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Soil CO_2 emissions under different land-use managements in Mato Grosso do Sul, Brazil

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A R T I C L E I N F O

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A B S T R A C T

Understanding the variability of soil CO_2 emission across several land use and cover (LULC) classes and biomes and its relationship with climate variables is important to drive strategies that contribute to meeting local and international demands for sustainable development and low carbon agriculture. The hypothesis of this research is that soil CO_2 emission *in situ* (FCO_2) is variable between LULCs across different biomes and that there may be an association between soil CO_2 flux and environmental variables such as temperature and soil moisture. This study evaluated FCO_2, measured by a portable EGM-5 CO_2 gas analyzer, CO_2Flux model (obtained by remote sensing approach), soil moisture (SM), soil temperature (ST) and relationship between these variables in different LULC classes. We identified LULCs can contribute to carbon neutralization actions over the Cerrado, Atlantic Forest and Pantanal biomes located in State of Mato Grosso do Sul (MS), Brazil. Four LULC classes were evaluated in each biome: agriculture (soybean cultivation), pasture, eucalyptus plantation, and native vegetation. A principal component analysis (PCA) was performed to verify the relationship between biomes and LULC classes with the variables evaluated, and a Pearson correlation plot was created to assess the relationship between the variables evaluated. The lowest FCO_2 values were found in eucalyptus and soybean crops, regardless of biome. Our findings reveal the existence of soil CO_2 flux variability between the different LULCs and biomes. Pasture in Pantanal and Atlantic Forest biomes exhibited the highest FCO_2 values. Eucalyptus cultivation and native forest showed negative CO_2Flux values, regardless of biome. Lower FCO_2 values were also observed for soybean cultivation. Such findings reinforce that native vegetation function as carbon sinks and that, therefore, their conservation is vital for the mitigation of CO_2 emissions. However, soybean and eucalyptus farming can be strategic for low carbon agriculture in MS and carbon neutralization projects by simultaneously contribute to economic and sustainable development of the regions covered by the biomes evaluated here.

1. Introduction

Tropical soils, rich in biodiversity, play a crucial role in carbon stored, holding about a third of the soil carbon worldwide (Jackson et al., 2017). Soil respiration, also referred to as carbon dioxide efflux (FCO_2) from soil, is an essential element of GHG emissions to the atmosphere in natural ecosystems (Cunha et al., 2021). The temporal variability of FCO_2 is influenced by biotic and abiotic factors, such as changes in temperature, moisture, physical attributes, litter amount, and organic matter content (Cunha et al., 2021; Schwendenmann et al., 2003; Silva et al., 2016; Vicent et al., 2006).

In recent years, major sources of CO_2 emissions have been these actions, through fossil fuel burning activities, which eventually release many tons of carbon into the atmosphere. Furthermore, there are also the impacts of alterations in land use and land cover (LULC), converting native ecosystems are transformed into new agricultural and livestock

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frontier areas (Felizardo, 2022; Scarabel, 2021; Toledo, 2009). The replacement of native vegetation areas with agriculture can lead to alterations in the physical, chemical, and biological characteristics of the soil, triggering an imbalance in the dynamics of organic matter deposition, which consequently increases the carbon emission in the form of gases into the atmosphere (Assunção et al., 2019; Rosset et al., 2014; Sales et al., 2018).

Although action against global climate change (13th Sustainable Development Goal - SDG) is a global concern, Brazil is committed to reducing its carbon footprint (United Nations, 2022). Through Nationally Determined Contributions (NDC) established in the Paris Agreement (UNFCCF COP21), the country has committed to reduce GHG emissions by 43% below 2005 levels by 2030. One of the actions in the agricultural sector is to recovering 15 million hectares of degraded pastures by 2030. Data from the System for Estimating Emissions and Removals of Greenhouse Gases (SEEG, 2021) reveals that land use change and the livestock sector are the country's biggest emitters, accounting for around 70% of total CO_2 equivalent emissions for the period from 1990 to 2020.

Although agriculture and livestock are one of the sectors responsible for global CO_2 emissions, it is Brazil's main economic activity, accounting for 8% of the country's Gross Domestic Product last year (IBGE, 2023). Brazil is the largest global exporter of agricultural commodities, such as soybeans, sugar, beef, poultry, paper and cellulose (BRASIL, 2023). Brazil, along with other countries in the world, such as the BRIC (Brazil, Russia, India and China) countries, which make up 42% of the world's population, are among the countries with the highest agricultural production. Agriculture is considered one of the main drivers of sustainable development in developing countries and in the context of the SDGs, it is an essential tool for eradicating absolute poverty (Agboola and Bekun, 2019; Pata, 2021). Rafiq et al. (2016), in a study employing three different panel data estimators, reported that agriculture play a significant role in reducing pollution in 53 selected countries. Likewise, Agboola and Bekun (2019) reported that agriculture has an insignificant positive impact on CO_2 emissions in Nigeria. Therefore, there is a significant need to know the dynamics of soil CO_2 in different LULCs in order to identify which systems absorb more CO_2, acting as sinks. Such information will contribute for further progress in adopting more sustainable technologies for agricultural development worldwide and Brazil (Buainain et al., 2020; Pata, 2021).

In some Brazilian regions, where the agricultural frontier is partially consolidated, LULC changes and soil management are varied (Santos, 2019). The State of Mato Grosso do Sul (MS), whose predominant economy is agricultural, ranks 11th in greenhouse gas (GHG) emissions and is the fifth largest national producer of grains (Coutinho et al., 2019; IBGE, 2022), with agricultural activities contributing 56% of emissions and 33% from land use change (SEEG - System for Estimating Gas Emissions, 2021). MS still consists of three biomes: Cerrado, Atlantic Forest, and Pantanal, which has recently undergone an accelerated process of replacing native vegetation by the advance of agricultural frontiers (Araujo et al., 2023; Carvalho et al., 2014; Lapola et al., 2014; Thomazini et al., 2015).

Additionally, climatic variables have a direct relationship with FCO_2 to the atmosphere, the major factors being soil moisture and temperature (Brito et al., 2010). Thus, knowing the variability of FCO_2 emissions in agricultural areas and its relationship with climatic variables is crucial to drive sustainable development as well as contribute to supplying the growing carbon markets (Petrielli et al., 2023; Reisch, 2021). Understanding the dynamics of CO_2 flux in different LULC in each biome of MS is crucial for the adoption of strategies that contribute to meeting state and international demands for sustainable development and zero carbon. The hypothesis of this research is that FCO_2 is variable between LULCs across different biomes and that there may be an association between soil CO_2 flux and environmental variables such as temperature and soil moisture. The objectives of the study were i) to estimate the FCO_2, the CO_2 flux model (obtained by remote sensing), temperature (ST) and soil moisture (SM), ii) to evaluated the relationship between these variables in different LULC classes and iii) identify LULCs that have a lower CO_2 flow and consequently contribute to carbon neutralization actions in the Cerrado, Atlantic Forest, and Pantanal biomes.

2. Material and methods

2.1. Study area

The investigation was carried out in MS, situated in Brazil Midwest region. Spanning across an expanse of 357,145.32 km^2 and comprising 78 municipalities, this region boasts a rich tapestry of edaphoclimatic characteristics. These characteristics are widely distributed across three distinct biomes: the Cerrado, the Atlantic Forest, and Pantanal (Fig. 1). The altitudes within Mato Grosso do Sul exhibit considerable variation, ranging from 24 to 1000 m above sea level, marking it as a diverse and geographically dynamic region within South America.

With 22% of the entire Brazilian territory, the Cerrado biome is the second largest in South America and covers an astonishing 65% of the unique features of MS, and is marked by the transition from warm low-latitude to temperate mid-latitude mesothermal climates (Sartori et al., 2018). MS is home to 25% of the Pantanal, featured by long-term floods that happen every year (Mioto et al., 2012). Atlantic Forest is a biome composed of mountain ranges, valleys and plateaus. Characterized as one of the most diverse and widespread tropical forests in South America, it is considered to be the most endangered Brazilian biome (Clemente et al., 2017).

Four LULC classes were evaluated in each biome: agriculture, pasture, eucalyptus plantation, and native vegetation. For the class agriculture, areas that grow soybean during the first crop season (know as "safra") with a history of at least four crop years were chosen. In these areas, the evaluations occurred during the vegetative peak of the crop, approximately 60 days after emergence (DAE). The remaining evaluations were carried out in areas containing each LULC for at least four years. Soybean is the main agricultural crop in the state of Mato Grosso do Sul, corresponding to 8.9% of the land use and occupations in the State (MapBiomas, 2023). Eucalyptus is the main forest genus planted in the state of Mato Grosso do Sul, which currently has the 3rd largest area of eucalyptus plantations and the 2nd largest increase in the area of eucalyptus plantations in the country (IBÁ, 2022). Pasture is the main land use and cover in the State of MS, accounting for around 36% of all land cover in the State (MapBiomas, 2023). The abovementioned factors were decisive in choosing these LULCs for the present study. Additionally, native vegetation was evaluated as a way of having a reference LULC, i.e. areas with optimal CO_2 flow conditions due to the absence of anthropization.

The evaluations in the Cerrado, Pantanal, and Atlantic Forest biomes were carried out within the municipalities of Chapadão do Sul, Aquidauana and Deodápolis, respectively (Fig. 1 and Table 1). These municipalities have edaphoclimatic conditions that are representative of the biomes in which they are located (Silva Junior et al., 2020; Oliveira-Júnior et al., 2020; Abreu et al., 2022; Viana et al., 2023), as well as having areas with the different land uses and occupation evaluated (soybean, eucalyptus, pasture, and native vegetation) with a known history of management, in addition to being easily accessible in terms of infrastructure and logistics for mobility, which were crucial aspects for conducting this research. Such factors were the reasons why these sites were chosen to represent the three biomes under study.

2.2. Data

For soil CO_2 emission *in situ* (FCO_2) assessments, the portable EGM-5 system (PP-Systems, Amesbury, USA), model AGA560, was used at 100 points for each LULC in each biome. EGM-5 system has been used for in-situ data acquisition in recently published studies (Hong et al., 2023; Liu et al., 2023; Yerli and Sahin, 2023; Witcombe et al., 2023). This

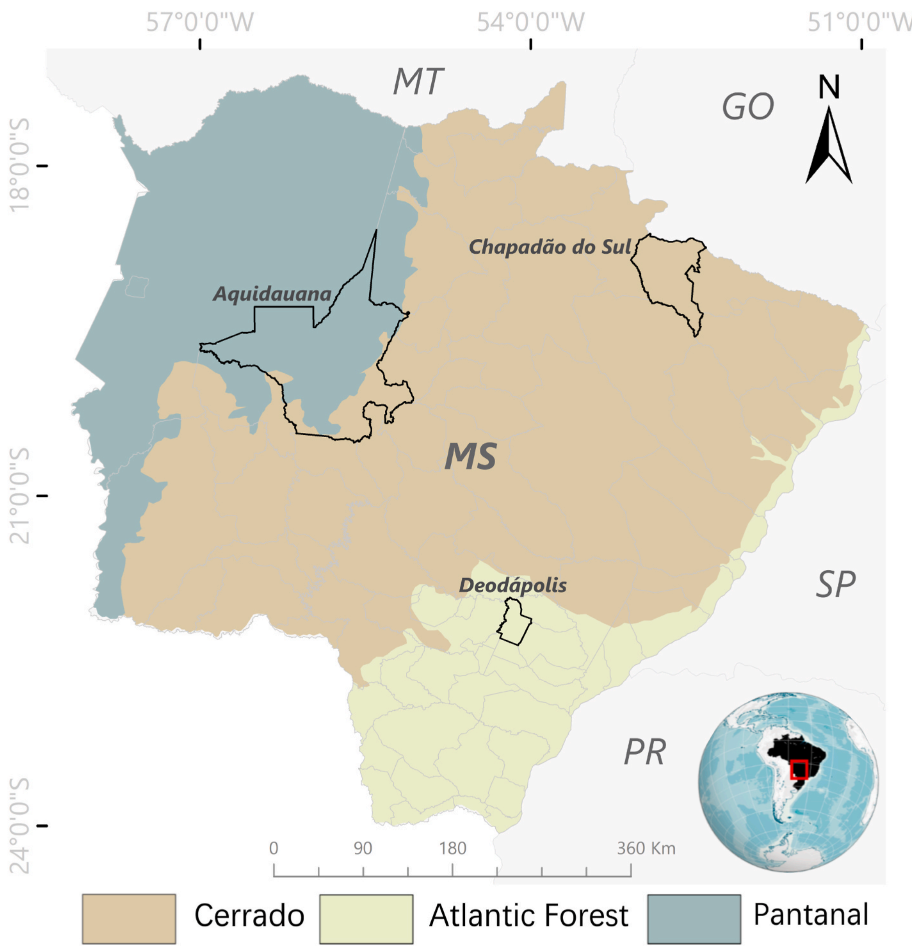

Fig. 1. Location of municipalities (Chapadão do Sul, Aquidauana and Deodápolis) in the different biomes of the State of Mato Grosso do Sul (MS), Brazil.

Table 1
Geographical coordinates of land use and land cover (LULC) evaluated in Cerrado, Pantanal, and Atlantic Forest biomes of Mato Grosso do Sul.

Biome	Agriculture	Pasture	Eucalyptus plantation	Native vegetation
Cerrado	−52.62096, −18.771551	−52.707946, −18.786943	−52.622081, −18.772064	−52.714427, −18.784041
Pantanal	−55.672558, −20.451933	−55.670038, −20.448707	−55.669118, −20.449092	−55.673781, −20.451619
Atlantic Forest	−54.255447, −22.238415	−54.242234, −22.245747	−54.152372, −22.23503	−54.235582, −22.238022

The first value in each cell refers to the longitude relative to West Greenwich (Western Hemisphere), while the value after the comma refers to the latitude relative to the Southern Hemisphere.

equipment monitors the variations of CO_2 concentration inside the soil chamber by means of optical absorption spectroscopy in the infrared spectral region (ACS041). The soil chamber is a closed system with an internal volume of 854.2 cm^3 and a circular contact area of 83.7 cm^2, which was attached to PVC collars inserted 24 h in advance into the soil at each point. This procedure stems from the fact that the direct insertion of the chamber on the soil can lead to disturbances causing additional CO_2 emissions from the soil.

FCO_2 was measured at each sampling point by adjusting the air CO_2 concentration inside the chamber according to a quadratic regression over the time after its closing and water offset. The measuring procedure to assess CO_2 emissions from the soil took 30 s at each point and the barometric pressure inside the chamber was calculated every 1.0 s, totaling 30 readings per sampling point. FCO_2 (μmol m^{-2} s^{-1}) was calculated according to Equation (1), proposed by Parkinson (1981):

$$FCO2 = \frac{dC}{dT} \times \frac{P}{1013} \times \frac{273}{273 + T} \times \frac{V}{A} \times 44.615 \quad (1)$$

Wherein: dC is the variation in CO_2 concentration (ppm); dT is the process execution time (1 s); P is the measured barometric pressure (mbar); T is the air temperature in °C; V is the volume of the EGM-5 chamber (m^3); A is the area of the PVC rings installed in the soil (m^2).

The soil temperature at the same collection points was monitored using a temperature sensor that is an integral component of the ACS044 system. It consists of a 20 cm rod that is inserted inside the soil at 5 cm from the place where the PVC collars were previously installed for the evaluation of soil CO_2 emission. Similarly, soil moisture was recorded using a HydraProbe sensor device (Stevens), This probe consists of a probe with three 12 cm rods that were inserted inside the soil perpendicular to the surface, also 5 cm from the PVC collars. The soil moisture value is derived from the time it takes an electric current to travel 32 mm from one rod to another. Soil temperature and soil moisture assessments were performed together with soil CO_2 emission assessments. All measurements *in situ* along the LULC took place in the same week between November 16th and 19th, 2022. During these evaluations there was no rain in the evaluated areas.

CO_2Flux model (Rahman et al., 2001) was adopted as a way of estimating CO_2Flux via remote sensing data and to assess the effectiveness of the vegetation-related carbon sequestration in the same 100 points of each LULC and biome evaluated. For this purpose, the scaled photochemical reflectance index (sPRI) was calculated according to equation (2) (Gamon et al., 1997; Martins and Baptista, 2013). This index is related to the carotenoid content in the leaves and, consequently, to the CO_2 storage rate (Rahman et al., 2001).

$$sPRI = \left[\left(\frac{B-G}{B+G}\right)+1\right]\times 0.5 \quad (2)$$

Wherein: *A* and *Ve* are the spectral reflectance in the blue and green bands, respectively;

Subsequently, the NDVI (Normalized Difference Vegetation Index) was calculated using Equation (3) (Tucker, 1979). This index is associated with the vigor of photosynthetically active vegetation (Rahman et al., 2001)

$$NDVI = \frac{N-R}{N+R} \quad (3)$$

where N and R are the near-infrared and red spectral reflectance, respectively;

Equation (4) calculates the CO_2Flux (μmol m^{-2} s^{-1}), proposed by Santos (2017), multiplied by NDVI and sPRI. Negative values (−) indicate net carbon absorption (photosynthesis) by the surface and positive values (+) indicate carbon loss to the atmosphere (respiration).

$$CO2Flux = 13.63 - (66.207 * (NDVI * sPRI)) \quad (4)$$

Refining the accuracy and calibration of the CO_2Flux model in Brazil, using direct measurement of CO_2 fluxes through the turbulent vortex covariance technique, as described by Goulden et al. (1996) and validated by Della-Silva et al. (2022). The spectral reflectance used for CO_2Flux calculation were obtained using images from the fully automated cloud-based Planet platform (https://www.planet.com/products/platform) for online image download, processing, and management with a 3 m spatial resolution.

2.3. Approach

In the analyses carried out with R software, boxplots were generated to verify the dispersion of the variables in each LULC and biome. Principal component analysis (PCA) was applied to verify the relationship between the variables evaluated with the LULC classes and biomes. A rotated component matrix was included to establish a simple relationship between the factors and the components using the Varimax orthogonal rotation in combination with the Kaiser's normalization (equalizing communalities temporarily while rotating). Subsequently, a Pearson correlation plot was made to verify whether there is a linear relationship between the variables evaluated.

3. Results

Soil CO_2 emission *in situ* (FCO_2) showed high variability between biomes and LULC classes (Table 2, Fig. 2). Regardless of the biome, the lowest values were obtained in eucalyptus and soybean cultivation (agriculture). In these LULC, the Cerrado biome presented the lowest values. The significant impact of land use activities, with pasture management, in the Pantanal and Atlantic Forest biomes resulted in elevated FCO_2 levels. Native forest presented intermediate FCO_2 and similar values across biomes.

Soil temperature (ST) showed high variability in the Cerrado and Atlantic Forest biomes in all LULC classes, except for the native forest. Pantanal showed the lowest ST variability and means, regardless of LULC. In Cerrado, soybean cultivation presented the highest mean ST. On the other hand, eucalyptus plantation presented the highest mean in the Atlantic Forest. Soil moisture (SM) obtained the lowest means and variability in eucalyptus cultivation, especially in the Cerrado and Pantanal biomes. The SM values in the native forest showed higher variability in the Pantanal biome, while the other biomes showed similar mean and variability. In Pasture, the lowest mean SM was obtained in the Pantanal, while in soybean cultivation the lowest mean was observed in the Cerrado.

Table 2
Mean ± standard error for the variables soil CO_2 emission *in situ* (FCO_2), soil moisture (SM), soil temperature (ST), and CO_2Flux evaluated in different land uses and land cover in the biomes of Mato Grosso do Sul, Brazil.

Biome	Agriculture	Pasture	Eucalyptus plantation	Native vegetation
	Soil CO_2 emission *in situ*			
Cerrado	1.33 ± 0.04	2.60 ± 0.10	1.03 ± 0.04	3.73 ± 0.08
Pantanal	1.03 ± 0.06	6.26 ± 0.12	2.46 ± 0.06	4.08 ± 0.19
Atlantic Forest	2.35 ± 0.08	6.50 ± 0.15	3.03 ± 0.07	5.02 ± 0.08
	Soil moisture			
Cerrado	2.74 ± 0.14	7.45 ± 0.24	0.89 ± 0.11	4.89 ± 0.18
Pantanal	5.48 ± 0.25	1.99 ± 0.26	0.50 ± 0.06	6.49 ± 0.27
Atlantic Forest	5.55 ± 0.18	6.61 ± 0.35	4.12 ± 0.14	3.87 ± 0.13
	Soil temperature			
Cerrado	41.25 ± 0.41	33.99 ± 0.22	32.96 ± 0.28	30.92 ± 0.08
Pantanal	26.51 ± 0.06	26.70 ± 0.04	27.42 ± 0.02	26.37 ± 0.01
Atlantic Forest	32.72 ± 0.37	26.88 ± 0.03	33.51 ± 0.12	33.33 ± 0.06
	CO_2Flux			
Cerrado	5.33 ± 0.08	14.69 ± 0.07	−2.73 ± 0.08	−1.12 ± 0.05
Pantanal	0.43 ± 0.16	0.45 ± 0.03	−2.98 ± 0.05	−4.21 ± 0.07
Atlantic Forest	−2.80 ± 0.05	1.51 ± 0.05	−3.12 ± 0.05	−2.73 ± 0.06

Eucalyptus cultivation and native forest showed negative CO_2Flux values, regardless of biome. The remaining LUC classes presented positive CO_2Flux means in all biomes, except for soybean cultivation in the Atlantic Forest. Higher variability was found in soybean cultivation compared to the other LULC classes.

Fig. 3 shows the PCA for the variables evaluated in the three biomes of the State of Mato Grosso do Sul. It is evident from that the points sampled in the Cerrado biome are the most separated from the others in the biplot. These points are close to the ST vector, as this biome obtained the lowest means and variability for its LULC classes. The similarity between Atlantic Forest and Pantanal is associated with the FCO_2 vector, where these biomes obtained the highest means and variability for this variable.

The values in Table 3 for factor loadings indicate the contribution of each variable for rotated component. The results clearly showed that RC1 was having a high proportion of variation of 0.35 with greater contribution from CO2flux (0.81) and SM (0.78), while in the RC2 factor there was a high loading for FCO2 (0.79) and ST (0.69).

Fig. 4 shows the PCA for the variables evaluated in the LULC classes in each biome. It is possible to verify that in the Cerrado biome (Fig. 4A), LULC classes presented distinct behaviors associated with specific variables. Native forest had higher FCO_2 means, while pasture had the highest SM means in this biome. The other variables (CO_2flux and ST) were associated with soybean cultivation.

In the Atlantic Forest (Fig. 4B) and Pantanal (Fig. 4C), pasture differed from other LULC by presenting higher FCO_2 and lower CO_2Flux means. Native forest was similar to soybean and eucalyptus cultivation in this biome, especially in terms of ST values in Atlantic Forest. In Pantanal, there was higher similarity between soybean cultivation and native forest, which was associated with the highest SM means. Eucalyptus cultivation in the Pantanal biome was associated with slightly higher ST means compared to the other LULC classes.

Pearson's correlations between the variables evaluated along the biomes are presented in Fig. 5. The variable FCO_2 correlated negatively

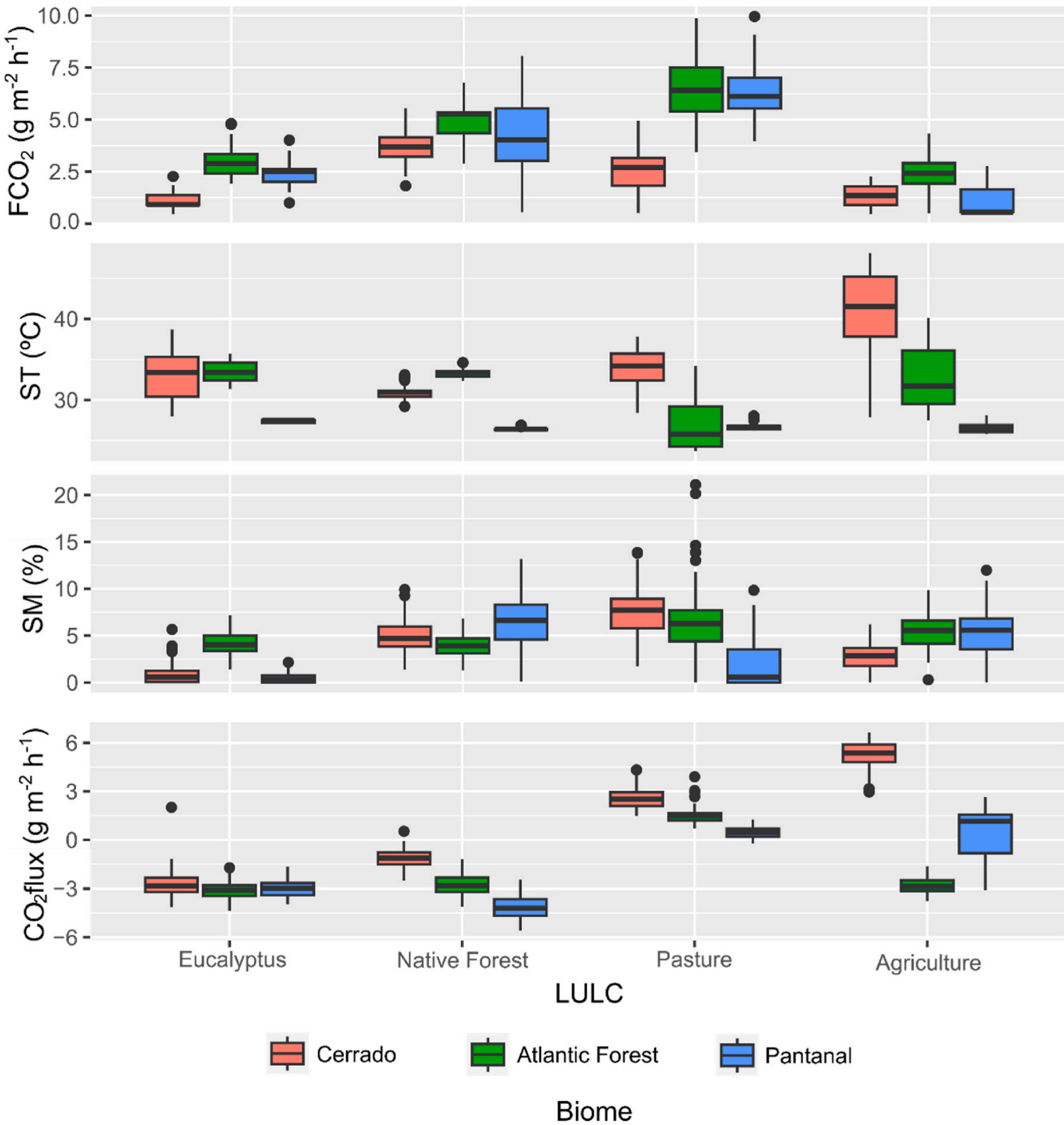

Fig. 2. Boxplot for the variables soil CO_2 emission *in situ* (FCO_2), soil moisture (SM), soil temperature (ST), and CO_2Flux evaluated in different land uses and land cover in the biomes of Mato Grosso do Sul, Brazil.

and at intermediate magnitude with ST, with emphasis on the Atlantic Forest, where this correlation presented greater magnitude, while in the Pantanal it was null. Specific correlations occurred positively between FCO_2 x SM and FCO_2 x CO_2Flux in the Cerrado and Atlantic Forest biomes, respectively.

There was a negative correlation between ST and SM in moderate magnitude in the Pantanal and Atlantic Forest biomes. In Cerrado, a positive correlation was observed between ST and CO_2flux, while in the Atlantic Forest this correlation was negative. The correlation between SM and CO_2flux, revealed a complex interplay of these variables, exhibited low and moderate magnitudes in the Cerrado and Atlantic Forest biomes, respectively.

4. Discussion

Differences in soil carbon dioxide flux *in situ* between LULC classes and biomes can be induced by soil property conditions, vegetation composition, soil organic matter (SOM), and interactions between these factors. The amount of carbon contained in SOM is being lost since the 1850s by land use change and increasing pressure on agroecosystems by rising global demand for energy and food (Hossain, 2020; Lal, 2010; Sanderman et al., 2017).

In this study, there was variability in FCO_2 between LULC and biomes, a fact reported in other research (Canteral et al., 2023; Lucena et al., 2023; Rossi et al., 2023; Tavanti et al., 2020), where the lowest FCO_2 values were found in eucalyptus and soybean cultivation, regardless of biome, indicating that these LULC have vegetation with lower metabolic activity, resulting in a lower CO_2 release to the atmosphere. According to Rossi et al. (2023) the lowest FCO_2 values in a time series are in the high and low-productive potential soybean LULC. These findings are relevant from an economic and environmental perspectives, as they indicate that eucalyptus and soybean may be crops to be considered in carbon neutralization strategies within sustainable development approaches, such low carbon agriculture. These crops can be part of strategies aimed at replacing areas with degraded pastures, for example, or even in association with productive pasture areas, such as in

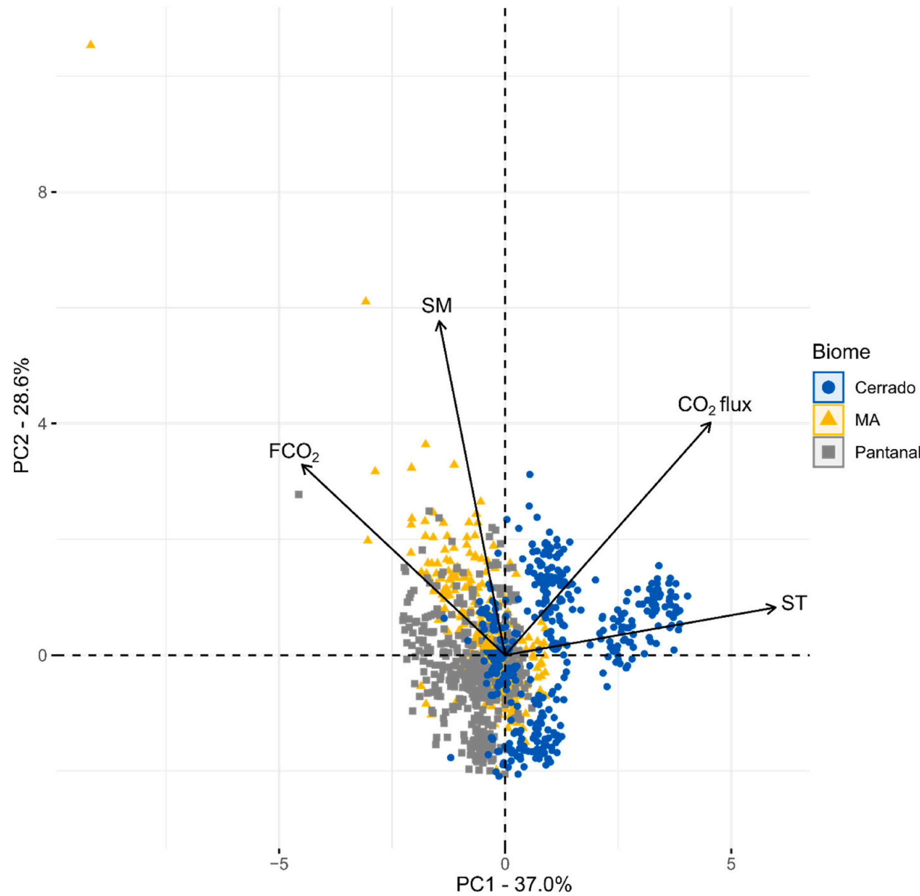

Fig. 3. Principal component analysis for the variables soil CO_2 emission *in situ* (FCO_2), soil moisture (SM), soil temperature (ST), and CO_2Flux evaluated in the biomes Cerrado, Atlantic Forest (MA) and Pantanal of Mato Grosso do Sul, Brazil.

Table 3
Factor loadings for rotated component (RC) matrix for the variables soil CO_2 emission *in situ* (FCO_2), soil moisture (SM), soil temperature (ST), and CO_2Flux evaluated in different land uses and land cover in the biomes of Mato Grosso do Sul, Brazil.

Variable	RC1	RC2
FCO_2	−0.33	0.79
SM	0.78	−0.29
ST	0.20	0.69
CO_2Flux	0.81	0.19
Proportion of variance	0.35	0.30

crop-livestock-forest integration systems.

On the other hand, the highest FCO_2 values were observed in the pasture, Pantanal, and Atlantic Forest biomes. Native forest showed intermediate values of FCO_2, without great variations among biomes. Ecosystems that have greater potential for water storage and regulation have higher soil CO_2 flux rates (McKnight et al., 2017). Thus, the type of vegetation cover and land use have a significant impact on soil CO_2 emissions (Chamizo et al., 2017; Ghimire et al., 2017; Lal, 2013).

Temperature and moisture are controls that most influence SOM dynamics and CO_2 respiration in soils, with higher rates of CO_2Flux model observed in soils with higher moisture and temperature (López-Santiago et al., 2023; Rosenzweig et al., 2016). SOM decomposition is temperature-dependent, and both direct (enzyme kinetics and microbial metabolism) and indirect (carbon substrate solubility and diffusion) effects of temperature play an important role (Conant et al., 2011; Ramesh et al., 2019; Sihi et al., 2016), where tropical evergreen forests usually have higher soil respiration rates due to their high net primary productivity (Ren et al., 2012; Rolando et al., 2017). No study has presented a single equation showing the temperature dependence of soil respiration, and the relationship of variation between different ecosystems and soil types.

Changes in soil carbon sequestration have a marked influence on the global carbon cycle and climate change (Ramesh et al., 2019). However, detecting the management practices and land uses that act as carbon sinks is essential for establishing strategies to mitigate climate change. Our results revealed negative CO_2Flux values for eucalyptus and native forest areas in all biomes, indicating that these LULC classes act as carbon reservoirs, sequestering CO_2 from the atmosphere. These negative values are directly linked to the photosynthetically active radiation (PAR) absorbed by the green biomass of the studied sites, i.e., the canopy photosynthetic capacity present in the LULC (Della-Silva et al., 2022). The other LULC have positive CO_2Flux values in all biomes, except soybean cultivation in the Atlantic Forest, which had higher variability compared to the other LULC classes.

The State of Mato Grosso do Sul has recently become the largest pulp exporter of the country. Forestry sector, which is largely made up of eucalyptus plantations, is one of the main economic activities in the State, which as well as being concerned with economic growth, also has the ambitious goal of becoming a Carbon Neutral state by 2030. Considering the goals assumed by Brazil under the Paris Agreement under the United Nations Framework Convention on Climate Change, enacted by Federal Decree No. 9073 of June 5, 2017, the State of Mato Grosso do Sul joined the "Race to Zero" and "Under 2° Coalition" campaigns under the United Nations Framework Convention on Climate Change, and has sought public actions and policies that contribute to GHG emissions in various productive sectors. In this scenario, the LULCs evaluated in our study are of great importance in achieving these goals,

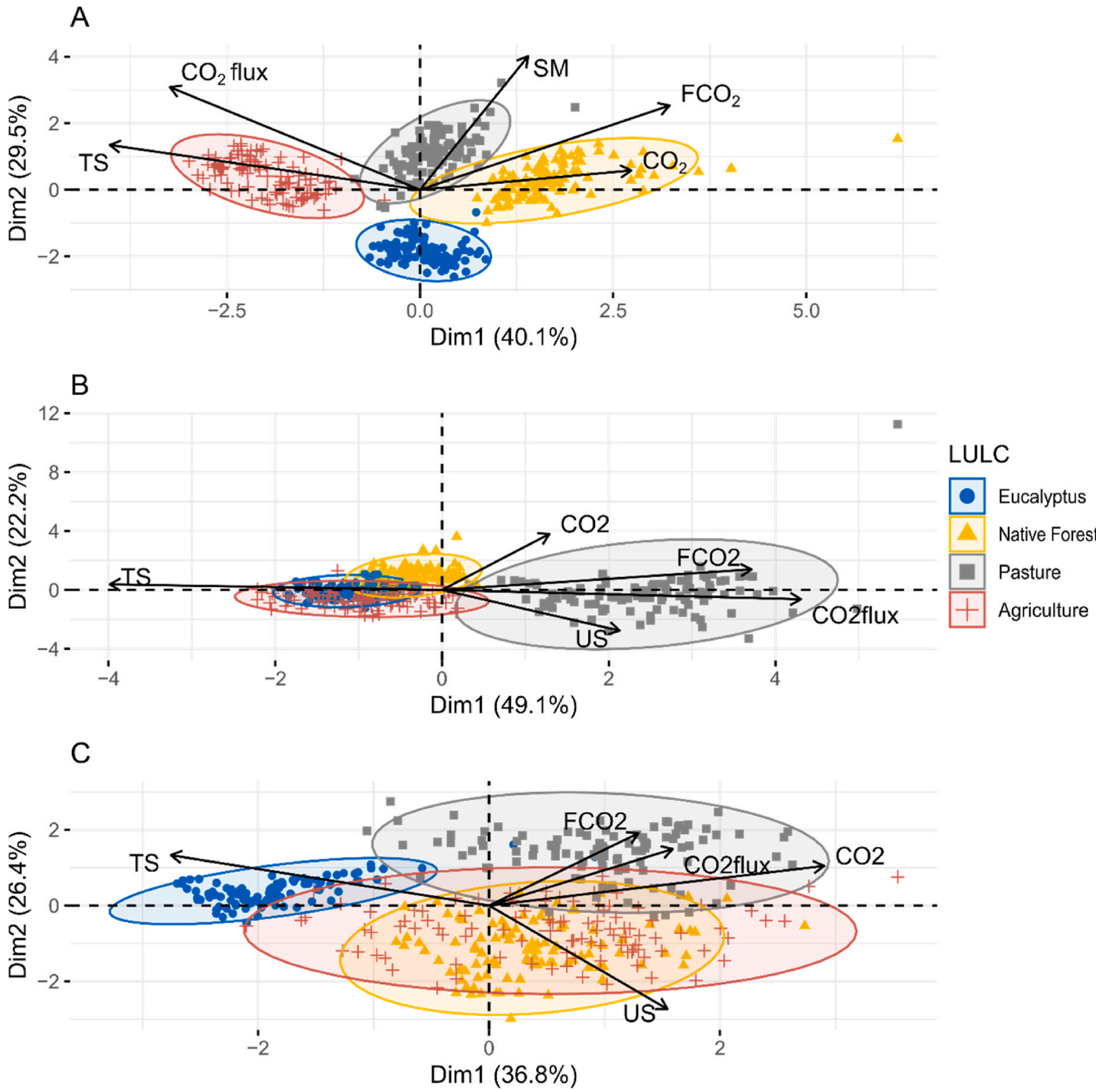

Fig. 4. Component analysis for the variables soil CO_2 emission *in situ* (FCO_2), soil moisture (SM), soil temperature (ST), and CO_2Flux evaluated in different land uses and land cover in the Cerrado (A), Atlantic Forest (B), and Pantanal (C) biomes of Mato Grosso do Sul, Brazil.

since the state government can create policies to encourage production systems that contribute to mitigating carbon emissions, such as the adoption of integrated livestock-forestry (LF) or crop-livestock-forestry systems (ICLF).

Integrated systems, such as ICLF, which combine crop, livestock and trees, or even livestock-forestry integration have been proposed as a more sustainable alternative for livestock production in the tropics due to its benefits from both an economic and sustainable perspective. Several studies has reported that ICLF can generate important benefits to the ecosystem, such as improvements in soil properties and biodiversity (Chakravarty et al., 2019; Mora et al., 2016). Portilho et al. (2018) verified that management systems under integrated crop-livestock farming in Southern State of Mato Grosso do Sul maintained a relatively diverse N cycling bacterial community, possibly promoting soil quality and N cycling processes. Our results point to the potential for eucalyptus plantations to sequester carbon, regardless of the biome evaluated. In this sense, the adoption of eucalyptus plantations in integration with pastures, which our study showed to be the LULC with the highest FCO_2, can be an important strategy to mitigate GHG emissions in the agricultural sector and consequently be implemented as a more sustainable technology for MS and Brazil to achieve the SDGs by 2030.

The Cerrado biome is separated from the other biomes in the biplot, being closer to the ST variable and exhibiting the lowest means and variability of ST among the LULC classes. Increased temperature can amplify CO_2 efflux, impacting atmospheric CO_2 concentrations. (Sanjita et al., 2022). High soil temperature, as presented by the relationship between ST and the Cerrado biome can affect and be affected by respiration rates of microorganisms influencing various physiological processes and potentially resulting in significant alterations in the community composition of the biotic soil component (Mohan, 2019). Conversely, the Atlantic Forest and Pantanal biomes present a similarity by being associated with the FCO_2 variable, showing the highest means and variability in these biomes by sharing some environmental characteristics due to this variable.

Tree species in forest soil biogeochemical processes and soil microbial communities provide organic matter through litter and roots (Zheng et al., 2017), which can shape soil microbial communities by altering soil abiotic variables such as pH and resource availability. (Lee et al., 2023). Soil pH influences the solubility of humic substances and the desorption of SOM from minerals. Higher pH increases the solubility of

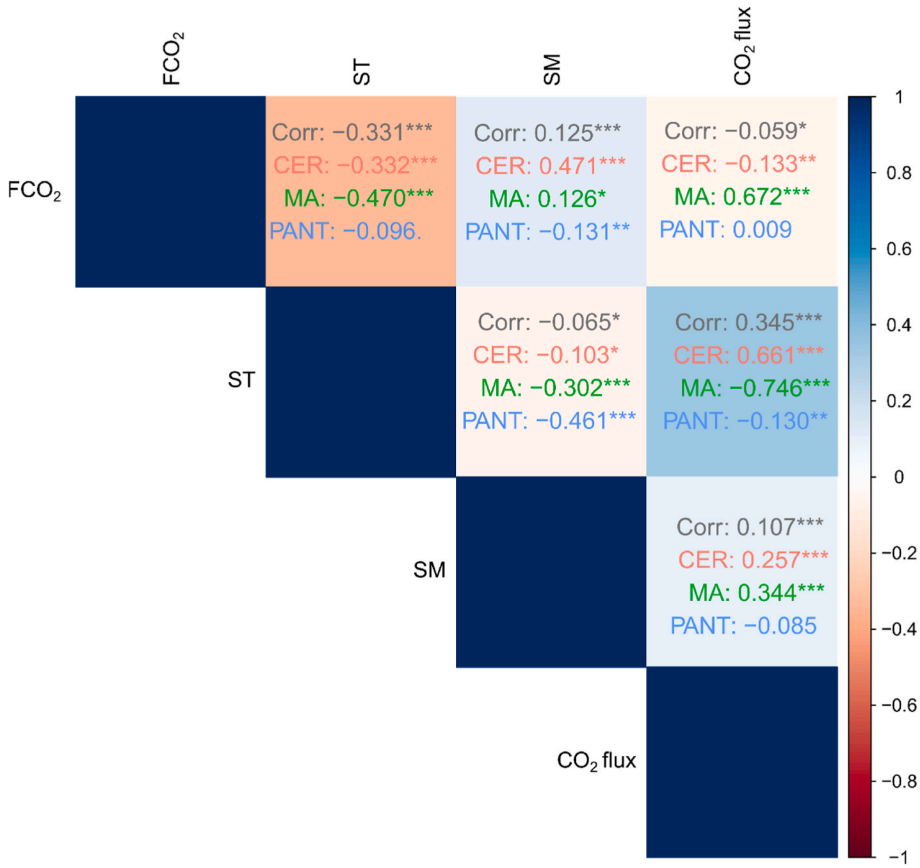

Fig. 5. Pearson correlation analysis for the variables soil CO_2 emission *in situ* (FCO_2), soil moisture (SM), soil temperature (ST), and CO_2Flux evaluated in different land uses and land cover in Cerrado (CER), Atlantic Forest (MA) and Pantanal (PANT) biomes of Mato Grosso do Sul, Brazil.

humic substances and promotes their dissolution, promoting higher microbial carbon use efficiency and possibly higher SOM sequestration (Ekström et al., 2011; Garbuio et al., 2011; Sihi et al., 2016).

There are complex interactions and different responses in each LULC class and biome with the variables. The results found indicate that the vegetation contained in the LULC, ST and SM play important roles in regulating soil carbon dioxide flux, with a negative relationship between FCO_2 and ST, especially in the Atlantic Forest, while this association was null in the Pantanal biome, as already reported in other studies (Canteral et al., 2023; Lucena et al., 2023; Moitinho et al., 2021a, 2021b; Rossi et al., 2023). Soil moisture has a beneficial influence on soil

soil respiration in seasonally rainy areas, while soil temperature has a negative influence, impacting root respiration on total FCO_2 (Lima et al., 2023; Meena et al., 2020; Silva et al., 2017). The variables assessed do not indicate a direct understanding of the relationships between them. Therefore, future research, such as controlled experiments or long-term studies, is needed to investigate the underlying mechanisms and confirm the observed relationships.

Future researches should be carried out in different geographical and climatic conditions to those assessed here, such as other municipalities within each biome and assessments at other seasons of the year. Measurements carried out in different locations and throughout the seasons require more time and financial and human resources, but could contribute to a broader understanding of the dynamics of FCO_2 and its relationship with factors such as local precipitation and temperature.

Further studies should also be carried out on land uses and occupations different from those evaluated here, which are the limitations of our study. Here, we limited the assessments to native vegetation and the main agricultural activities in the State of Mato Grosso do Sul (soybean, eucalyptus, pasture) as a way of obtaining a more comprehensive study focused on the major state's economic potentialities that can contribute to neutralizing carbon emissions in short and mid-term. However, there are other important LULCs in the State of MS, especially within agriculture, such as maize, sugarcane and cotton, which are important production systems not only for the State but for the entire country. Other locations in Brazil should also be evaluated in order to obtain information on the dynamics of FCO_2 in other biomes and different LULCs according to the socio-economic and sustainable potential of each region.

5. Conclusions

The results obtained here show the existence of soil CO_2 emission *in situ* (FCO_2) variability between the different LULCs and biomes. The lowest FCO_2 values were found in eucalyptus plantation and soybean cultivation, regardless of the biome. In these LULC classes, the Cerrado biome presented the lowest FCO_2 values. On the other hand, higher FCO_2 values were verified in pasture areas in the Pantanal and Atlantic Forest. The lowest soil temperature means were obtained in the Pantanal, regardless of LULC, while soil moisture obtained the lowest means and variability in eucalyptus cultivation, especially in the Cerrado and Pantanal. Eucalyptus cultivation and native forest showed negative CO_2Flux values, regardless of biome. In this scenario, our study reinforces that native vegetation areas function as carbon sinks and that, therefore, their conservation is vital for the mitigation of CO_2 emissions to the atmosphere. On the other hand, our findings also reveal that soybean and eucalyptus farming can be strategic activities for carbon neutralization projects, as they can simultaneously contribute to economic and sustainable development in Mato Grosso do Sul and other Brazilian regions that cover the biomes assessed here.

Future researches should be carried out in other geographical and climatic conditions different from those evaluated here, such as more municipalities within each biome, different land uses and occupation and long-term evaluations over different seasons of the year.

CRediT authorship contribution statement

Paulo Eduardo Teodoro: Conceptualization, Formal analysis, Project administration, Resources, Supervision, Writing – original draft. **Fernando Saragosa Rossi:** Data curation, Formal analysis. **Larissa Pereira Ribeiro Teodoro:** Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Dthenifer Cordeiro Santana:** Formal analysis. **Rafael Felippe Ratke:** Investigation. **Izabela Cristina de Oliveira:** Investigation. **João Lucas Della Silva:** Investigation. **João Lucas Gouveia de Oliveira:** Data curation. **Natielly Pereira da Silva:** Data curation. **Fábio Henrique Rojo Baio:** Data curation, Writing – review & editing. **Francisco Eduardo Torres:** Writing – original draft, Writing – review & editing. **Carlos Antonio da Silva Junior:** Conceptualization, Formal analysis, Project administration, Resources, Visualization, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

Abreu, M.C., Lyra, G.B., de Oliveira-Júnior, J.F., Souza, A., Pobočíková, I., de Souza Fraga, M., Abreu, R.C.R., 2022. Temporal and spatial patterns of fire activity in three biomes of Brazil. Sci. Total Environ. 844, 157138 https://doi.org/10.1016/j.scitotenv.2022.157138.

Agboola, M.O., Bekun, F.V., 2019. Does agricultural value added induce environmental degradation? Empirical evidence from an agrarian country. Environ. Sci. Pollut. Res. 26, 27660–27676. https://doi.org/10.1007/s11356-019-05943-z.

Araujo, A.P., Bicalho, A.M., Varga, I., 2023. Pantanal sustentável: sistemas alternativos de produção na pecuária bovina de corte. In: Zootecnia: Tópicos Atuais Em Pesquisa. Editora Científica Digital, Guarujá, pp. 168–180. https://doi.org/10.37885/230212186.

Assunção, S.A., Pereira, M.G., Rosset, J.S., Berbara, R.L.L., García, A.C., 2019. Carbon input and the structural quality of soil organic matter as a function of agricultural management in a tropical climate region of Brazil. Sci. Total Environ. 658, 901–911. https://doi.org/10.1016/j.scitotenv.2018.12.271.

BRASIL, 2023. Exportações do agronegócio fecham 2022 com US$ 159 bilhões em vendas - Ministério da Agricultura e Pecuária [WWW Document]. URL. https://www.gov.br/agricultura/pt-br/assuntos/noticias/exportacoes-do-agronegocio-fecham-2022-com-us-159-bilhoes-em-vendas#:~:text=Dezembro%2F2022&text=Os%20cinco%20principais%20setores%20exportadores,participa%C3%A7%C3%A3o%20de%2010%2C4%25.

Brito, L. de F., Marques Júnior, J., Pereira, G.T., La Scala Junior, N., 2010. Spatial variability of soil CO2 emission in different topographic positions. Bragantia 69, 19–27. https://doi.org/10.1590/S0006-87052010000500004.

Buainain, A.M., Favareto, A., Contini, E., Chaves, F.T., Henz, G.P., Garcia, J.R., Damiani, O., Vieira, P.A., Grundling, R.D.P., Nogueira, V.G.C., 2020. Desafios para a agricultura nos biomas brasileiros, Embrapa. Brasília.

Canteral, K.F.F., Vicentini, M.E., de Lucena, W.B., de Moraes, M.L.T., Montanari, R., Ferraudo, A.S., Peruzzi, N.J., La Scala, N., Panosso, A.R., 2023. Machine learning for prediction of soil CO2 emission in tropical forests in the Brazilian Cerrado. Environ. Sci. Pollut. Control Ser. 30, 61052–61071. https://doi.org/10.1007/s11356-023-26824-6.

Carvalho, J.L.N., Raucci, G.S., Frazão, L.A., Cerri, C.E.P., Bernoux, M., Cerri, C.C., 2014. Crop-pasture rotation: a strategy to reduce soil greenhouse gas emissions in the Brazilian Cerrado. Agric. Ecosyst. Environ. 183, 167–175. https://doi.org/10.1016/j.agee.2013.11.014.

Chakravarty, S., Pala, N.A., Tamang, B., Sarkar, B.C., Manohar, K.A., Rai, P., Puri, A., Vineeta, Shukla, G., 2019. Ecosystem services of trees outside forest. In: Sustainable Agriculture, Forest and Environmental Management. Springer Singapore, Singapore, pp. 327–352. https://doi.org/10.1007/978-981-13-6830-1_10.

Chamizo, S., Serrano-Ortiz, P., López-Ballesteros, A., Sánchez-Cañete, E.P., Vicente-Vicente, J.L., Kowalski, A.S., 2017. Net ecosystem CO 2 exchange in an irrigated olive orchard of SE Spain: influence of weed cover. Agric. Ecosyst. Environ. 239, 51–64. https://doi.org/10.1016/j.agee.2017.01.016.

Clemente, S.D.S., Oliveira, J.F.D., Passos Louzada, M.A., 2017. Hot spots in the Atlantic Forest of the State of Rio de Janeiro. Braz. J. Meteorol. 32, 669–677.

Conant, R.T., Ryan, M.G., Ågren, G.I., Birge, H.E., Davidson, E.A., Eliasson, P.E., Evans, S.E., Frey, S.D., Giardina, C.P., Hopkins, F.M., Hyvönen, R., Kirschbaum, M.U.F., Lavallee, J.M., Leifeld, J., Parton, W.J., Megan Steinweg, J., Wallenstein, M.D., Martin Wetterstedt, J.Å., Bradford, M.A., 2011. Temperature and soil organic matter decomposition rates - synthesis of current knowledge and a way forward. Glob Chang Biol 17, 3392–3404. https://doi.org/10.1111/j.1365-2486.2011.02496.x.

Coutinho, M., Bitencourt, M., Figueiredo-Neto, L., Figueiredo, A., 2019. A contribuição das atividades de base agropecuária na geração de emprego nos municípios de Mato Grosso do Sul (Brasil). Eure 45, 223–244. https://doi.org/10.4067/S0250-71612019000200223.

Cunha, José Maurício da, Campos, Milton César Costa, Gaio, D.C., Souza, Z.M. de, Soares, M.D.R., Silva, D.M.P. da, Simões, E.L., 2021. Emissão de CO2 do solo em áreas de terra preta arqueológica na região amazônica. In: Cunha, J.M., Campos, M.C.C., Brito Filho, E.G. (Eds.), Terra Preta Arqueológica: Atributos Morfológicos, Físicos, Químicos e Efluxo de CO2 Em Solos Sob Diferentes Usos Na Região Sul Do Amazonas. Atena Editora, Ponta Grossa, pp. 46–66. https://doi.org/10.22533/at.ed.2002107074.

Della-Silva, J.L., da Silva Junior, C.A., Lima, M., Teodoro, P.E., Nanni, M.R., Shiratsuchi, L.S., Teodoro, L.P.R., Capristo-Silva, G.F., Baio, F.H.R., de Oliveira, G., de Oliveira-Júnior, J.F., Rossi, F.S., 2022. CO_2Flux model assessment and Comparison between an airborne hyperspectral sensor and orbital multispectral imagery in southern amazonia. Sustainability 14. https://doi.org/10.3390/su14095458.

Ekström, S.M., Kritzberg, E.S., Kleja, D.B., Larsson, N., Nilsson, P.A., Graneli, W., Bergkvist, B., 2011. Effect of acid deposition on quantity and quality of dissolved organic matter in soil–water. Environ. Sci. Technol. 45, 4733–4739. https://doi.org/10.1021/es104126f.

Felizardo, L.M., 2022. Estoque de carbono nos biomas brasileiros com enfoque no cerrado e no cultivo de eucalipto no Mato Grosso do Sul. Universidade Estadual Paulista "Júlio Mesquita Filho," Ilha Solteira.

Gamon, J., Serrano, L., Surfus, J.S., 1997. The photochemical reflectance index: an optical indicator of photosynthetic radiation use efficiency across species, functional types, and nutrient levels. Oecologia 112, 492–501.

Garbuio, F.J., Jones, D.L., Alleoni, L.R.F., Murphy, D.V., Caires, E.F., 2011. Carbon and nitrogen dynamics in an oxisol as affected by liming and crop residues under No-till. Soil Sci. Soc. Am. J. 75, 1723–1730. https://doi.org/10.2136/sssaj2010.0291.

Ghimire, B., Ghimire, R., VanLeeuwen, D., Mesbah, A., 2017. Cover crop residue amount and quality effects on soil organic carbon mineralization. Sustainability 9, 2316. https://doi.org/10.3390/su9122316.

Goulden, M.L., Munger, J.W., Fan, S.-M., Daube, B.C., Wofsy, S.C., 1996. Measurements of carbon sequestration by long-term eddy covariance: methods and a critical evaluation of accuracy. Glob. Chang. Biol. 2, 169–182. https://doi.org/10.1111/j.1365-2486.1996.tb00070.x.

Hong, J., Kim, H., Lee, W., Yu, J., Fischer, T.P., Takahata, N., Sano, Y., Lee, H., 2023. Fault-related basins as carbon reservoirs: soil CO2 emissions in the SE Korean Peninsula. Catena 231, 107300. https://doi.org/10.1016/j.catena.2023.107300.

Hossain, M.B., 2020. Agricultural land use and management practice influence on efflux and influx of carbon between soil and the atmosphere: a review. Int J Plant Soil Sci 32, 31–48.

IBÁ, 2022. Relatório Anual 2022 - Indústria Brasileira de Árvores [WWW Document]. URL. https://www.iba.org/datafiles/publicacoes/relatorios/relatorio-anual-iba2022-compactado.pdf.

IBGE, 2022. Instituto Brasileiro de Geografia e Estatística [WWW Document]. URL. https://agenciadenoticias.ibge.gov.br/agencia-noticias/2012-agencia-de-noticias/noticias/35056-valor-de-producao-da-silvicultura-e-da-extracao-vegetal-cresce-27-1-e-chega-ao-recorde-de-r-30-1-bilhoes.

IBGE, 2023. Instituto Brasileiro de Geografia e Estatística [WWW Document]. URL https://sidra.ibge.gov.br/tabela/1846#/n1/all/v/all/p/-1/c11255/90687,90691,90696,90705,90706,90707,93404,93405,93406,93407,93408,102880/l/v,,c11255+t+p/resultado (accessed 10.30.23)..

Jackson, R.B., Lajtha, K., Crow, S.E., Hugelius, G., Kramer, M.G., Piñeiro, G., 2017. The ecology of soil carbon: pools, vulnerabilities, and biotic and abiotic controls. Annu. Rev. Ecol. Evol. Syst. 48, 419–445. https://doi.org/10.1146/annurev-ecolsys-112414-054234.

Lal, R., 2013. Soil carbon management and climate change. Carbon Manag. 4, 439–462. https://doi.org/10.4155/cmt.13.31.

Lal, R., 2010. Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. Bioscience 60, 708–721. https://doi.org/10.1525/bio.2010.60.9.8.

Lapola, D.M., Martinelli, L.A., Peres, C.A., Ometto, J.P.H.B., Ferreira, M.E., Nobre, C.A., Aguiar, A.P.D., Bustamante, M.M.C., Cardoso, M.F., Costa, M.H., Joly, C.A., Leite, C. C., Moutinho, P., Sampaio, G., Strassburg, B.B.N., Vieira, I.C.G., 2014. Pervasive transition of the Brazilian land-use system. Nat Clim Chang 4, 27–35. https://doi.org/10.1038/nclimate2056.

Lee, J., Zhou, X., Seo, Y.O., Lee, S.T., Yun, J., Yang, Y., Kim, J., Kang, H., 2023. Effects of vegetation shift from needleleaf to broadleaf species on forest soil CO2 emission. Sci. Total Environ. 856, 158907 https://doi.org/10.1016/j.scitotenv.2022.158907.

Lima, J.R. de S., Souza, R.M.S., Sampaio, E.V. de S.B., Antonino, A.C.D., Souza, E.S. de, Medeiros, É.V. de, Duda, G.P., Ferreira, C.R.P.C., Menezes, R.S.C., Hammecker, C., 2023. Moisture, temperature and respiration of two soil classes under pasture and tropical dry forest in the semiarid Brazilian region. J. Arid Environ. 214, 104981. https://doi.org/10.1016/j.jaridenv.2023.104981.

Liu, Y., Lin, J., Yue, H., 2023. Soil respiration estimation in desertified mining areas based on UAV remote sensing and machine learning. Earth Sci. Informatics. https://doi.org/10.1007/s12145-023-01094-5.

López-Santiago, J.G., Villanueva-López, G., Casanova-Lugo, F., Aryal, D.R., Pozo-Leyva, D., 2023. Livestock systems with scattered trees in paddocks reduce soil CO2 fluxes compared to grass monoculture in the humid tropics. Agrofor. Syst. 97, 209–221. https://doi.org/10.1007/s10457-022-00799-8.

Lucena, W.B., Vicentini, M.E., Santos, G.A.D.A., Silva, B.D.O., Costa, D.V.M. Da, Canteral, K.F.F., Neira Román, J.A., Rolim, G.D.S., Panosso, A.R., La Scala Jr., N., 2023. Temporal variability of the CO2 emission and the O2 influx in a tropical soil in contrasting coverage conditions. J South Am Earth Sci 121, 104120. https://doi.org/10.1016/j.jsames.2022.104120.

MapBiomas Project, 2023. Collection 8 of the annual land cover and land use maps of Brazil (1985-2022. https://doi.org/10.58053/MapBiomas/VJIJCL,MapBiomasData, V1.

Martins, L.N., Baptista, G.D., 2013. Multitemporal analysis of forest carbon sequestration in the Carão Settlement project, Acre. Braz. J. Phys. Geogr. 6 (06), 1648–1657.

McKnight, J.Y., Harden, C.P., Schaeffer, S.M., 2017. Soil CO 2 flux trends with differences in soil moisture among four types of land use in an Ecuadorian páramo landscape. Phys. Geogr. 38, 51–61. https://doi.org/10.1080/02723646.2016.1256101.

Meena, A., Hanief, M., Dinakaran, J., Rao, K.S., 2020. Soil moisture controls the spatio-temporal pattern of soil respiration under different land use systems in a semi-arid ecosystem of Delhi, India. Ecol Process 9, 15. https://doi.org/10.1186/s13717-020-0218-0.

Mioto, C.L., Paranhos Filho, do Amaral Albrez, E., 2012. Contribution to the characterization of the Pantanal sub-regions. Entre-Lugar 3 (6), 165–180.

Mohan, J.E., 2019. Ecosystem Consequences of Soil Warming: Microbes, Vegetation, Fauna and Soil Biogeochemistry. Academic Press.

Moitinho, M.R., Ferraudo, A.S., Panosso, A.R., da Silva Bicalho, E., Teixeira, D.D.B., de Andrade Barbosa, M., Tsai, S.M., Borges, B.M.F., de Souza Cannavan, F., de Souza, J. A.M., La Scala, N., 2021a. Effects of burned and unburned sugarcane harvesting systems on soil CO2 emission and soil physical, chemical, and microbiological attributes. Catena 196, 104903. https://doi.org/10.1016/j.catena.2020.104903.

Moitinho, M.R., Teixeira, D.D.B., Bicalho, E. da S., Panosso, A.R., Ferraudo, A.S., Pereira, G.T., Tsai, S.M., Borges, B.M.F., La Scala, N., 2021b. Soil CO2 emission and soil attributes associated with the microbiota of a sugarcane area in southern Brazil. Sci. Rep. 11, 8325. https://doi.org/10.1038/s41598-021-87479-2.

Mora, F., Balvanera, P., García-Frapolli, E., Castillo, A., Trilleras, J.M., Cohen-Salgado, D., Salmerón, O., 2016. Trade-offs between ecosystem services and alternative pathways toward sustainability in a tropical dry forest region. Ecol. Soc. 21, art45. https://doi.org/10.5751/ES-08691-210445.

Oliveira-Júnior, J.F. de, Teodoro, P.E., Silva Junior, C.A. da, Baio, F.H.R., Gava, R., Capristo-Silva, G.F., Gois, G. de, Correia Filho, W.L.F., Lima, M., Santiago, D. de B., Freitas, W.K., Santos, P.J. dos, Costa, M. da S., 2020. Fire foci related to rainfall and biomes of the state of Mato Grosso do Sul, Brazil. Agric. For. Meteorol. 282–283, 107861 https://doi.org/10.1016/j.agrformet.2019.107861.

Parkinson, K.J., 1981. An improved method for measuring soil respiration in the field. J. Appl. Ecol. 221–228.

Pata, U.K., 2021. Linking renewable energy, globalization, agriculture, CO2 emissions and ecological footprint in BRIC countries: a sustainability perspective. Renew. Energy 173, 197–208. https://doi.org/10.1016/j.renene.2021.03.125.

Petrielli, G.P., Nogueira, G.P., Henzler, D. de S., de Souza, N.R.D., Bruno, K.M.B., Luciano, A.C., dos, S., le Maire, G., Hernandes, T.A.D., 2023. Integrating carbon footprint to spatialized modeling: the mitigation potential of sugarcane ethanol production in the Brazilian Center-South. Resour. Conserv. Recycl. 189, 106725 https://doi.org/10.1016/j.resconrec.2022.106725.

Portilho, I.I.R., Savin, M.C., Borges, C.D., Tsai, S.M., Mercante, F.M., Roscoe, R., de Carvalho, L.A., 2018. Maintenance of N cycling gene communities with crop-livestock integration management in tropical agriculture systems. Agric. Ecosyst. Environ. 267, 52–62. https://doi.org/10.1016/j.agee.2018.08.005.

Rafiq, S., Salim, R., Apergis, N., 2016. Agriculture, trade openness and emissions: an empirical analysis and policy options. Aust. J. Agric. Resour. Econ. 60, 348–365. https://doi.org/10.1111/1467-8489.12131.

Rahman, A.F., Gamon, J.A., Fuentes, D.A., Roberts, D.A., Prentiss, D., 2001. Modeling spatially distributed ecosystem flux of boreal forest using hyperspectral indices from AVIRIS imagery. J. Geophys. Res. Atmos. 106, 33579–33591. https://doi.org/10.1029/2001JD900157.

Ramesh, T., Bolan, N.S., Kirkham, M.B., Wijesekara, H., Kanchikerimath, M., Srinivasa Rao, C., Sandeep, S., Rinklebe, J., Ok, Y.S., Choudhury, B.U., Wang, H., Tang, C., Wang, X., Song, Z., Freeman II, O.W., 2019. Soil Organic Carbon Dynamics: Impact of Land Use Changes and Management Practices: A Review, pp. 1–107. https://doi.org/10.1016/bs.agron.2019.02.001.

Reisch, R.D.N., 2021. O potential brasileiro para gerar créditos de carbono através da conservação florestal, reflorestamento e produção agrícola sustentável. Geografia Física e Meio Ambiente 1, e61662.

Ren, W., Tian, H., Tao, B., Huang, Y., Pan, S., 2012. China's crop productivity and soil carbon storage as influenced by multifactor global change. Glob Chang Biol 18, 2945–2957. https://doi.org/10.1111/j.1365-2486.2012.02741.x.

Rolando, J.L., Dubeux, J.C., Perez, W., Ramirez, D.A., Turin, C., Ruiz-Moreno, M., Comerford, N.B., Mares, V., Garcia, S., Quiroz, R., 2017. Soil organic carbon stocks and fractionation under different land uses in the Peruvian high-Andean Puna. Geoderma 307, 65–72. https://doi.org/10.1016/j.geoderma.2017.07.037.

Rosenzweig, S.T., Carson, M.A., Baer, S.G., Blair, J.M., 2016. Changes in soil properties, microbial biomass, and fluxes of C and N in soil following post-agricultural grassland restoration. Appl. Soil Ecol. 100, 186–194. https://doi.org/10.1016/j.apsoil.2016.01.001.

Rosset, J.S., Lana, M.D.C., Pereira, M.G., Schiavo, J.A., Rampim, L., Sarto, M.V.M., Seidel, E.P., 2014. Carbon stock, chemical and physical properties of soils under management systems with different deployment times in western region of Paraná, Brazil. Semin Cienc Agrar 35, 3053. https://doi.org/10.5433/1679-0359.2014v35n6p3053.

Rossi, F.S., La Scala, N., Capristo-Silva, G.F., Della-Silva, J.L., Teodoro, L.P.R., Almeida, G., Tiago, A.V., Teodoro, P.E., Silva Junior, da, C.A., 2023. Implications of CO2 emissions on the main land and forest uses in the Brazilian Amazon. Environ. Res. 227, 115729 https://doi.org/10.1016/j.envres.2023.115729.

Sales, A., Resende Silva, A., Alberto Costa Veloso, C., Jorge Maklouf Carvalho, E., Maia Miranda, B., 2018. Carbono orgânico e atributos físicos do solo sob manejo agropecuário sustentável na Amazônia legal. COLLOQUIUM AGRARIAE 14, 1–15. https://doi.org/10.5747/ca.2018.v14.n1.a185.

Sanderman, J., Hengl, T., Fiske, G.J., 2017. Soil carbon debt of 12,000 years of human land use. Proc. Natl. Acad. Sci. USA 114, 9575–9580. https://doi.org/10.1073/pnas.1706103114.

Sanjita, C., Thounaojam, R.S., Singh, ThB., Singh, N.D., 2022. Soil CO2 efflux variability influenced by different factors in the subtropical sacred groves of Manipur, North-East India. Trop. Ecol. 63, 650–663. https://doi.org/10.1007/s42965-022-00225-1.

Santos, C.V.B.D., 2017. Spectral Modeling to Determine CO_2 Flux in Preserved and Regenerating Caatinga Areas. State University of Feira de Santana [s. l.].

Santos, T.C., 2019. Impactos das mudanças de uso da terra e manejo nos estoques de carbono do solo em diferentes biomas brasileiros. Universidade Federal de Alagoas, Rio Largo.

Sartori, Â.L.B., Pott, V.J., Pott, A., de Carvalho, F.S., 2018. Check-list of the Angiosperms of the Chaco of Mato Grosso do Sul. Iheringia Série Botânica 73, 22–33.

Scarabel, G.B., 2021. Variação espaço-temporal do CO2 atmosferico e da Fluorescencia da clorofila induzida pelo sol para o Estado do Mato Grosso do Sul. Universidade Estadual Paulista, Jaboticabal.

Schwendenmann, L., Veldkamp, E., Brenes, T., O'Brien, J.J., Mackensen, J., 2003. Spatial and temporal variation in soil CO2 efflux in an old-growth neotropical rain forest, La Selva, Costa Rica. Biogeochemistry 64, 111–128. https://doi.org/10.1023/A:1024941614919.

SEEG - System for Estimating Gas Emissions, 2021. Estimativa de emissões de gases de efeito estufa no Brasil em 2021 [WWW Document]. URL https://plataforma.seeg.eco.br/territories/mato-grosso-do-sul/card?year=2021&cities=false (accessed 6.12.23)..

Sihi, D., Gerber, S., Inglett, P.W., Inglett, K.S., 2016. Comparing models of microbial–substrate interactions and their response to warming. Biogeosciences 13, 1733–1752. https://doi.org/10.5194/bg-13-1733-2016.

Silva, C.M. da, Vasconcelos, S.S., Mourão Júnior, M., Bispo, C.J.C., Kato, O.R., Silva Junior, A.C. da, Castellani, D.C., 2016. Variação temporal do efluxo de CO2do solo em sistemas agroflorestais com palma de óleo na Amazônia Oriental. Acta Amazon 46, 1–12. https://doi.org/10.1590/1809-4392201500193.

Silva, P.F. da, Lima, J.R. de S., Antonino, A.C.D., Souza, R., Souza, E.S., de Silva, J.R.I., Alves, E.M., 2017. Seasonal patterns of carbon dioxide, water and energy fluxes over the Caatinga and grassland in the semi-arid region of Brazil. J. Arid Environ. 147, 71–82. https://doi.org/10.1016/j.jaridenv.2017.09.003.

Silva Junior, C.A. da, Teodoro, L.P.R., Teodoro, P.E., Baio, F.H.R., Pantaleão, A. de A., Capristo-Silva, G.F., Facco, C.U., Oliveira-Júnior, J.F. de, Shiratsuchi, L.S., Skripachev, V., Lima, M., Nanni, M.R., 2020. Simulating multispectral MSI bandsets (Sentinel-2) from hyperspectral observations via spectroradiometer for identifying soybean cultivars. Remote Sens. Appl. Soc. Environ. 19, 100328 https://doi.org/10.1016/j.rsase.2020.100328.

Tavanti, R.F.R., Montanari, R., Panosso, A.R., La Scala, N., Chiquitelli Neto, M., Freddi, O. da S., Paz González, A., de Carvalho, M.A.C., Soares, M.B., Tavanti, T.R., Galindo, F.S., 2020. What is the impact of pasture reform on organic carbon compartments and CO2 emissions in the Brazilian Cerrado? Catena 194, 104702. https://doi.org/10.1016/j.catena.2020.104702.

Thomazini, A., Mendonça, E.S., Souza, J.L., Cardoso, I.M., Garbin, M.L., 2015. Impact of organic no-till vegetables systems on soil organic matter in the Atlantic Forest biome. Sci. Hortic. 182, 145–155. https://doi.org/10.1016/j.scienta.2014.12.002.

Toledo, J.J., 2009. Influência do solo e topografia sobre a mortalidade de árvores e decomposição de madeira em uma floresta de terra firme na Amazônia Central, Manaus. Instituto Nacional de Pesquisas da Amazônia - INPA, Manaus.

Tucker, C.J., 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens. Environ. 8, 127–150. https://doi.org/10.1016/0034-4257(79)90013-0.

United Nations, 2022. United Nations | peace. dignity and equality on a healthy planet [WWW Document]. URL. https://www.un.org/en/.

Viana, L.F., do Amaral Crispim, B., Kummrow, F., Alice de Lima, N., Amaral Dias, M., Carolina Montagner, C., Henrique Gentil Pereira, R., de Barros, A., Barufatti, A., 2023. Occurrence of contaminants of emerging concern and their risks to the Pantanal Sul-Mato-Grossense aquatic biota, Brazil. Chemosphere 337, 139429. https://doi.org/10.1016/j.chemosphere.2023.139429.

Vicent, G., Shahriari, A., Lucot, E., Badot, P., Epron, D., 2006. Spatial and seasonal variations in soil respiration in a temperate deciduous forest with fluctuating water table. Soil Biol. Biochem. 38, 2527–2535. https://doi.org/10.1016/j.soilbio.2006.03.009.

Witcombe, A.M., Tiemann, L.K., Chikowo, R., Snapp, S.S., 2023. Diversifying with grain legumes amplifies carbon in management-sensitive soil organic carbon pools on smallholder farms. Agric. Ecosyst. Environ. 356, 108611 https://doi.org/10.1016/j.agee.2023.108611.

Yerli, C., Sahin, U., 2023. Pre-sowing soil carbon dioxide emissions of the following year from the silage maize field irrigated with different levels of wastewater in conventional and direct sowing practices. J. Water Clim. Chang. 14, 1358–1370. https://doi.org/10.2166/wcc.2023.012.

Zheng, X., Wei, X., Zhang, S., 2017. Tree species diversity and identity effects on soil properties in the Huoditang area of the Qinling Mountains, China. Ecosphere 8, e01732. https://doi.org/10.1002/ecs2.1732.