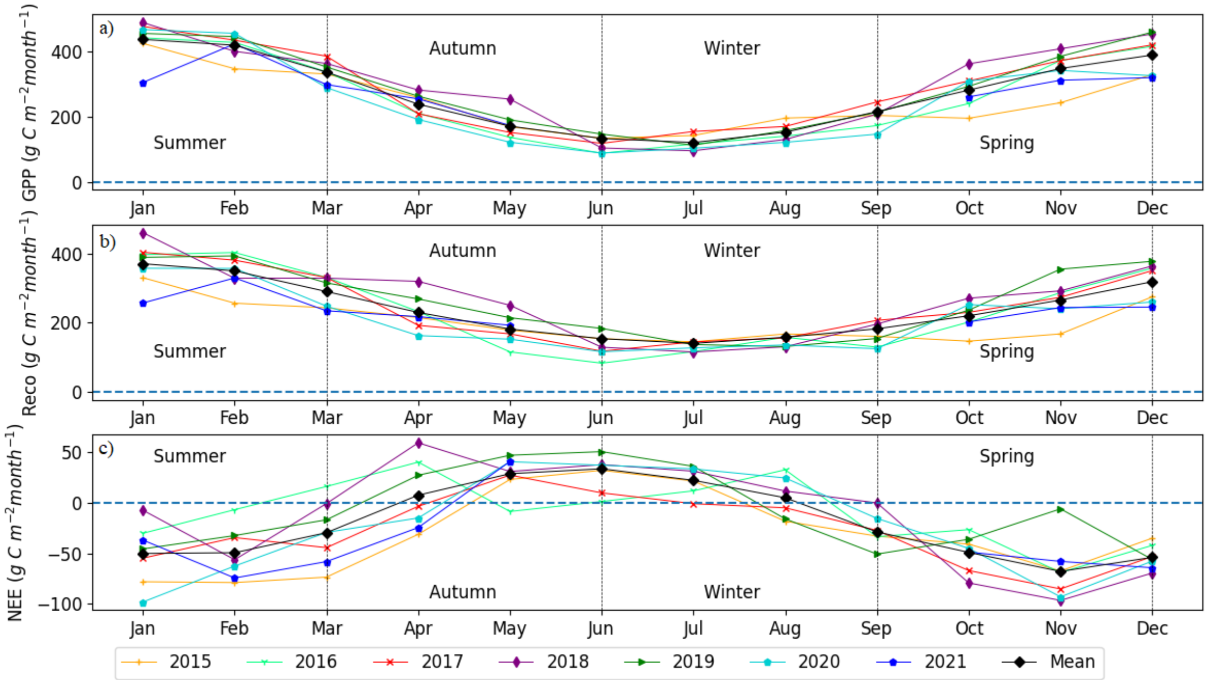
February's monthly average daily cycle showed the highest mean values of the diurnal absorption peak (~-22.6 µmol CO_2 m^{-2} s^{-1}) and the highest mean values of nocturnal emission (~ 10 µmol CO_2 m^{-2} s^{-1}). June showed the lowest mean values of peak absorption (~-7.0 µmol CO_2 m^{-2} s^{-1}) and the lowest mean values of nocturnal emission (~3.5 µmol CO_2 m^{-2} s^{-1}), which is quite similar to the diurnal cycle of July. The average daily NEE for the six years analyzed was -2.35 g CO_2 m^{-2} d^{-1}, with November being on average the largest absorber (-7.91 g CO_2 m^{-2} d^{-1}) and June the largest emitter (3.57 g CO_2 m^{-2} $d)^{-1}$.

Figure 3. All half-hourly net ecosystem exchange of CO_2 (NEE) measurements from 2015 to 2021. The blue line represents the half-hourly monthly cycle.



In the monthly accumulations, GPP and R_{eco} show strong interannual variability, with higher values in January (R_{eco} between 259 and 464 g C m^{-2} $month^{-1}$; GPP between 296 and 470 g C m^{-2} $month^{-1}$) and lower values in June (R_{eco} between 80 and 110 g C m^{-2} $month^{-1}$; GPP between 110 and 120 g C m^{-2} $month^{-1}$) (Figure 4). The annual average range of R_{eco}/GPP was 88%. In general, NEE showed more pronounced variability in each month than GPP and R_{eco} (Figure 4), with values reaching twice the mean for each given month. On average, September to March showed negative NEE values, whereas the NEE was positive from April to August (i.e., on average, from April to August, there were seven months in which the system absorbed CO_2 from the atmosphere (negative NEE) and five months in which the system was an emitter of CO_2 to the atmosphere (positive NEE) (Figure 4). Only June was an emitter in all years, but September through January were all absorbers. November is, on average, the largest absorber and June the largest emitter. An atypical NEE value was observed for November 2019 that was very close to neutrality, unlike the other years analyzed, which may be related to increased respiration of the ecosystem for the same year, since the GPP was similar to the average values for this month.

Figure 4. Monthly cumulative values of the (a) gross primary productivity (GPP), (b) ecosystem respiration (R_{eco}), and (c) net ecosystem exchange (NEE). The black dotted line indicates the 6-year average for each month.



The statistical relationship between NEE and meteorological and soil variables was evaluated in the monthly averages through Pearson's correlation coefficient (Table 2). The NEE showed a higher correlation with Rg (R = -0.8) followed by T_{air}, T_{soil}, and VPD (R = -0.6); inversely, when NEE increased, these variables decreased. The SWC and Prec did not show a significant correlation, and this is likely because the soil was classified as wet in most of the analyzed period.

The GPP and R_{eco} showed correlation greater than 0.8 with Rg and T_{air}. Between them, the correlation was at the maximum (R = 1), standing for that both are directly correlated and showing that the increase in photosynthetic activity (GPP) by solar radiation increases ecosystem respiration (R_{eco}).

Table 2. Pearson's correlation coefficient (R) between NEE and meteorological and soil variables for different time scales.

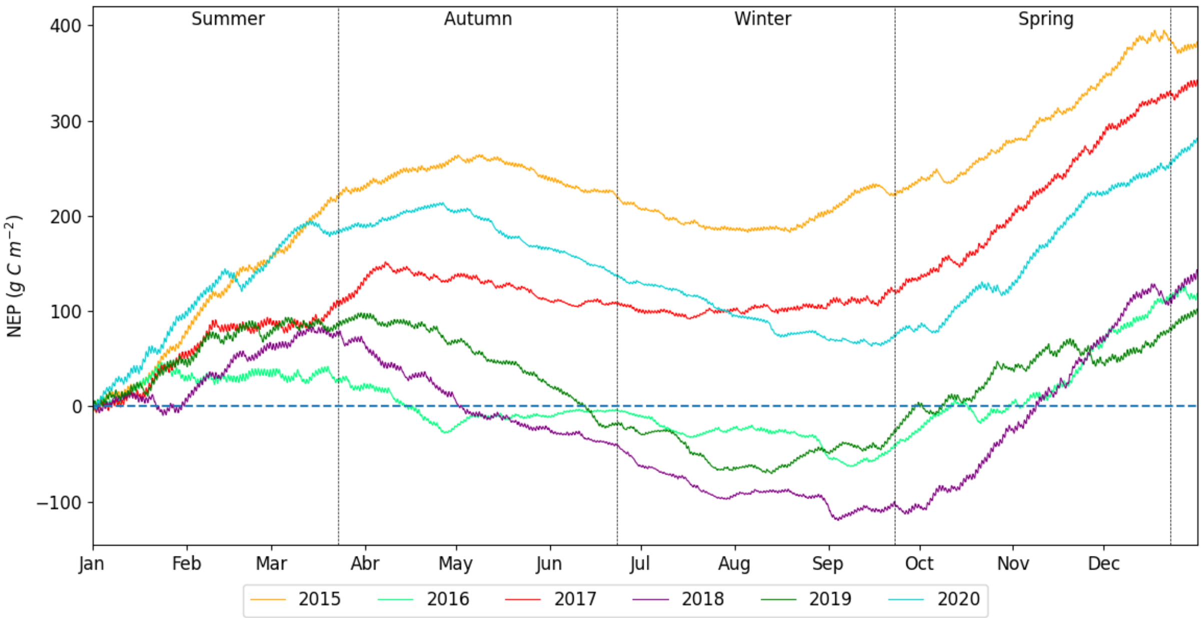
			Seasonal				Management	
	Monthly	Annual	Spring	Summer	Autumn	Winter	Hot	Cold
NEE x Rg	-0.8	0.2	-0.1	-0.8	0.1	-0.3	-0.3	-0.3
NEE x T_{air}	-0.6	-0.2	-0.3	0.2	0.6	-0.9	-0.2	-0.5
NEE x VPD	-0.6	-0.2	0.4	-0.5	-0.2	-0.8	0.1	-0.5
NEE x T_{soil}	-0.6	-0.5	-0.8	-0.7	0.7	-0.4	0.3	0.0
NEE x SWC	0.3	0.2	0.3	0.3	0.1	-0.1	-0.7	-0.3
NEE x Prec	0.1	-0.4	0.2	0.5	-0.5	-0.2	-0.2	-0.5
NEE x pasture height		-	-	-	-	-	-0.8	-
NEE x leaf forage mass		-	-	-	-	-	-0.3	-
NEE x weight gain		-	-	-	-	-	0.1	-

3.5. NEE CUMULATIVE

The annually cumulative NEE and evaluated periods of the production system (hot and cold) are listed in Table 1. All hot-season periods were CO_2 absorbers with an average value of (-268.71 g C m^{-2}), while the cold seasons generally emitted CO_2 with an average of (53.51 g C m^{-2}), although the cold seasons of 2017 and 2021 were absorbers. The ecosystem behaved as a carbon sink of -227.1 g C m^{-2} $year^{-1}$ on the 6-year average, with the highest absorption in 2015 and the lowest in 2019. The annually cumulative NEE from January 1 for each year of the study is presented in Figure 5, in which one can see that 2016, 2018, and 2019 were C sources from April, May, and the end of June, respectively, but returning to absorption between October and November. Winter emissions could not offset the absorptions from January to April in the other years.

The slope pattern of the NEE accumulation curve is quite similar in the spring periods (Figure S2, S3, S4 and S5), although the summer, fall, and winter periods showed much variability with the fall and winter periods, including years of CO_2 uptake (2015 and 2017). The year 2015 and 2017 showed the highest absorption during the year and were characterized by fall and winter with little or almost neutral absorption (winter 2015) and lower absorption in summer. The year 2019, which showed the lowest annual emission, had the highest absorption in the summer but the lowest absorption in the spring and high emission in the autumn.

Figure 5. Cumulative NEE throughout the years.



Pearson's correlations between environmental variables and NEE in the annual period (Table 2) showed no significant relationship for Rg, T_{air}, VPD, and SWC ($R < 0.2$) and showed an inverse correlation with T_{soil} ($R = -0.5$) and Prec ($R = -0.4$). The correlations between the integrated NEE in the seasonal and management periods of each year show many variabilities, for example, NEE vs. Rg, which for the summer, was $R = -0.8$ and $R = -0.3$ in the winter, while NEE vs. T_{air} was $R = -0.9$ in the winter and $R = -0.2$ in the summer. Only SWC and pasture height had $R > 0.7$ with NEE in the management periods. Therefore, no single variable can explain the interannual and interseasonal variability of NEE.

The anomalies of the monthly values compared to the mean of each month were analyzed for the components of NEE and the environmental variables, allowing us to investigate possible causes of inter-seasonal variability, as proposed by Rutledge et al. (2015). No relationships were found between anomalies in NEE and anomalies in environmental variables ($R^2 < 0.2$) (Figure S6). The anomalies between GPP and R_{eco} showed the highest relationship ($R^2 = 0.72$), although they did not explain the anomalies in NEE (Figure S7).

4. DISCUSSION

4.2. SEASONAL AND INTERANNUAL VARIABILITY IN CO_2 EXCHANGE

The dynamics of CO_2 in the rotational grazing system in the Pampa biome show seasonality with high GPP and R_{eco} values during the spring-summer seasons and lower values in the fall-winter period, following the seasonal pattern of solar radiation and air temperature. Both GPP and R_{eco} show monthly mean values almost four times higher in summer than winter. The difference between GPP and R_{eco} was greater in the summer than winter, and GPP drove this difference in the summer and R_{eco} in the winter; thus, NEE presents a characteristic seasonal variability with carbon absorptions in the spring and summer and emissions in fall-winter. During the fall-winter season, the ecosystem starts to emit CO_2. From April onwards, the NEE becomes positive, except for 2016. In April of 2016, a strong cold front occurred, dropping the average daily temperature by approximately 20 °C in less than ten days, decreasing R_{eco}. According to the INMET conventional station (WMO 83936), there was no frost in this period, and therefore vegetation death did not occur; hence, despite decreasing the GPP-NEE, this change was not as significant given the decrease rate was lower in the GPP than R_{eco}. Moreover, the NEE remained negative between April and June, although very close to neutral values. In the fall-winter season, the dominant C4 grasses in natural pasture decrease their photosynthetic capacity, with a considerable accumulation of senescent material from the earlier growing season (Royo Pallares et al., 2005). This period is also marked by frost phenomena caused by rapid radioactive loss during the night combined with low temperatures, clear skies, and light winds, creating a layer of ice on the plants (Araujo Frangipani et al., 2021). Although livestock production was not assessed in this period, cattle grazed the area on a rotational basis until 2019. In 2020 and 2021, cattle grazed freely between the plots.

The beginning of the spring-summer season is marked by a rise in GPP and R_{eco} values. From the end of August and during September, there was a reversal in NEE values (Figure 4) and the ecosystem began to absorb CO_2; in all years, we observe seasonality although with inter-annual variability. In late winter, the radiation begins to intensify, gradually increasing the temperature until it reaches its maximum values in the summer, which provides grass growth associated with regular rainfall (Hoeppner and Dukes, 2012). In November and December

(2020 and 2021), precipitation was below the climatological normal, resulting in lower GPP and R_{eco} values. Although January 2021 registered precipitation above the climatological average, the non-resultant fluxes of GPP and R_{eco} recorded were the lowest compared to all other years. This may be related to the previous long period with below-average rainfall, leaving the SWC with values below 0.19 m^3 m^{-3} (Figure 2f) and rainfall only in the final days of the month, impairing plant development. An atypical NEE value was observed for November 2019 (Figure 4), which was close to neutrality, unlike the other analyzed years. Additionally, we noted an increase in ecosystem respiration for the same year for this month (Figure 4). This event may be related to the weakness of the pasture that presented the lowest mass of forage for the years evaluated as well as the lowest mass of leaves and low quality (Table 1), resulting in a delay in the start date of grazing for the respective year, which started days later than in previous years. Consequently, the lowest animal load was allocated, resulting in the lowest weight gain of animals in the years analyzed.

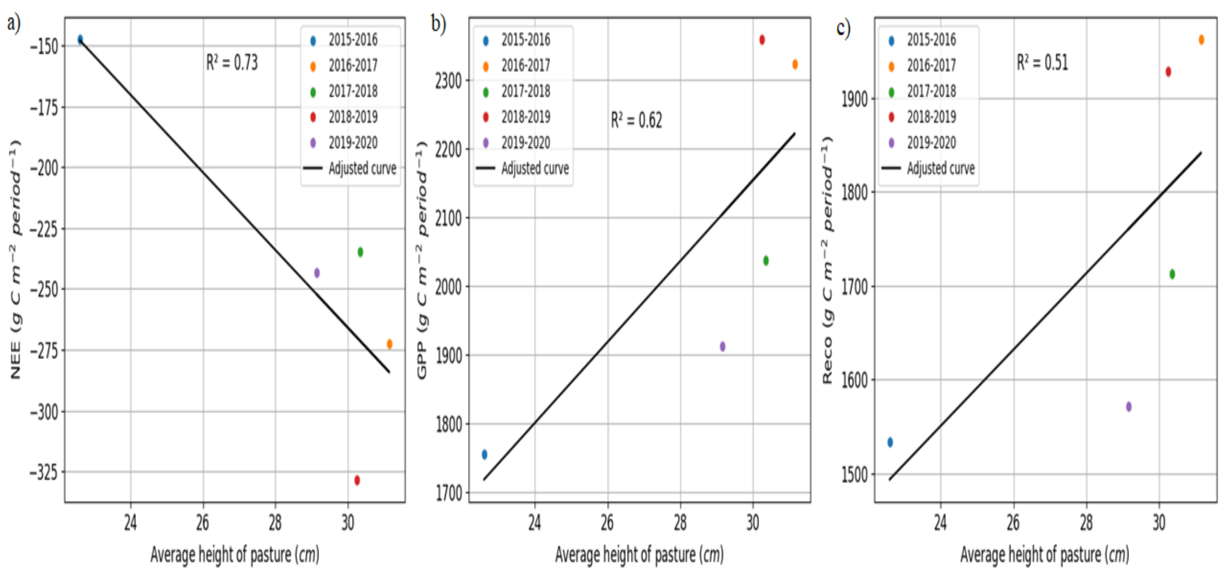
In the six years evaluated, the pasture under a rotational management system in the Pampa biome behaved as an annual CO_2 sink ranging from -381.2 ± 19 to -101.0 ± 5 g C m^{-2} y^{-1} with a mean value of -227.1 g C m^{-2} y^{-1}. Research using the EC method has shown that on average, grassland ecosystems behaved as CO_2 sinks, as reported by (Rutledge et al., 2015), who found a mean 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 in New Zealand. (De la Motte et al., 2016) reported a mean NEE of -141 g C m^{-2} y^{-1} over five years (2010-2015) in a permanent pasture in southern Belgium with intensive management and fertilizer application. (Gomez-Casanovas et al., 2018) investigated the effects of grazing on C fluxes of subtropical pastures in Florida State (USA) and found that NEE was -136 ± 6 g C m^{-2} y^{-1} in the grazed pasture, while NEE was 83 ± 4 g C m^{-2} y^{-1} in the ungrazed pasture (in 2014). Therefore, although within the range, our findings show a five-year average higher than other studies.

It was not possible to establish a relationship between the environmental variables and inter-seasonal variability of NEE investigated from the anomalies in environmental variables and anomalies in NEE. This seems to be a characteristic of grasslands, as De la Motte et al. (2016), who also analyzed the carbon balance of an intensively managed permanent grassland in Belgium, did not find any relationship between these anomalies.

We did not observe a direct relationship between animal productivity and NEE during the analyzed period. However, the relationships between pasture height and NEE and its components are linear and can be identified and analyzed, as per Figure 6. Higher CO_2 uptake periods occurred when the pasture was 28-35 cm high (Figure 6a), and similar values have been reported by de Souza Filho et al., (2019), who showed that proper grazing management could improve animal production and mitigate the environmental impact from livestock in Brazil. The authors reported that tall grass heights (23-30 cm) could reduce 13 and 14% of GHG emissions from the whole livestock sector in southern Brazil. This is the height at which grazing must be introduced because from then on, a more significant accumulation of stems and dead material will occur (Carvalho and Batello, 2009; Silva and Nascimento Júnior, 2007).

In general, with increasing pasture height, we observed an increase in GPP and R_{eco} (Figure 6b). Nonetheless, other studies such as (Grant e King, 1983; Parsons et al., 1988; Hodgson 1990; Carvalho et al., 2006) reported pasture height with reduced photosynthesis due to the low quality of the pasture, having older plants with reduced photosynthetic capacity. In this situation, R_{eco} remains high while GPP decreases (Bircham and Hodgson, 1983; Silva et al., 2009). The use of rotational management is precisely to optimize animal grazing and plant growth, and the presence of cattle is important for GPP to be higher than R_{eco} with the rotation of animals (Figure 6) (Wang et al., 2021).

Figure 6. Correlation between seasonal (NEE), total ecosystem respiration (R_{eco}) and gross primary productivity (GPP) seasonal and pasture height (a, b, c).



4.3. GRAZING

Maintaining stable meat production and optimizing forage consumption requires careful herd management by the farmer, continuously adapting stocking rate to grass availability. Since pasture regrowth depends on weather conditions and photosynthetic surfaces, it is logical to conclude that management is done in response to weather conditions. As a consequence of this link, the impacts of climate and management on NEE are difficult to distinguish and sometimes offset each other. This could explain why a clear relationship between NEE and climate anomalies was not found in this study and other similar works (Wayne et al., 2008; Rutledge et al., 2017;). Thus, CO_2 exchanges in a grassland ecosystem represent coupling between grazing management and climatic conditions due to complex interactions with biogeochemical and hydrological factors (Rutledge et al., 2017; Wang et al., 2021).

Grazing directly affects NEE via cattle respiration and indirectly via biomass consumption, natural fertilization through excreta, and soil compaction (Jérôme et al., 2014). A high livestock stocking rate could impact the carbon balance by reducing GPP through defoliation and stimulating GPP by removing less productive plant material before senescence (Jérôme et al., 2014). As shown by the results of Casanova et al. (2018), the grazed system shows greater capacity as an atmospheric carbon sink than the ungrazed one. These results corroborate studies that have indicated that grazing increases the pasture CO_2 drain (Wilsey et al., 2002; Shao et al., 2013). Cattle ranching in the Pampa biome and management type have an important influence on the vegetation of pastures, and this activity is the most appropriate for the maintenance and preservation of this biome (Overbeck et al., 2007; Pillar et al., 2009; Jaurena et al., 2021).

Rotational management provides greater control over grazing intensity and is elaborated according to the following indicators: defoliation intensity, pasture height, forage production, and allocated animal load. These indicators allow the balance between pasture growth and rotation of grazing animals (Zanini et al., 2012; Wang et al., 2021). As the grazing cycle in the adopted rotational system is defined by the accumulation of the daily thermal amplitude, we have a management that relates to variables such as global radiation and air temperature, which in turn are atmospheric forcers correlated with CO_2 fluxes, so that the time cattle remain on the pasture depends on the same variables responsible for intensifying the photosynthesis process (Schmitt et al., 2010; Confortin et al., 2010; Quadros et al., 2015). Therefore, in addition to considering the morphology of the local pasture when calculating the animal capacity of the system, we still have the permanence of the animals in each plot defined by climatic factors. This management attempts to maximize pasture and animal production availability, indirectly increasing GPP. The pastures found in the region of the Pampa biome have as a characteristic the coexistence of grass species of winter growth with metabolic cycle C3 and summer growth C4 (Nabinger et al., 2000). Although this coexistence of species exists, summer growth species are predominant, which provides cold seasons with lower forage supply, reducing animal productivity and the photosynthetic capacity of plants in these seasons. This scenario can be observed by the sharp decrease in GPP at the beginning of the fall-winter season and increased CO_2 assimilation by the ecosystem at the beginning of the hot season (spring-summer) provided by the regrowth of summer growth grass species (Figure 4).

The average stocking rate of animals in the experimental area during the five-year hot season was 944.1 kg LW ha^{-1}, which corresponds to 2.1 AU ha^{-1}, (1 AU, animal unit, is equivalent to 450 kg LW). This stocking rate is almost double the average stocking rate used in cattle ranching systems based on the native pasture in the Pampa Biome (IBGE, 2007). The weight gain value per hectare in the study period was 117 kg LW ha^{-1} in the spring period; this result is higher if compared to the average of 70 kg LW ha^{-1} of Rio Grande do Sul State (Nabinger et al., 2009).

This experiment was conducted in a natural pasture area of the Pampa biome, where the pasture receives no addition of chemical or organic fertilizers, only manure from grazing animals. No sowing or cutting of forage is performed, and the cattle present in the grazing area did not receive supplementation during the study period and animal evaluation. Thus, the carbon input to the ecosystem is only through carbon assimilation by plants or GPP.

This paper showed that pastures under rotational management in the Pampa Biome perform an important ecosystem service of absorbing CO_2 from the atmosphere. Some studies have shown that ruminant grazing can also mitigate GHG emissions when combined with appropriate management practices (Neely et al., 2009; Vasconcelos et al., 2018). In this study, we did not evaluate CH_4 emissions, which is an important GHG as it has a global warming power 28 times higher than CO_2 and is mainly emitted by the enteric fermentation of ruminants. However, Cezimbra et al., (2021) estimated the emission of CH_4 by beef cattle in a native grassland ecosystem of the Pampa Biome in southern Brazil (~300 km from our study site and under the same climate and soil type) and found an emission per area of about 55.7 kg CH_4 ha^{-1} y^{-1} for a forage supply similar to our study and animals with similar age, weight, and breed. Hence, by converting the CH_4 into CO_2-eq, grazing was responsible for 1559.6 kg CO_2-eq ha^{-1}

of emission. If we use this methane emission rate to calculate a global warming potential (GWP) of CO_2 and CH_4 in our study (GWP = NEE_{CO2} + $CH4_{CO2\text{-}eq}$), converting the NEE into CO_2 (-227.1 g C m^{-2} $year^{-1}$ = - 8327.0 kg CO_2 ha^{-1}), we will have GWP = - 6767.4 kg CO_2-eq ha^{-1}. Thus, grazing on the natural pastures of the Pampa biome offsets methane emissions by the animals, resulting in an absorption balance of over six tons of CO_2-eq ha^{-1}; alternatively, for each kg of meat produced on average, the ecosystem absorbed 57.8 kg CO_2-eq (6767.4 kg CO_2-eq ha^{-1}/117 kg LW ha^{-1}).

5. CONCLUSIONS

Livestock production in a natural pasture of the Pampa biome under rotational management presented itself as an atmospheric CO_2 sink in six years evaluated using the Eddy Covariance method, ranging from -101.0 ± 5 to -381.2 ± 19 g C m^{-2} $year^{-1}$, with a average of -227.1 g C m^{-2} $year^{-1}$, Strong seasonal variability was found, and in general, in the spring/summer seasons, the ecosystem was a CO_2 sink and a CO_2 source in the fall/winter. The analyzed period showed inter-seasonal climatic variability, although it was not possible to identify which factor was determining the variability in the NEE results.

Furthermore, the rotational grazing management employed in the study area is directly related to the region’s climatology and physiology of the plants found there, making the identification of individual management contributions to carbon sequestration complex. The potential for atmospheric CO_2 sequestration in the analyzed pasture was, on average, higher than most studies in pastures worldwide using the same method.

Therefore, livestock activity in natural pastures of the Pampa biome can act as an important sink for atmospheric CO_2 when using management that seeks a balance between animal production and environmental preservation. Appropriate grazing management in Pampa biome natural grasslands could offsets methane and CO_2 emissions providing a potential of absorption above six ton CO_2 eq/ha.

6. SUPLEMENTARY MATERIAL

Figure S1 – Energy balance representation for the study area.

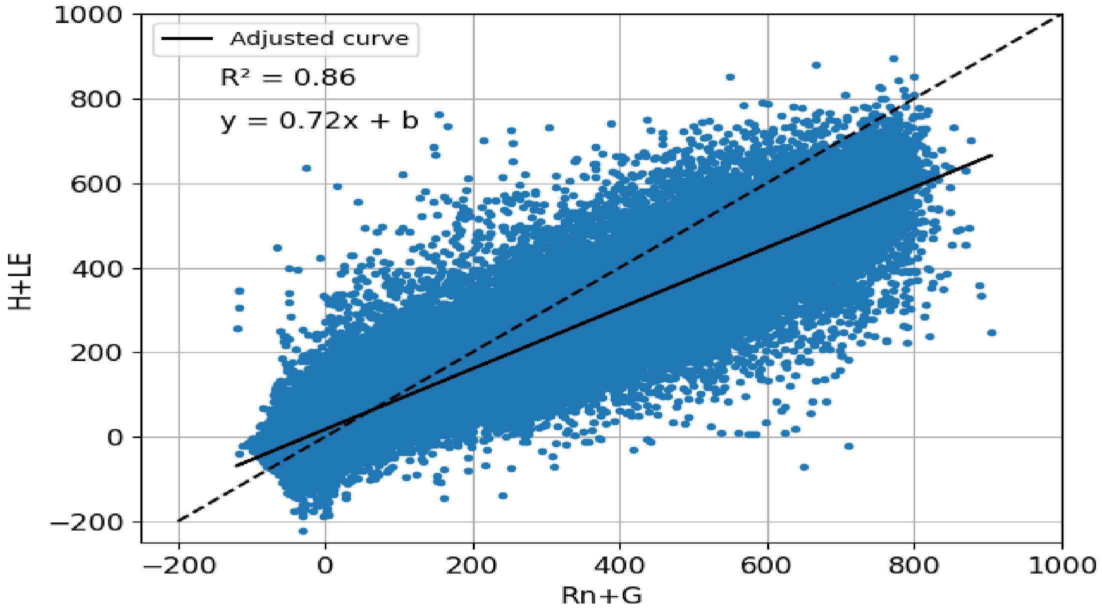


Figure S2 – Accumulated NEE spring season.

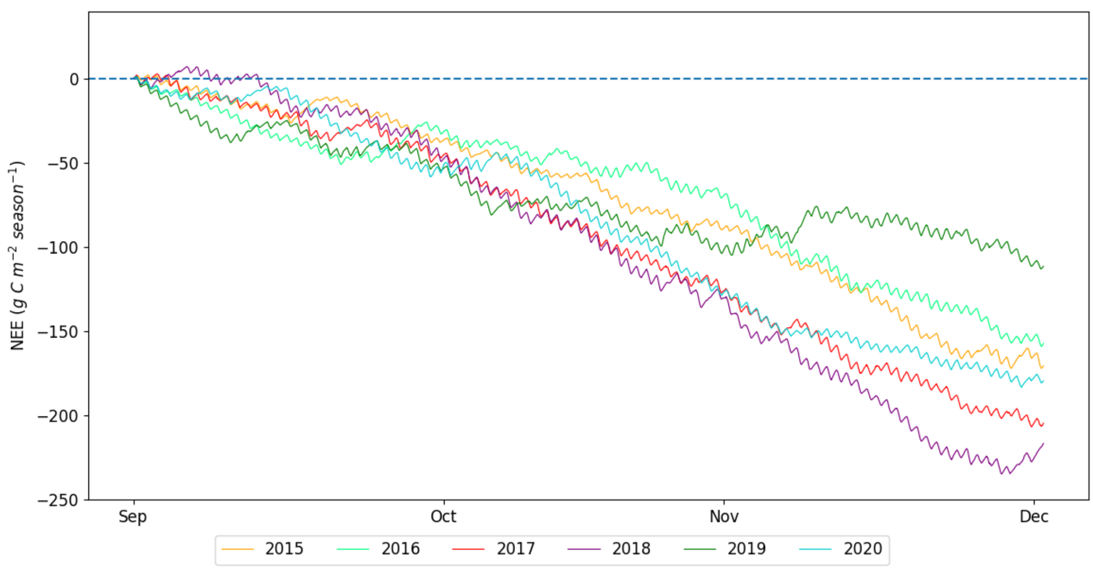


Figure S3 – Accumulated NEE summer season.

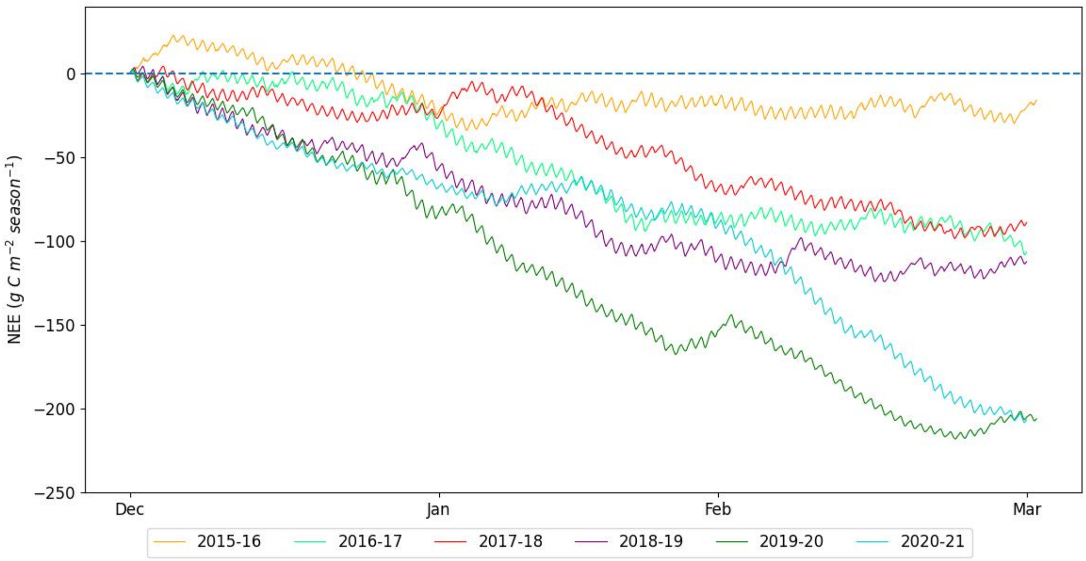


Figure S4 – Accumulated NEE autumn season.

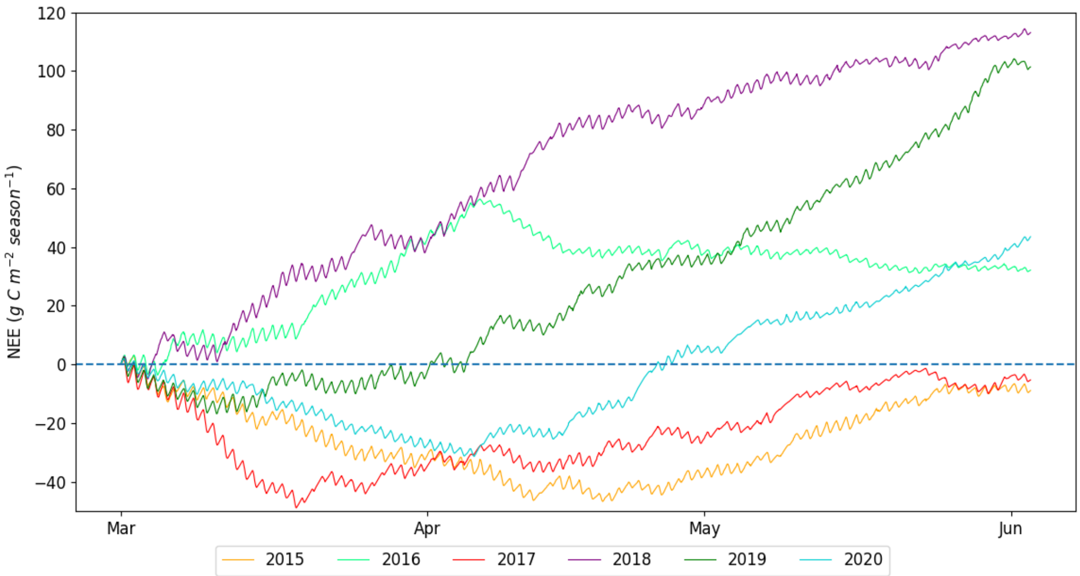


Figure S5 – Accumulated NEE winter season.

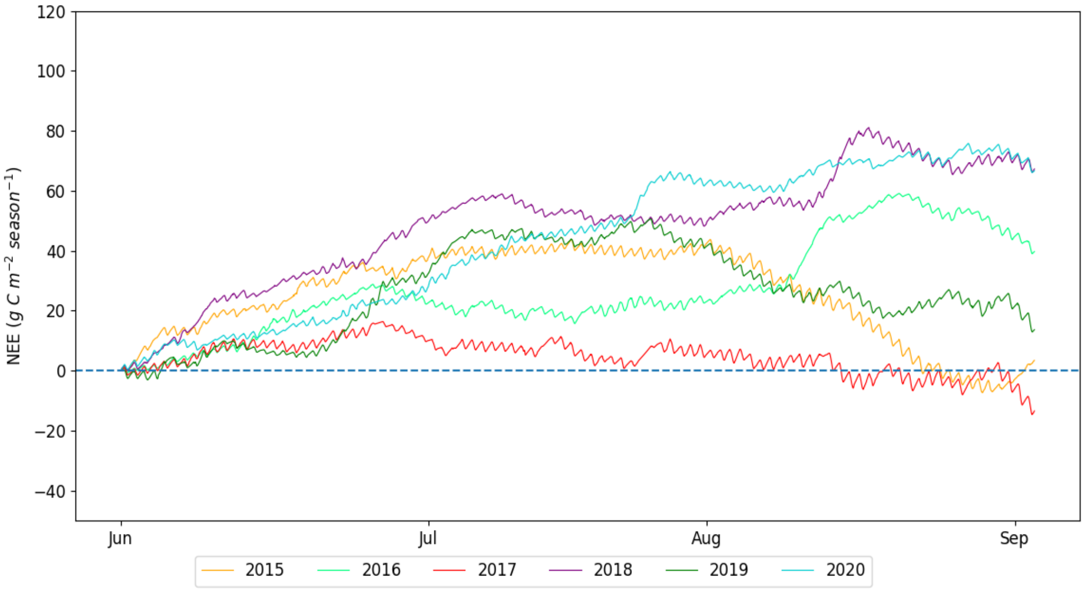


Figure S6 – Anomalies between NEE and environmental variables (T, Rg, VPD).

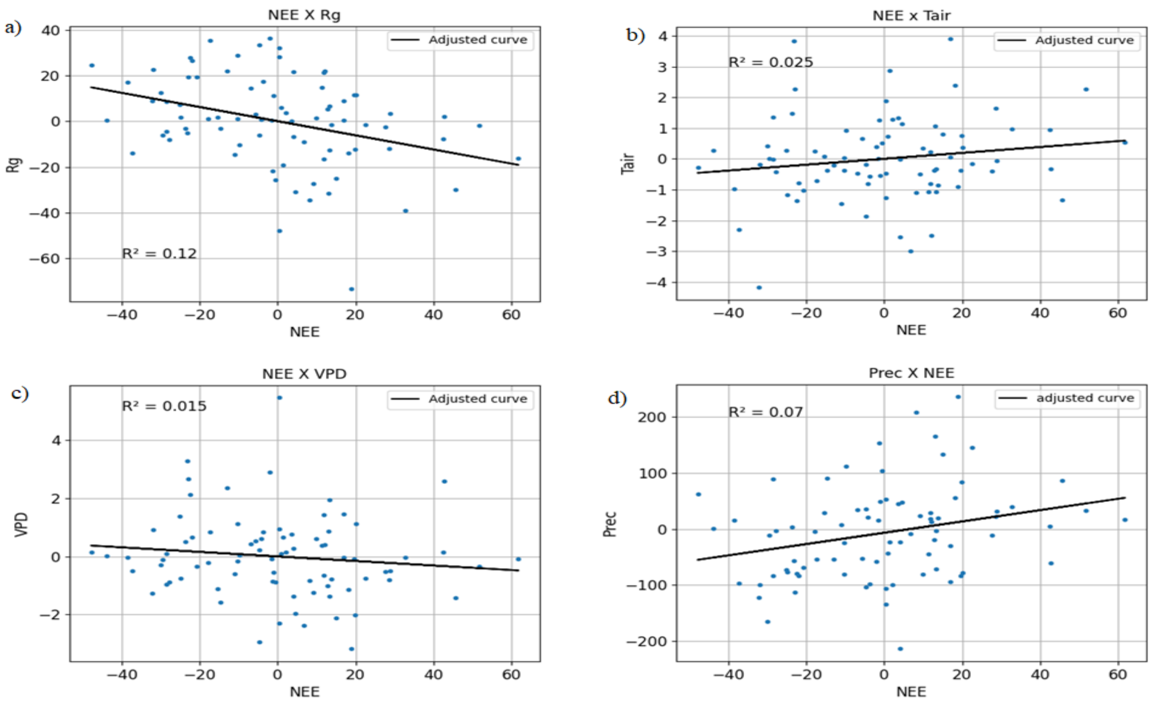
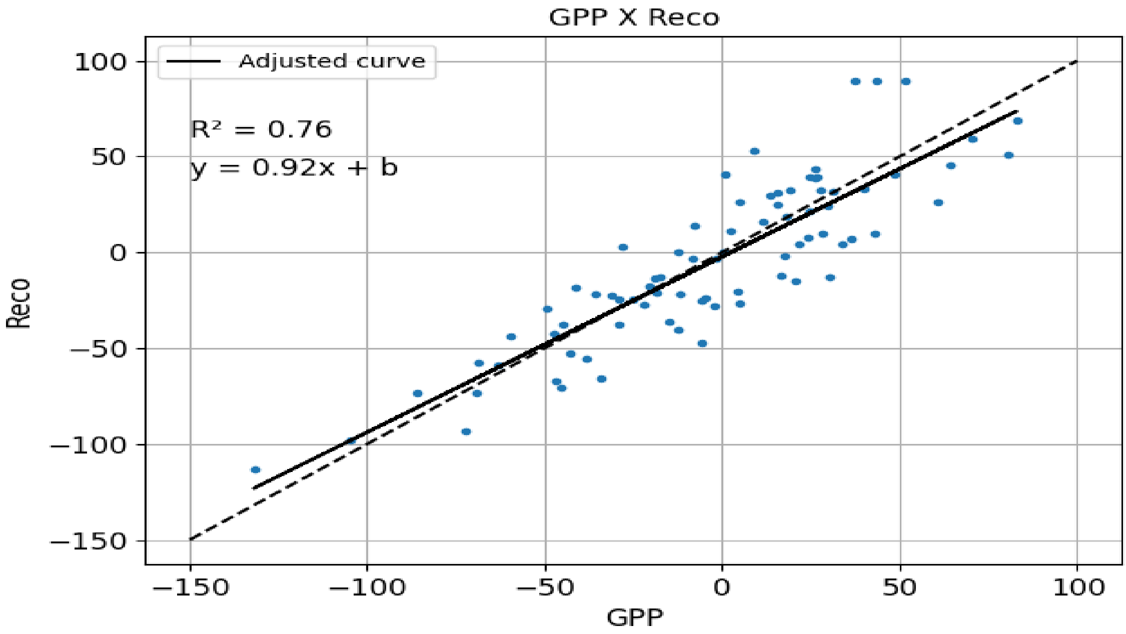


Figure S7 – Anomalies between GPP and Reco.



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4 CONSIDERAÇÕES FINAIS

Consideramos de que o bioma Pampa e seus ecossistemas de pastagens naturais empregados na produção pecuária sob manejo adequado, prestam relevante papel ambiental, como manutenção da paisagem deste bioma e sequestro de carbono, além da produção de carne. O ecossistema de pastagem nativa utilizado para pecuária num sistema de manejo rotacionado atuou como sumidouro de CO_2 da atmosfera em todos os anos analisados. A variabilidade anual de NEE mostrou valores entre -101 gC m^{-2} ano^{-1} (2019) e -381.2 gC m^{-2} ano^{-1} (2015), com valor médio anual, para os 5 anos completos analisados, de -227.1 gC m^{-2} ano^{-1}.

Analisar as relações do manejo pecuário no balanço de carbono da área é uma tarefa complexa, devido à dificuldade em distinguir os diversos fatores que acabam influenciando na dinâmica da troca de CO_2, como os fatores ambientais e climatológicos. De fato, o manejo pecuário empregado na área de estudo mostrou uma produtividade animal acima da média para o estado do Rio Grande do Sul. Desta forma, podemos concluir que é possível unir a produção pecuária com a mitigação de CO_2, através de manejos de pastoreio adequados.

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