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What is the impact of pasture reform on organic carbon compartments and CO_2 emissions in the Brazilian Cerrado?

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ABSTRACT

The emission of CO_2 from the soil in agricultural areas is the result of the interaction of several factors, including soil and crop management practices and local edaphoclimatic conditions. The dynamics of organic carbon (OC), in the midst of reform processes in agricultural areas, can be used as an indicator of chemical soil quality because carbon loss is directly related to its lability, quality, or decomposition capacity. This study aimed to evaluate the impact of the reform of degraded pastures in the soil organic matter compartment and its effect on mitigating CO_2 emissions. The study was carried out in the municipality of Selvíria, Mato Grosso do Sul, Brazil, in two areas destined for extensive beef cattle grazing, subsidized by the forage plant *Urochloa brizantha* cv. Marandu. Geostatistical meshes were installed in the areas, and soil samples of deformed and undeformed structures were taken to evaluate the physical and chemical attributes of the soil. The results indicated that soil management practices, followed by the cultivation of sorghum intercropped with *U. brizantha*, increased the total OC (TOC) stocks through the stable fraction (OC associated with the mineral fraction) and consequent reduction in CO_2 emissions from the soil. This highlights the spatial variability in CO_2 emissions and how soil attributes affect the flow of CO_2 into the atmosphere. The use of multivariate geostatistics has made it possible to forecast CO_2 emissions from the soil. This small-scale study provides a theoretical basis for the large-scale spatial monitoring of biogeochemical processes that control CO_2 emissions in agricultural ecosystems, particularly in degraded pasture areas.

1. Introduction

With a commercial herd of approximately 215.2 million animals, Brazil is the largest beef producer and exporter worldwide (IBGE, 2015). However, the practice of extensive cattle ranching in the country, a low-tech and profitable productive model, has led to the transition of land use from pasture to crops, especially sugar cane (*Saccharum officinarum* L.) (Silva Costa et al., 2012). It is estimated that around 32 million ha of pasture show some stage of degradation in the Brazilian Cerrado (Soares et al., 2020). This change in the use of degraded pasture areas for sugar cane cultivation has stimulated the greater disposal of animals, including matrices in semi-confined areas.

This condition can be justified by problems related to the quality and structure of the soil, which does not provide input for the maximum productive expression of pastures. Extensive production systems have low C stocks in the surface horizons of the soil (Almeida et al., 2015),

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low fertility and acidity gradients (Vieira et al., 2008), and superficial soil compaction (de Assis Valadão et al., 2015), which characterize these areas as extractive and degraded systems. In addition to these soil conditions providing low animal productivity, degraded pastures contribute to increased losses of soil organic matter due to reductions in the quantity and quality of organic material added to the soil. This increases the greenhouse gas emissions per kilogram of meat or milk produced (IPCC, 2017). In this context, it is necessary to adopt sustainable land management (SLM) to maintain continuous soil cover, considering not only the amounts of organic matter input, but also the quality of the added material (Sanz et al., 2017). Management practices, such as adequate fertilization, periodic corrections to soil acidity, rotation, and adequate animal stocking capacity, are viable alternatives for the recovery of degraded pastures that can lead to increased beef productivity in the country.

Among the four groups of SLM technologies considered for grazing lands proposed by the United Nations Convention to Combat Desertification (UNCCD), vegetation management leads to a higher increase in soil organic carbon (SOC). In addition to grazing management improving beef production, this practice minimizes the negative impacts of grazing by recovering degraded lands, which can lead to carbon sequestration with a suggested average of 0.35 t ha^{-1} $year^{-1}$ C. Depending on the climatic region, it can vary between 0.02 and 0.8 t ha^{-1} $year^{-1}$ of C (Sanz et al., 2017).

The process of CO_2 emission from soil is associated with increased microbial activity, mainly through soil preparation and other management activities, such as liming (Almaraz et al., 2009; Fuentes et al., 2006) and fertilization (Yang et al., 2017). Initially, soil preparation during pasture reform operations increases CO_2 emission rates from the soil into the atmosphere because of the solubilization of carbonates (from limestone) and the rupture of soil aggregates, in which part of the C occlusion becomes more susceptible to mineralization, owing to its exposure to microbial action supported by increased oxygenation and soil temperature (Schwartz et al., 2010; Silva et al., 2014). However, after a short period of time, there is a reduction in the labile fractions of SOM, the basal microbial activity decreases, and a new dynamic balance is established (Six et al., 2006). This causes medium- and long-term reductions in CO_2 emissions and increases in carbon stocks in the soil.

As it is still a recent event, there are few studies on tropical areas that characterize the CO_2 emission process and assess changes in physical carbon compartments after pasture reform with crop transition. To the best of our knowledge, the multivariate geostatistical approach has never been used to study the influence of soil attributes on carbon compartments and CO_2 emissions. In this sense, the hypothesis of the study is that with the reform of pastures through liming and fertilization, it will be possible to increase the stock of the stable fraction of organic C in the soil, which will contribute to increases in C stocks in the long term and thus reduce CO_2 emissions into the atmosphere. This study aimed to evaluate the impact of degraded pasture reform on the physical compartment of SOM and its effect on mitigating CO_2 emissions.

2. Material and methods

2.1. Study location

The study was conducted in the municipality of Selvíria, Mato Grosso do Sul, Brazil (20° 21′ 58.2″ S, 51° 24′ 47.8″ W, altitude 357 m). The climate of the region, according to the Köppen classification, is defined as Aw (humid tropical), with rainy seasons in summer and dry conditions in winter, an average annual temperature of 25 °C, an annual precipitation of 1330 mm, and a relative humidity of 66%. The local soil was classified as Latossolo Vermelho distrófico (LVd), according to Sistema Brasileiro de Classificação do Solo (Embrapa, 2018), or loamy sand Oxisol, according to the Soil Survey Staff (2014), with a clay content in the 0.00–0.20 m layer of 130 g kg^{-1}, silt content of 60 g kg^{-1}, and sand content of 810 g kg^{-1}, as determined by the pipette method (Embrapa, 2017). The chemical characteristics of the soil before the implementation of the experiment were as follows: organic matter content of 17.0 g kg^{-1}, pH in $CaCl_2$ of 4.9, P of 5.8 mg kg^{-1}, K of 0.6 $mmol_c$ kg^{-1}, Ca of 9.4 $mmol_c$ kg^{-1}, Mg of 10.5 $mmol_c$ kg^{-1}, Al of 0.9 $mmol_c$ kg^{-1}, total cation exchange capacity of 40.5 $mmol_c$ kg^{-1}, and saturation by bases of 50.1%, determined according to the methodology proposed by Van Raij et al. (2001).

In 1989, the study area was opened, mechanized, and later divided into 11 plots with dimensions ranging from 1.0 to 3.0 ha. These plots were used for the exploitation of extensive beef cattle, with the planting and grazing of Marandu grass (*Urochloa brizantha* Marandu). In the years 2002, 2008, and 2013, there were corrections of soil acidity and application of inputs in the areas: 1.5 t ha^{-1} of dolomitic limestone and 31 kg ha^{-1} of urea (45% N), 123 kg ha^{-1} of triple superphosphate (40% P_2O_5 and 10% Ca), and 47 kg ha^{-1} of potassium chloride (60% K_2O). In 2017, the pasture management system was changed in some of the farm plots, with the aim of cultivating forage sorghum (*Sorghum bicolor* [L.] Moench) after acidity and fertilization corrections in the rainy season for silage production (Fig. 1). For this, the pasture was removed using a heavy disk harrow and, later, dolomitic limestone was applied at a dose of 1.0 t ha^{-1}, according to the calculated need for a 60% base saturation increase. Then, the limestone was incorporated with an intermediate grid, and the ground was leveled with a light disk grid. Basic fertilization was carried out with 45 kg ha^{-1} of urea (45% N), 175 kg ha^{-1} of triple superphosphate (40% P_2O_5 and 10% of Ca), and 67 kg ha^{-1} of chloride potassium (60% K_2O) in the throwing system. Later, the sorghum was sown in a consortium with *U. brizantha*, also in the throwing system. The calculated population density of sorghum plants was 150,000 plants ha^{-1}.

2.2. Treatments, sampling schemes, and soil analysis

Among the 11 plots, two were selected to determine and map the physical and chemical attributes of the soil. The main difference between the selected areas was the pasture management system adopted. One of the areas has been renovated, as described above, with a view to cultivating sorghum for silage production in consortium with *U. brizantha*, and another area has remained unchanged since 2013 (Fig. 1). In both areas, the average animal stocking rate was 3 animal units ha^{-1} $year^{-1}$. During the cultivation of sorghum for approximately 100 days, there was no animal grazing. After the sorghum harvest, the area was again grazed by the animals.

Two georeferenced sampling meshes were installed in each of the areas, with dimensions equivalent to 2.7 and 1.4 ha, containing 70 and 65 points, respectively, distributed and spaced arbitrarily, as shown in Fig. 2. The sampling was irregular to detail the spatial dependence of soil attributes over short and long distances (Soares et al., 2020) (see Fig. 2).

Deformed structure samples were collected with the aid of a Dutch-type auger in the 0.00–0.15 m layer to determine the levels of available P, K, Ca, and Mg; H potential in $CaCl_2$ (pH); exchangeable Al; potential acidity at pH 7.0 (H + Al); cation exchange capacity (CEC) at pH 7.0; base saturation (BS); and Al saturation (m%), according to the methodology proposed by Van Raij et al. (2001). The clay, silt, and sand contents were determined using the pipette method, according to the methodology proposed by Embrapa (2017).

The C content was determined following the method described by Cambardella and Elliott (1992). After passing the soil samples through a 0.053 mm sieve, the particulate organic C (POC) was separated from the organic C (OC) associated with the mineral fraction (OCAM), in which only the POC was determined, and the OCAM was obtained by the difference between the total OC (TOC) and POC. To determine the TOC content, 10 mL of 1 M HCl was added to 10 g of soil to remove the carbonates (inorganic carbon from limestone). After this procedure, the

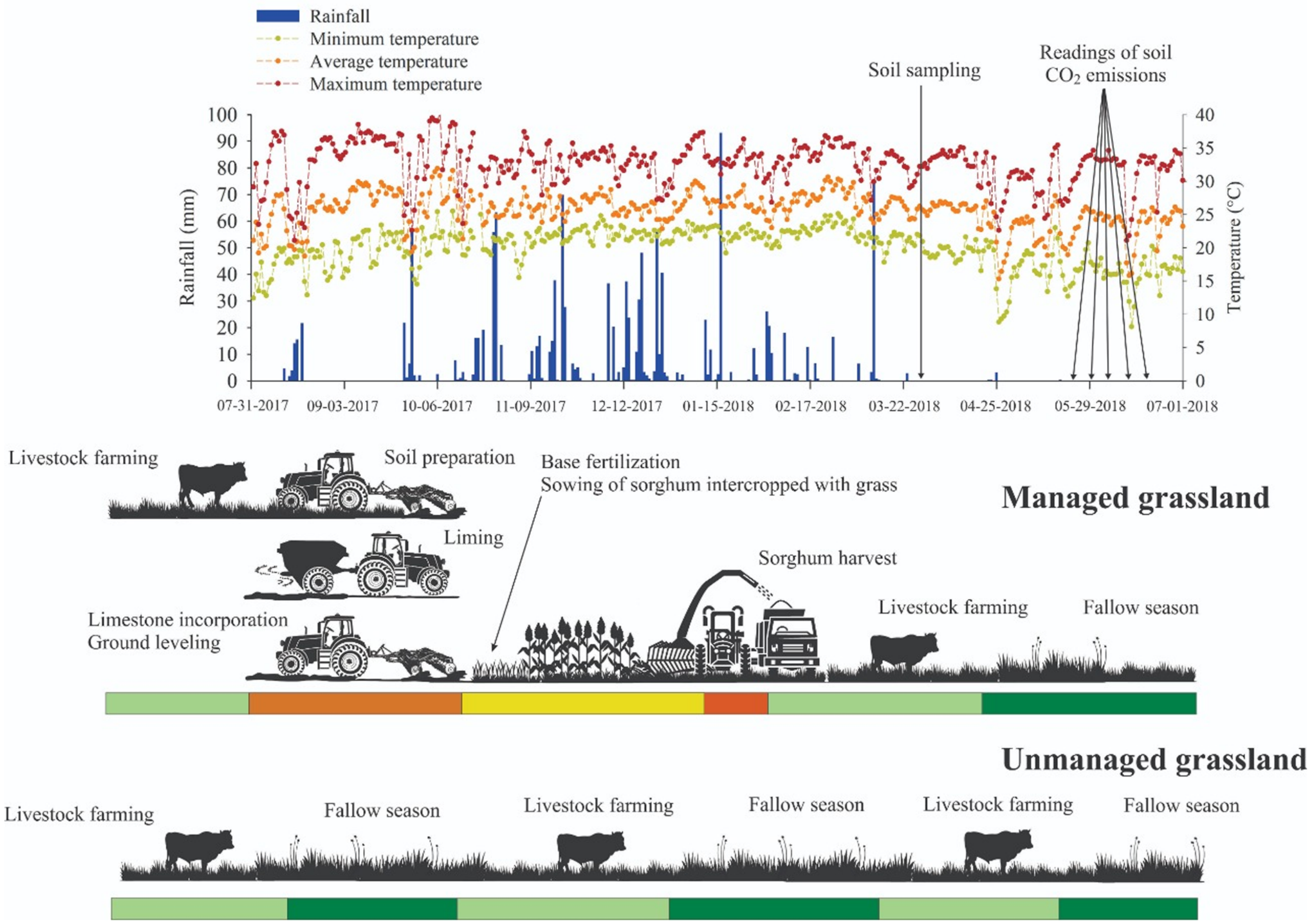

Fig. 1. Daily minimum, average, and maximum precipitation and temperatures during the period of conducting the experiment in an Oxisol. The illustrations below the graph correspond to the management histories of the areas as well as their respective realization dates, as shown in the X-axis of the graph.

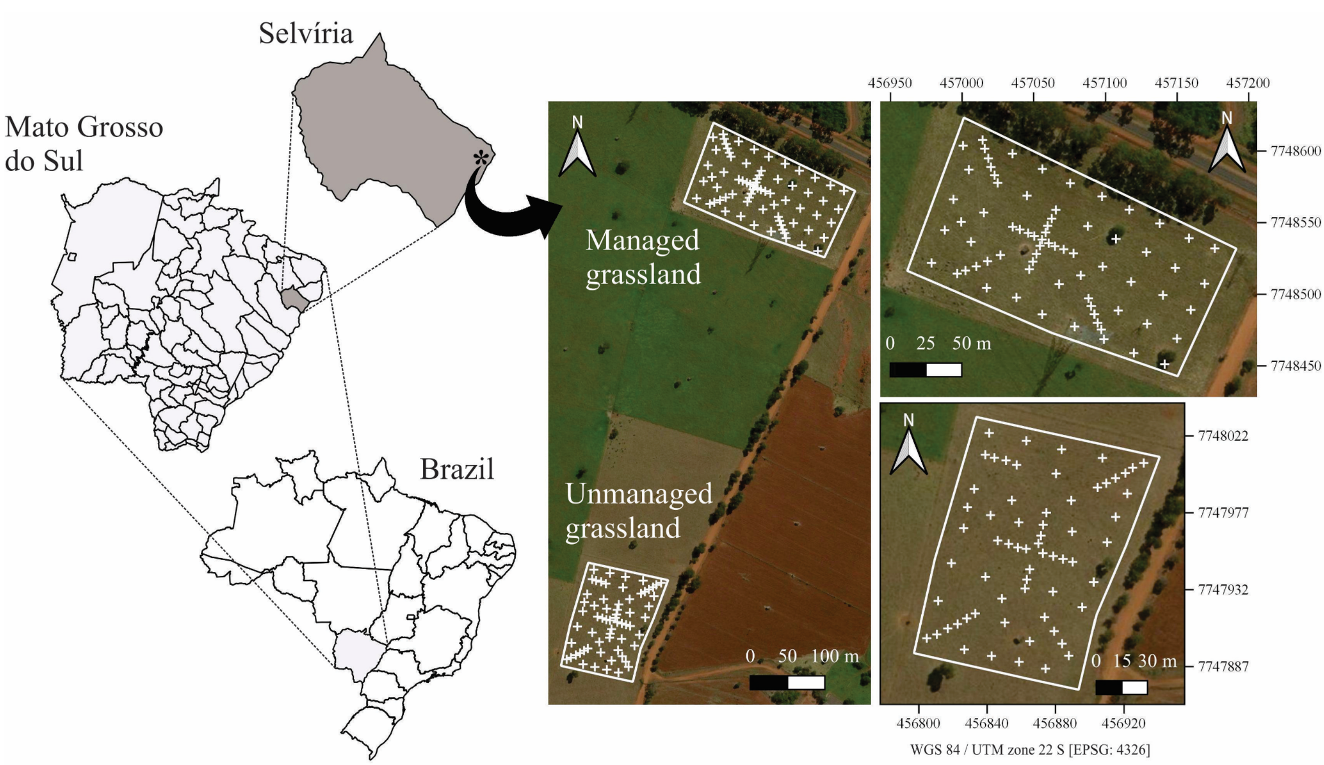

Fig. 2. Study location and representation of sampling meshes with respective georeferenced points (+) in the areas of managed and unmanaged pastures.

soil was oven dried at 60 °C for 15 h. Then, the soil was macerated and analyzed according to the methodology proposed by Yeomans and Bremner (1988). From the 10 g samples used for TOC determination, 5 g was used for the particle size separation of OCAM and POC. These fractions were determined following the same methodology used for TOC analysis. The stocks of OC (S-OC), POC (S-POC), and OCAM (S-OCAM) were calculated according to the methodology of Soares et al. (2020), in which the contents of each fraction were multiplied by the soil bulk density and soil depth, according to Eq. (1):

$$Stocks\ (Mg\ ha^{--1}C) = OC\ (\%) \times soil\ depth\ (m) \times bulk\ density\ (Mg\ m^{--3}) \times 100 \quad (1)$$

To compare carbon stocks between equal soil masses, corrections were calculated based on the equivalent soil mass method (Ellert and Bettany, 1995), using the soil bulk density of native forest areas as a reference. An adjustment was used to estimate the corrected stocks, in which the corrected depth (Depth. Corr.) (m) was obtained using Eq. (2):

$$Depth.\ Corr. = (BDr/BDc) \times Depth\ ref.\,, \quad (2)$$

where BDr is the bulk density of the reference (native forest) close to the sampling area (Mg m^{-3}), BDc is the bulk density to be corrected (Mg m^{-3}), and Depth ref. is the reference depth for equal masses.

Measurements of CO_2 emissions from soil (CO_2-F) were carried out in the field for a period of approximately one month (25/05/2018, 31/05/2018, 06/05/2018, 14/06/2018, and 20/06/2018), using two portable LiCor systems (LI-8100) (Fig. 1), as described by Rigon et al. (2018). The systems were coupled in PVC collars 8.5 cm in height and 10 cm in diameter, previously installed at the sampling points of the geostatistical meshes. The system monitors changes in the concentration of CO_2 within a chamber using optical absorption spectroscopy in the infrared spectrum (IRGA). The chamber is a closed system with an internal volume of 854.2 cm^3 and a circular area in contact with the ground of 83.7 cm^2. The CO_2-F averages were obtained considering the entire evaluation period, estimated by the area below the emission curves. The average values of georeferenced emissions over the evaluation days are included in the supplementary documents (Supplementary I). Over time, CO_2 emissions were monitored in three different seasons, with variations in temperature and rainfall. Monitoring of CO_2 emissions were carried out at specific locations (five randomized points that were not georeferenced) to confirm the emission patterns between different periods and management systems (Supplement II).

2.3. Statistical analysis

First, a descriptive analysis of the data was performed by calculating the mean, median, mode, minimum and maximum values, coefficient of variation, asymmetry, and kurtosis of the two areas shown in Fig. 2. The hypothesis of normal data distribution was performed using the Shapiro–Wilk normality test (Shapiro and Wilk, 1965). Thus, outliers were removed from the dataset, respecting the limit of 5% of the total observations, and values found beyond three times the interquartile range in the box plot chart were considered non-standard. The means of the variables were compared between the areas established using the '*bootstrap*' technique, based on 1000 random resamplings with reposition, according to the method described by Christie (2004). Therefore, it was also possible to establish the upper and lower limits of the confidence interval of the mean at 95% probability. Thus, averages presenting common values within their confidence intervals, where the error bars overlap, did not differ from each other. However, the absence of common values indicated a significant difference (at 5% probability) between them.

As the study did not have a parametric statistical design, it was decided to use a multivariate statistical method. For that reason, canonical correlation analysis (CCA) was used, which is similar to a multiple regression; however, it simultaneously correlates several dependent variables (U) and several independent variables (V) (Hair et al., 2007). With CCA, the analysis of the interrelationships between the physical and chemical attributes of the soil (V) and the stable fraction of organic soil C stocks (U) is made possible. The data were standardized to have a mean of 0 and variance of 1.

In this way, it was possible to determine four canonical functions or four pairs of canonical statistical variables. Multivariate significance tests (Wilks' lambda, Lawley-Hotelling Trace, Pillai-Bartlett Trace, and Roy's Largest Root) were used to assess the significance of canonical root pairs. In addition, canonical loads-that is, the correlations between the original variables and their respective canonical statistical variables and the crossed canonical loads that represent the correlation between an original variable of a certain group and the canonical statistical variable of the other group-were estimated (Protásio et al., 2014). In the canonical analysis, we also determined the redundancy index that expresses the amount of variance in a canonical statistical variable (dependent or independent) explained by the other canonical statistical variable.

Multivariate data analysis has been widely used to reduce the number of variables with minimal information loss. Therefore, for the mapping of soil attributes in the two areas, it was decided to map the scores of the canonical variables. The spatial dependence of the canonical variables was verified by geostatistical analysis, in which theoretical semivariograms were calculated. Spherical, exponential, and Gaussian semivariogram models were tested. The selection criteria of the models were as follows: the lowest root of the sum of squared residuals, highest R^2, linear coefficients close to zero, and slope close to one (Qin et al., 2019; Yao et al., 2019). The classification of the spatial variability dependence (SVD) was performed based on the nugget and threshold ratio ($C/C + C_0$) (Cambardella et al., 1994). To complement the interpretation of the CCA kriging maps, individual maps of the C organic fractions were generated, following the same criteria (Supplementary III).

All statistical analyses were performed using R software version 3.6.2 and the "agricolae", "nortest", "cca", and "geoR" packages. Kriging maps were edited using the QGIS 3.10 software.

3. Results

3.1. Descriptive analysis and bootstrap inference

According to the descriptive analysis (Table 1), a high range of values was found for almost all variables evaluated. The variation coefficients were also high (above 30%), except for clay, sand, pH, K, Ca, Mg, H + Al, CEC, BS, S-OC, S-OCAM, S-POC, and CO_2-F. High amplitudes of P, Al, and m% should be highlighted, as they ranged from 1.0 to 11.0 mg kg^{-1}, 0.0 to 2.0 $mmol_c$ kg^{-1}, and 0.0–6.0%, respectively. The Shapiro–Wilk test confirmed a non-normal distribution for most of the evaluated attributes. Despite these results, it was considered that the clay, silt, pH, P, K, Ca, H + Al, BS, and CO_2-F data showed a distribution tending to normal, owing to the similarity between the average and median values and the asymmetry and kurtosis values being close to zero. Although normality is

Table 1
Descriptive analysis of soil attributes, normality test and comparison of averages depending on pasture management systems.

Attributes[1]	Average	Median	Minimum	Maximum	Coefficients			S-W ≥ Pr	F p-value	Unmanaged Grassland	ManagedGrassland
					Variation	Kurtosis	Skewness				
Clay (g kg^{-1})	128.36	126.54	98.80	164.81	7.95	0.19	1.47	0.00 NN	0.06	131.01 A	126.13 A
Silt (g kg^{-1})	61.43	68.17	17.43	95.13	31.74	−0.56	−0.74	0.00 NN	< 0.001*	47.20B	73.47 A
Sand (g kg^{-1})	810.62	808.90	764.99	872.75	2.75	0.26	−0.37	0.26 NO	< 0.001*	822.16B	800.86 A
pH	5.16	5.10	4.40	6.30	7.58	0.41	−0.44	0.00 NN	< 0.001*	4.91B	5.38 A
P (mg dm^{-3})	5.22	5.00	1.00	11.00	51.82	0.12	−0.78	0.00 NN	< 0.001*	3.52B	6.65 A
K ($mmol_c$ dm^{-3})	0.55	0.50	0.20	0.94	29.59	0.22	−0.66	0.00 NN	< 0.001*	0.45B	0.64 A
Ca ($mmol_c$ dm^{-3})	12.13	12.00	5.00	19.00	29.41	−0.04	−1.01	0.00 NN	< 0.001*	9.18B	14.63 A
Mg ($mmol_c$ dm^{-3})	10.65	11.00	6.00	15.00	18.45	0.07	−0.23	0.02 NO	< 0.001*	9.95B	11.25 A
H + Al ($mmol_c$ dm^{-3})	17.23	18.00	10.00	25.00	21.52	0.45	−0.28	0.00 NN	< 0.001*	20.00 A	14.89B
Al ($mmol_c$ dm^{-3})	0.51	0.00	0.00	2.00	140.10	1.07	−0.23	0.00 NN	< 0.001*	0.90 A	0.18B
CEC ($mmol_c$ dm^{-3})	41.56	41.50	31.50	54.80	11.99	0.34	−0.28	0.07 NO	< 0.001*	40.24B	42.68 A
BS (%)	58.51	59.00	37.00	78.00	17.43	−0.19	−0.74	0.03 NO	< 0.001*	49.96B	65.73 A
m (%)	1.42	0.00	0.00	6.00	147.28	1.04	−0.61	0.00 NN	< 0.001*	2.82 A	0.24B
S-OC (Mg ha^{-1})	16.67	16.71	14.79	18.86	4.73	−0.04	0.03	0.72 NO	< 0.001*	16.24B	17.02 A
S-OCAM (Mg ha^{-1})	6.50	6.43	5.26	8.06	9.68	0.31	−0.68	0.02 NO	< 0.001*	9.72B	10.55 A
S-POC (Mg ha^{-1})	10.17	10.26	7.72	11.98	7.61	−0.53	0.37	0.05 NO	0.68	6.52 A	6.48 A
CO_2-F (μmol m^{-2} s^{-1})	1.17	0.98	0.94	1.54	18.90	0.22	−1.90	0.00 NN	< 0.001*	1.40 A	0.97B

[1] CEC: cation exchange capacity at pH 7, BS: base saturation, m%: aluminum saturation, S-OC: total organic carbon stock, S-OCAM: organic carbon stock associated with the mineral fraction, S-POC: particulate organic carbon stock, CO_2-F: CO_2 emission from soil. Uppercase letters classify pasture management systems by the confidence intervals obtained in the bootstrap test at 0.05 probability.

not a requirement for multivariate and geostatistical analyses, outliers were removed from the data set.

Comparing pasture management systems, the macronutrient content and soil acidity were improved by fertilization and liming. This was confirmed by the average pH values and K, P, Ca, and Mg contents, which were higher in the managed pasture system (Table 1). This increase was up to 9.6% for pH, 42% for K, 89% for P, 59.3% for Ca, and 13% for Mg. Despite these increases, the levels of P and K were still close to the critical levels established for this type of soil, which are 10 mg dm^{-3} for P and 0.61 $mmol_c$ dm^{-3} for K (Vilela et al., 2004).

The H + Al and Al concentrations reaffirmed the improvement in soil edaphic conditions in the managed pasture area. A reduction of up to 25.6% in the H + Al concentration was observed, which was essentially attributed to the complexation of exchangeable Al (Table 1). Thus, the average m% values were 91% lower in the managed pasture area. Supporting these results, the effects of chemical soil management were not evident on CEC, which did not differ between management systems, and the value of 41.6 $mmol_c$ kg^{-1} (general average) can be used to represent the current condition of the two areas.

The S-OC values were classified as satisfactory, S-OC > 12 Mg ha^{-1}, in the two systems evaluated (Carvalho et al., 2010), with a greater accumulation of C in the managed pasture area by up to 5% (~0.8 Mg ha^{-1}) (Table 1). The adopted pasture management system (extensive livestock with a moderate stocking rate) was favorable for the accumulation of C in the surface horizons of the soil. Consequently, this increase was due to the more decomposed physical fraction (S-OCAM), or heavy fraction, which corresponded to most of the S-OC, representing 59.9% in the area of unmanaged pasture and 62% in the area of managed pasture. In contrast, S-POC stocks did not differ between the evaluated pasture management systems. As for soil respiration (CO_2-F), emissions were lower in the managed pasture area, with an average of 0.97 μmol m^{-2} s^{-1} (Table 1). The CO_2-F reduction observed in the unmanaged pasture area was up to 31%.

Both areas studied had a loamy sand texture class with minimal variation in clay content (131 and 126 g kg^{-1}) (Table 1). Therefore, the clay content, which could act as a controller of the C content of the soil, was not a major factor in this study, owing to the physical protection it exercises over the SOM (Bruun et al., 2015; Miranda et al., 2016).

3.2. Multivariate approach

The canonical correlations obtained between sets of selected soil attributes are shown in Table 2, with their respective canonical determination coefficients (R^2) and significance tests. All canonical correlations obtained were significant ($p < 0.05$), with values between 0.94 and 0.38. The first pair of canonical correlations explained approximately 57% of the joint variation of attributes, making it the most important pair for interpretation (Fig. 3).

Table 2
Canonical eigenvalues and correlations for the studied soil attributes.

Caninical variable pairs[a]	Canonical correlation	Canonical R^2 (eigenvalue)	DF[b]	Approximation of F[c]			
				Wilks' Lambda	Hotelling-Lawley Trace	Pillai-Bartlett Trace	Roy's largest root
(U1, V1)	0.935	0.873	52	9.27**	16.92**	5.66**	217.32**
(U2, V2)	0.591	0.349	36	2.86**	2.93**	2.67**	
(U3, V3)	0.423	0.179	22	2.03**	2.04**	1.93**	
(U3, V4)	0.379	0.143	10	1.96**	1.98**	1.83**	

[a]U*n*: canonical variable for attributes related to soil organic carbon, V*n*: canonical variable for physical and chemical attributes of the soil. [b]DF corresponds to the degree of freedom. [c]** significant at 0.01 probability.

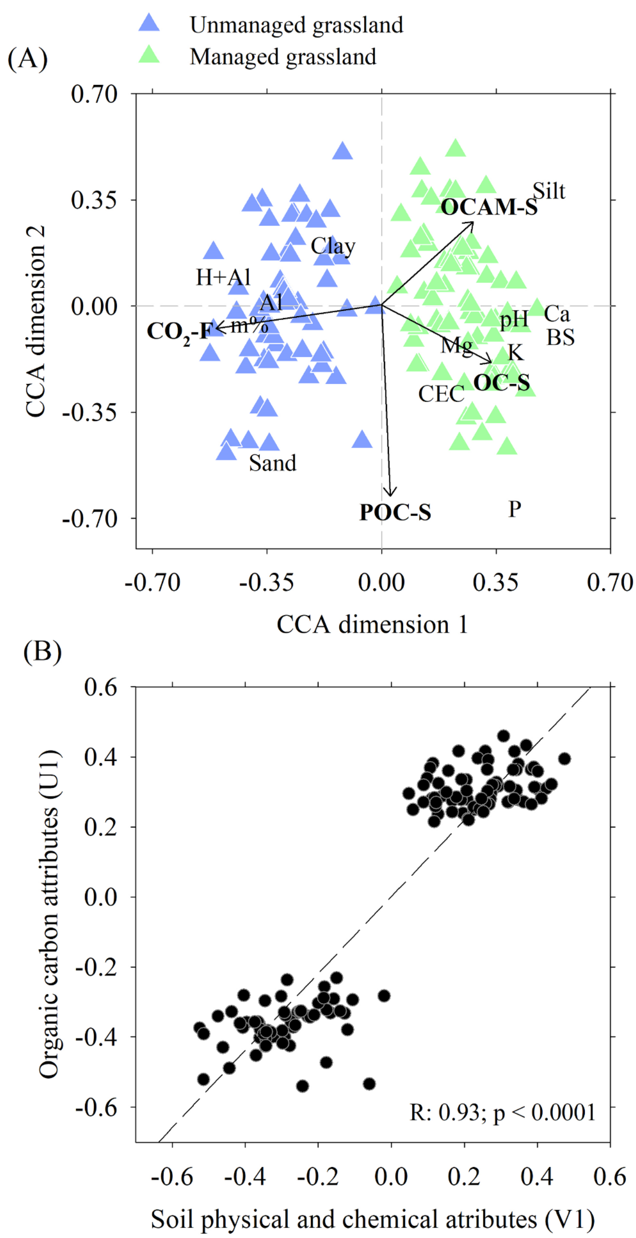

Fig. 3. (A) Ordering diagram of the first pair of canonical variables represented by the physical and chemical attributes of the soil (CCA dimension 1) and attributes related to organic carbon (CCA dimension 2). (B) Scatter plot of the first pair of standardized canonical variables.

Because of the significance of the correlations presented, it can be concluded that the selected groups are not independent. The canonical R^2 found was equal to 0.87 for the first canonical pair and 0.35 for the second pair. Therefore, U_k was the best linear combination in the prediction of V_k and vice versa, with $k = 1$ and 2, respectively, (Table 2). Thus, the standardized values of the pair of canonical variables with the highest correlation (U_1 and V_1) can be seen in Fig. 4. It can be inferred that the high values of canonical variables that represented the physical and chemical attributes of the soil (V_1) were associated with the high values of canonical variables that represented the attributes related to OC (U_1).

The correlations between the variables of the canonical component that represents them (U_k and V_k), called canonical loads as well as the correlations of these variables with another canonical component, known as transversal canonical loads, are presented in Table 3. Such values are useful for understanding the meaning of canonical variables; the greater the absolute value of a canonical charge, the greater the representation of the soil attribute in the respective canonical component. Therefore, it was observed that the canonical variable U_1 represented 88.39% of the total variation in the group of attributes related to the OC fractions, and V_1 represented 17.64% of the total variation in the soil physical and chemical attributes. For the physical and chemical attributes of the soil, the highest values of canonical correlation (in module) were observed for the Ca concentration in the soil (0.85), BS% (0.85), silt content (0.71), potential acidity (–0.75), and m% (–0.67) (Table 4). The attributes related to OC showed greater associations with CO_2-F (–0.92), S-OC (0.55), and S-OCAM (0.51). Therefore, the high values of V_1 (better soil fertility condition) were associated with low values of CO_2-F and high values of S-OC and S-OCAM.

The dispersion of scores in relation to canonical charges is clearly seen in Fig. 4A. The ordering diagram of the first pair of canonical variables indicated that the S-OCAM and S-OC attribute concentrations were opposite to those of CO_2-F. Similarly, the silt content, pH in $CaCl_2$, V%, CEC, and concentrations of Ca, Mg, K, and P, were opposite to the levels of H + Al, Al, m%, clay, and sand. A clear difference in the scores from pasture management systems can be seen in the diagram. The green points represented by the managed pasture system were more positively correlated with the attributes related to soil fertility (CCA dimension 1), S-OC, and S-OCAM (CCA dimension 2). In contrast, the blue points, represented by the unmanaged pasture system, were more negatively correlated with H + Al, Al, m% (CCA dimension 1), and CO_2-F (CCA dimension 2).

3.3. Geostatistical analysis

The results of the spatial analysis of soil attributes and canonical loads are shown in Table 4. All of the attributes evaluated, with the exception of K, Ca, CEC, and BS contents and m% of the degraded pasture area, silt, sand, and H + Al contents and m% of the managed pasture area, showed spatial dependence. The quality of fit of the semivariogram models could be confirmed by the coefficients of determination being above 0.50, and by the root mean square errors (RMSEs) being close to zero. Cross-validation of all assessed properties indicated linear coefficients near zero, with the exception of attributes related to soil particle size and slope coefficients near one, with correlation coefficients (r) ranging from 0.15 to 0.90 between the values estimated by semivariograms and observed values.

The range (A_0) of the semivariogram indicates the stabilization of the semivariation when the threshold ($C_0 + C$) is reached. Through this parameter, it was possible to observe that the canonical loads U_1 and V_1, from both areas, presented values of A_0 ranging from 5.8 to 74.0 m (Table 4). The V_1 loads were A_0 lower than those of U_1, indicating that the spatial continuity of the physical and chemical properties of the soil is less in relation to the attributes related to OC. Based on the adjusted semivariograms, canonical loads were interpolated by ordinary kriging (Fig. 4).

From the maps of V_1 and U_1, it was clear that the scores were different in the managed and unmanaged pasture areas. In the unmanaged pasture system, in places of low fertility (represented by negative scores on the V_1 maps), CO_2-F reached 1.64 μmol m^{-2} s^{-1} and S-OCAM stocks were < 8.0 Mg ha^{-1} (Fig. 4A). In contrast, in locations with S-OC

Table 3
Correlations between carbon attributes and physical and chemical attributes of the soil, based on canonical correlation analysis (CCA).

Dependent Attributes	Canonical loads				Canonical cross-loading			
	U1	U2	U3	U4	V1	V2	V3	V4
S-OC	0.55	−0.19	0.30	−0.10	0.59	−0.32	0.70	−0.25
S-POC	0.06	−0.59	0.04	−0.01	0.06	−0.99	0.09	−0.02
S-OCAM	0.51	0.29	0.27	−0.09	0.55	0.48	0.63	−0.25
CO_2-F	−0.92	−0.08	0.03	0.00	−0.99	−0.14	0.08	0.00
EP (%)	88.39	6.56	3.09	1.96	–	–	–	–
IR	39.14	–	–	–	–	–	–	–
Independent Attributes	**Canonical loads**				**Canonical cross-loading**			
	V1	V2	V3	V4	U1	U2	U3	U4
Clay	−0.21	0.19	0.10	0.39	−0.20	0.11	0.04	0.15
Silt	0.71	0.33	0.06	−0.24	0.66	0.20	0.02	−0.09
Sand	−0.52	−0.51	−0.21	−0.07	−0.48	−0.30	−0.09	−0.03
P	0.65	−0.66	−0.08	−0.12	0.61	−0.39	−0.03	−0.05
pH	0.66	−0.04	0.29	0.37	0.62	−0.03	0.12	0.14
K	0.65	−0.15	0.04	−0.29	0.61	−0.09	0.02	−0.11
Ca	0.85	−0.03	0.24	−0.07	0.79	−0.02	0.10	−0.03
Mg	0.40	−0.13	0.58	0.09	0.37	−0.08	0.24	0.04
H + Al	−0.75	0.10	0.04	−0.45	−0.70	0.06	0.02	−0.17
Al	−0.56	0.01	−0.08	−0.12	−0.53	0.01	−0.03	−0.05
CEC	0.33	−0.29	0.76	−0.17	0.31	−0.17	0.32	−0.07
BS	0.85	−0.10	0.10	0.16	0.79	−0.06	0.04	0.06
m%	−0.67	−0.07	−0.21	−0.14	−0.63	−0.04	−0.09	−0.05
EP (%)	17.64	10.53	9.37	4.65	–	–	–	–
IR	60.86	–	–	–	–	–	–	–

S-OC: total organic carbon stock, S-OCAM: organic carbon stock associated with the mineral fraction, S-POC: particulate organic carbon stock, CO_2-F: CO_2 emission from soil, CEC: cation exchange capacity at pH 7, BS: base saturation, m%: aluminum saturation. EP: corresponds to the explained percentage. IR is redundancy index.

values close to 18.0 Mg ha^{-1}, the CO_2-F was 0.97 µmol m^{-2} s^{-1}, which equaled the condition of the managed pasture. The CO_2-F, S-OC, and S-OCAM maps confirm this spatial correspondence in the unmanaged pasture area (Supplementary III).

The attributes related to C showed different behaviors in the managed pasture area (Fig. 4B). In places with the best fertility conditions (represented by scores above 0.24 on the V_1 maps), emissions of 0.99 µmol m^{-2} s^{-1} were recorded; these values were the highest in the managed pasture system. The CO_2-F values fluctuated between 0.94 and 0.99 µmol m^{-2} s^{-1} in this system (Fig. 4B). S-OC between 15.5 and 18.5 Mg ha^{-1} corresponded to locations with S-POC between 5.5 and 8.0 Mg ha^{-1} and S-OCAM between 9.0 and 12.0 Mg ha^{-1}, and were the sites with the highest C and CO_2 emissions. The CO_2-F, S-OC, and S-OCAM maps confirm this spatial correspondence in the unmanaged pasture area (Supplementary III).

4. Discussion

4.1. Effects of pasture reform on soil attributes and CO_2 emissions

The net negative charge of the soil and the negative surface electric potential are the main electrochemical changes caused by liming in tropical acidic soils with a predominance of variable charges (Soares and Alleoni, 2008). The increase in CEC is a consequence of the deprotonation of the ferrol and aluminol groups present in oxides and hydroxides, in the broken edges of 1:1 clay minerals, and the ionization of functional groups of organic matter (phenolic and carboxylic groups), caused by the adsorption of hydroxyls (Ribeiro et al., 2011). Based on the results obtained, it was found that the application of 1.0 t ha^{-1} of dolomitic limestone was sufficient to remove exchangeable Al; however, it did not cause a substantial increase in the CEC. It is assumed that this fact could be related to the quality of C in the soil in recent years.

Most CEC in tropical soils originates from soil organic matter (Reichert et al., 2016), and is caused by the protonation and deprotonation of functional carboxylic and phenolic groups (Petter et al., 2017). In agricultural systems that carry out extensive beef cattle farming, the material contributed is basically from the cultural remains of the pastures, and in some cases other crops may be planted to reform the pastures, as occurred in this study. The material from pasture crop remains has a high C:N ratio (> 20: 1) (Guo et al., 2012; Torres et al., 2005) as well as high concentrations of lignin (between 60 and 80 g kg^{-1} [$KMnO_4$ method]) and cellulose (between 245 and 340 g kg^{-1}) (Herrero et al., 2001). Under these conditions, humic acids are more likely to form during the humidification of soil OM because of their high resistance to the breakdown of hydrocarbon bonds by microorganisms (Bikovens et al., 2010).

During the humification of OM, functional groups are formed that interact with the environment (Bai et al., 2015). Among the functional groups, the carboxylic and phenolic groups stand out—carboxylic groups have pKa values close to three, thus deprotonating under lower pH conditions (between 4.0 and 5.0), while phenolic groups deprotonate under higher pH conditions (above 7.0) (Bai et al., 2015). In fulvic acids, aliphatic chains (phenolic compounds) predominated, and humic acids were predominant over aromatic chains (carboxylic compounds). Therefore, there may be no increase in CEC even under increased humid organic matter conditions, as observed in our study.

Comparing our results with other studies using the same land use and varying only management, the C accumulation in the soil after management (0.78 t ha^{-1}) was 122% greater than the average suggested (0.35 t ha^{-1}) by the UNCCD, staying within the range depending on the climate region (0.02–0.8 t ha^{-1}) (Sanz et al., 2017). When compared to other land uses (agricultural restored ecosystems) where the rate of carbon accumulation in the soil is 0.15 t ha^{-1} in dry and hot regions (Armstrong et al., 2003) and 0.1–1 t ha^{-1} in humid regions with cold climates (West and Post, 2002), our results are greater than expected for regions with dry and hot climates and within the range predicted for humid and cold climates.

Table 4
Parameters of semivariograms adjusted for the canonical components obtained and attributes of the soil submitted to two pasture management systems.

Attributes[a]	Model	C_0	$C_0 + C$	A_0	R^2	RMSE	SVD[b] (%)	Cross-validation[c]		
								a	b	R
	Unmanaged grassland									
V1	Exp	7.5×10^{-4}	0.01	5.80	0.52	5.2×10^{-4}	93.1	0.01	1.04	0.44
U1	Sph	0.01	0.06	55.00	0.91	1.5×10^{-3}	73.1	0.00	0.93	0.69
Clay	Exp	1.60	218.20	23.50	0.90	8.91	99.3	−0.99	1.01	0.66
Silt	Sph	1.00	383.50	40.50	0.81	22.14	99.7	2.23	0.97	0.71
Sand	Exp	1.00	692.80	31.50	0.97	13.27	99.9	−62.0	1.07	0.79
P	Gau	2.55	5.78	37.70	0.72	0.35	55.6	0.03	0.98	0.50
pH	Gau	0.01	0.04	13.90	0.65	4.6×10^{-11}	63.6	0.06	0.99	0.30
K	Nug	0.01	0.01	–	–	–	–	–	–	–
Ca	Nug	4.77	4.77	–	–	–	–	–	–	–
Mg	Exp	0.31	2.94	10.30	0.93	0.05	89.4	1.85	0.81	0.20
H + Al	Sph	0.55	9.90	39.40	0.93	0.27	94.5	0.99	0.95	0.63
Al	Gau	0.11	0.66	11.80	0.91	0.02	84.0	−0.05	1.09	0.19
CEC	Nug	18.70	18.70	–	–	–	–	–	–	–
BS	Nug	43.53	43.53	–	–	–	–	–	–	–
m%	Nug	5.58	5.58	–	–	–	–	–	–	–
S-OC	Exp	1.0×10^{-3}	0.52	13.30	0.89	0.01	99.8	−1.22	1.07	0.43
S-OCP	Sph	0.03	0.40	72.50	0.95	0.01	93.5	0.46	0.93	0.75
S-OCAM	Sph	0.01	0.75	51.70	0.97	0.01	97.8	1.07	0.89	0.70
CO_2-F	Exp	3.9×10^{-4}	2.3×10^{-3}	30.40	0.94	5.5×10^{-5}	83.6	−0.03	1.02	0.76
	Managed grassland									
V1	Exp	5.7×10^{-3}	0.01	35.20	0.70	3.2×10^{-4}	50.4	−0.01	1.09	0.35
U1	Gau	0.03	0.07	74.00	0.90	1.5×10^{-3}	58.2	−0.01	1.01	0.72
Clay	Sph	2.56	17.47	43.50	0.76	0.85	85.3	13.71	0.89	0.37
Silt	Nug	89.29	89.29	–	–	–	–	–	–	–
Sand	Nug	202.62	202.62	–	–	–	–	–	–	–
P	Gau	1.83	6.61	64.80	0.90	0.22	72.3	0.07	1.00	0.66
pH	Exp	1.0×10^{-4}	0.14	10.05	0.84	5.1×10^{-3}	99.9	0.04	0.99	0.25
K	Exp	0.01	0.02	19.30	0.63	6.5×10^{-4}	50.2	0.00	0.99	0.21
Ca	Sph	3.07	6.14	44.00	0.84	0.13	50.0	0.23	0.99	0.41
Mg	Exp	0.48	3.00	13.40	0.73	0.10	84.0	0.42	0.98	0.36
H + Al	Nug	5.29	5.29	–	–	–	–	–	–	–
Al	Gau	0.02	0.21	16.91	0.80	0.01	86.4	0.00	0.93	0.15
CEC	Exp	6.96	28.83	39.40	0.93	0.64	75.9	−2.43	1.06	0.61
BS	Exp	17.89	39.40	18.60	0.81	0.83	54.6	4.08	0.94	0.36
m%	Nug	0.38	0.38	–	–	–	–	–	–	–
S-OC	Sph	0.08	0.48	143.00	0.94	0.01	83.3	0.87	0.95	0.65
S-OCP	Exp	1.0×10^{-4}	0.24	29.90	0.93	6.2×10^{-3}	99.9	−0.07	1.01	0.90
S-OCAM	Exp	0.04	0.22	15.20	0.76	0.01	78.9	0.08	0.99	0.57
CO_2-F	Sph	5.0×10^{-5}	1.8×10^{-4}	141.90	0.94	4.5×10^{-6}	69.6	0.13	0.86	0.52

[a]V1 and U2 correspond to the first pairs of canonical variables, CEC: cation exchange capacity at pH 7, BS: base saturation; m%: aluminum saturation; S-OC: total organic carbon stock, S-OCAM: organic carbon stock associated with the mineral fraction, S-POC: particulate organic carbon stock, CO_2-F: CO_2 emission from soil. Model: spherical (Sph), gaussian (Gau); exponential (Exp) e nugget effect (Nug). C_0, $C_0 + C$ and A_0 they are respectively: nugget effect, sill and range. RMSE: root mean square error. SVD: Classification of dependence on special variability.

Regarding CO_2 emissions, when comparing our results with emissions from areas with the same land use, it is noted that the emissions from our study in unmanaged (1.40 μmol m^{-2} s^{-1} = 1.45 g m^{-2} day^{-1} of C) and managed (0.97 μmol m^{-2} s^{-1} = 1 g m^{-2} day^{-1} of C) pastures (Table 1) were lower than in non-degraded pastures present in temperate climates in South Africa (~1.78 g m^{-2} day^{-1} of C) (Abdalla et al., 2018). This difference is attributed mainly to the climate, forage species, and management adopted in the area.

In relation to other land uses, our results (both in managed and unmanaged pastures) were below corn emissions (9.6 g m^{-2} day^{-1} C) in a humid continental climate in southern Hokkaido (Japan) (Li et al., 2015). This difference is related to the interaction between the source and carbon content with the increase in soil temperature and humidity. The interaction between these factors is primarily responsible for regulating CO_2 emissions.

4.2. Multivariate geostatistics: spatial distribution pattern of soil attributes

In our study, the humidified fraction of organic matter (S-OCAM) could be used as a sensitive indicator for agricultural management and preparation practices. S-OCAM was predominant over the accumulation of S-OC in the managed pasture area (Table 1 and Supplementary III). It is assumed that the S-OCAM compartment observed in the managed pasture area originated from organic materials recently added to the soil, such as the sorghum crop remains. In addition to the intended increase in pasture biomass, the addition of straw to the soil resulting from the cultivation of sorghum and inputs (liming and fertilization), possibly improved the edaphic conditions and reduced soil respiration. The trend of CO_2-F on carbon stocks was evident in the U_1 maps (Fig. 4). Approximately 69.4% of the managed pasture area corresponded to areas with higher values of S-OCAM and S-OC and lower values of CO_2-F. The other 30.6% of the area had emissions between 0.97 0.99 μmol m^{-2} s^{-1}. Approximately 50.1% of the unmanaged pasture area corresponded to areas with lower values of S-OCAM and S-OC and higher values of CO_2-F. Thus, it was possible to identify the "problematic" areas with the highest CO_2 emissions (1.36 to 1.49 μmol m^{-2} s^{-1}), determining management zones according to the S-OCAM (Fig. 4 Supplementary III).

Similarly, Yang et al. (2017) verified the effects of applying NPK fertilizers, corn straw, and biochar on the CO_2 emissions and OC fractions in the soil. The application of corn straw and biochar over three consecutive years provided a substantial increase in the non-labile

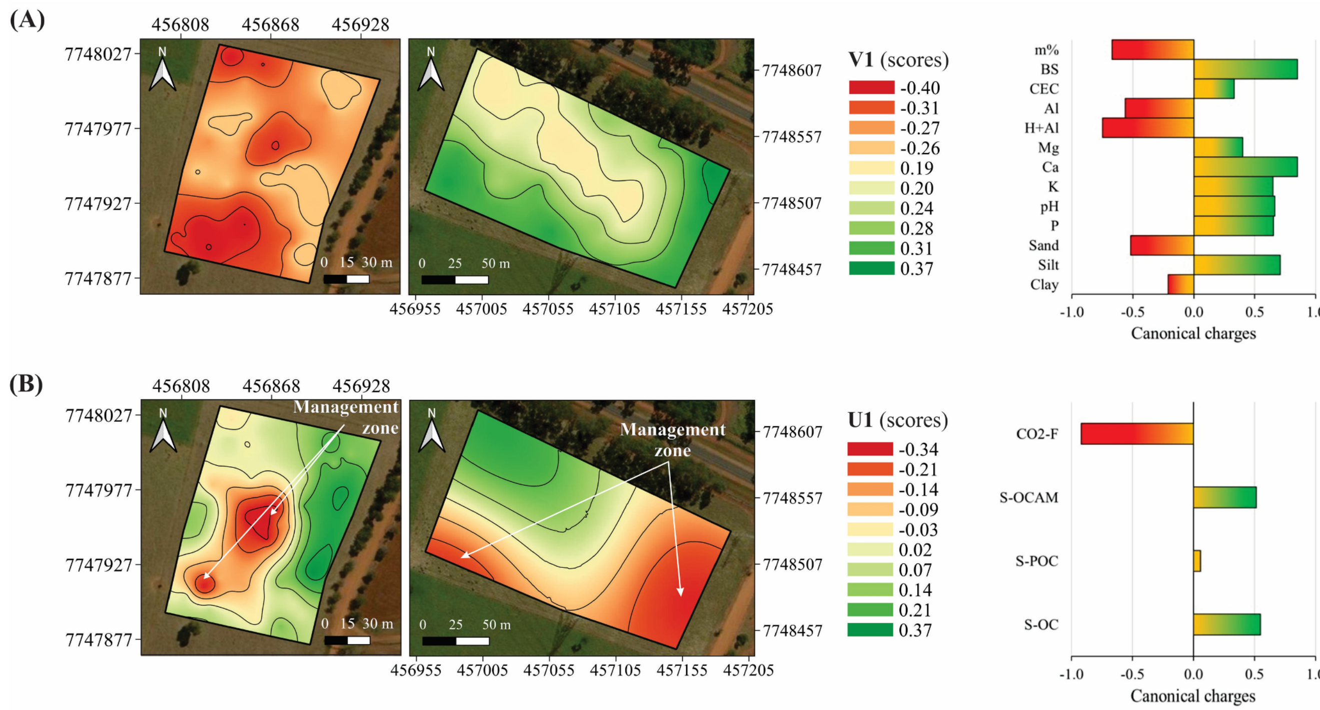

Fig. 4. Spatial distribution maps of the first pair of canonical variables represented by the physical and chemical attributes of the soil (V1 [A]) and attributes related to organic carbon (U1 [B]). Next to the maps are the graphs with the respective canonical load of each attribute listed in the canonical variable.

carbon fraction (OCAM), at an average rate of 0.57 g kg^{-1} $year^{-1}$. In contrast, the NPK fertilizer (120 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1}, and 60 kg K_2O ha^{-1} in the form of urea, simple superphosphate, and potassium sulfate, respectively), maintained stable labile C concentrations.

It was observed that in the managed pasture area, outside the management zone, the fertility condition was worse, even with lower CO_2 emissions (Fig. 4A). Therefore, it can be said that the S-OC did not limit the CO_2-F. In this case, the possible effect of the solubilization of limestone carbonates on CO_2-F readings must be taken into account, which, despite not being quantified in C stocks (due to the effect of HCl treatment), emissions may have occurred more intensely in these areas. The CEC and clay content maps can support this observation because of the effect of greater soil reactivity and, possibly, greater water retention and soil porosity in this location.

Studies by de Carvalho et al. (2018) in different agricultural systems (degraded pasture areas and reformed pasture with *U. brizantha*, rice, and sugar cane cultivation areas, and a eucalyptus reforestation area), reported that the soil microbial activity (parameterized by soil respiration) is generally limited by the availability of C and is strongly modulated by soil edaphic conditions. The multivariate approach made by the authors highlighted the C sensitivity of microbial biomass to the initial changes in the physical and chemical attributes of the soil, such as the concentrations of Al, Ca, and Mg.

In our study, it is important to note that the CO_2-F readings were taken during a period of low precipitation, with approximately 3 mm accumulated during this period (Fig. 1). This, along with the mechanical practice of turning the soil (Álvaro-Fuentes et al., 2007), which was carried out in the short term in the managed pasture area, may have substantially decreased the microbiological activity of the soil and caused a latent state (Delbem et al., 2011). It is known that turning the soil during pasture reform initially increases the CO_2-F rates for the atmosphere (Silva et al., 2014). With the possible disruption of soil aggregates, part of the occluded carbon becomes more susceptible to mineralization, due to its exposure to microbial action, which is supported by the increased soil oxygenation and temperature (La Scala et al., 2008; Schwartz et al., 2010). After a short period, the labile fractions of organic matter were reduced, and the microbial basal activity decreased (Six et al., 2006). The CO_2-F results obtained in our study clarify the effects of the pasture reform and OM inputs on the CO_2 emissions, which occurred in the short term, being sufficient to distinguish the management systems studied.

In this context, we must observe the system as a whole. On the one hand, there are the inputs of SOM, given by the cultivation of sorghum, and the consequent increase in S-OC, given by S-OCAM, through the production of biomass from the cultures (Table 2). In contrast, liming and nitrogen fertilization, which favor the emission of CO_2 by solubilizing carbonates and reducing the C:N ratio of organic matter, possibly due to the activity of microorganisms (Sainju et al., 2010). According to Soussana et al. (2007), the effects of nitrogen in OC pools varied between locations due to variations in pH, soil granulometry (clay content), and climate. Liming is another factor that must be considered. Liming leads to a greater production of root exudates, and often has unintended effects on microbial properties and their activities, which influence the decomposition of SOM (Hoffmann et al., 2014; Soussana et al., 2007). These management activities, therefore, have implications for soil C storage and sequestration.

To ensure the sustainable provision of various ecosystem services for tropical pastures, particularly fodder input for animal feed and the mitigation of climate change via C sequestration, further studies are needed to elucidate how climate change (e.g., warming, drought, and increased precipitation) will influence the storage and C flows of ecosystems. The effects of climate change on tropical pastures are still poorly understood and highlight the need for further research. As tropical pastures have long management regimes (i.e., intervals of reform), it is necessary to conduct more specific on-site experiments that consider the effects of climate change and management activities, such as the application of fertilizer, liming under different conditions, rainfall regimes, and animal grazing intensities. This will provide a better understanding of the mechanisms that operate in this region and will help inform appropriate decision-making.

4.3. From small-scale experimental to biome-scale applications

Studies published over time indicate that 50% to 70% (about 100 million ha) of pasture areas in Brazil are at some stage of degradation (Dias-Filho, 2014). Of these degraded pastures, approximately 32 million ha are located in the Cerrado biome (Galinari, 2014), the biome studied here.

If the 32 million ha of degraded pastures present in the Cerrado biome were reformed using the same management as in this study, an increase in the carbon stock of 0.78 t ha^{-1} (Table 1) after the pasture reform, it would be possible to accumulate 24.96 million t of C, equivalent to 91.46 million t of C-CO_2. Another projection, but one that is not very realistic owing to the variation in the measurement of CO_2 emissions imposed by climatic factors, would be to apply the difference in CO_2 emissions (0.43 μmol m^{-2} s^{-1}; Table 1) between the reformed and unreformed areas of the study to the 32 million ha of degraded pasture. By performing this projection on 32 million ha of land, it would be possible to reduce the emissions by 6.05 t s^{-1} CO_2.

The results of this study provide information that allows for greater use of agricultural systems, construction of soil fertility, and reduction in greenhouse gases. In addition, they could be used to help alter SOC dynamics, which is an important and fruitful area for future research on soil management and conservation in Brazil.

4.4. Main limitations of the study

In this study, we evaluated the impact of the reform of degraded pastures in the physical compartment of SOM and its effect on mitigating CO_2 emissions. Our evaluations were carried out under specific management, without evaluating the role of microbiology in CO_2 emission or the origin/loss of carbon through the analysis of the isotopic ratio. As tropical pastures have long management regimes (reform intervals), we encourage future studies to carry out more specific experiments on sites that consider the effects of climate change and management activities, such as the application of fertilizers and limestone, rain regimes, and grazing intensities of animals. These conditions, combined with isotopic and microbiological analyses, will provide a better understanding of the mechanisms that govern the change in carbon compartments and will help in making appropriate decisions for the creation of management zones to mitigate CO_2 emissions.

5. Conclusion

Soil management practices followed by the cultivation of sorghum intercropped with *U. brizantha* increases TOC stocks by means of the stable fraction (OC associated with the mineral fraction of the soil) and consequent reduction in CO_2 emissions from the soil.

The CO_2 emissions and TOC stocks associated with the mineral fraction can be used as indicators of chemical soil quality, as it is correlated with attributes related to soil fertility in the studied management systems.

The CO_2-F results obtained in our study clarified that the effects of pasture reform and OM inputs on the short-term CO_2 emissions were sufficient to distinguish the management systems studied.

Approximately 69.4% of the managed pasture area corresponded to areas with higher values of S-OCAM and S-OC and lower values of CO_2-F. The other 30.6% of the area had emissions between 0.97 and 0.99 μmol m^{-2} s^{-1}. Approximately 50.1% of the unmanaged pasture area corresponded to areas with lower values of S-OCAM and S-OC and higher values of CO_2-F. Thus, it was possible to identify the "problematic" areas with the highest CO_2 emissions (1.36–1.49 μmol m^{-2} s^{-1}), determining management zones according to the S-OCAM.

Our results provide valuable information for understanding the spatial patterns of the physical compartments of organic matter and the soil attributes that influence CO_2 emissions. Based on our results that the carbon compartment in the soil and CO_2 emissions are closely related to the climate and the quantity and quality of agricultural production, we recommend future studies in vulnerable regions where agricultural production is more sensitive to climatic fluctuations.

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.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2020.104702.

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