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SOIL CO_2–C EMISSIONS AND CORRELATIONS WITH SOIL PROPERTIES IN DEGRADED AND MANAGED PASTURES IN SOUTHERN BRAZIL

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ABSTRACT

Land degradation has been a global environmental issue, and its cause includes poorly managed grazing. Quantitative information is needed to support policy actions for food and water security and development. The objective of this study was to assess and characterize CO_2–C emissions in degraded (DP) and managed pasture (MP) areas located close to one another, describing their spatial–temporal variability and any correlation with possible controlling factors. A grid of 100 × 100 m with 102 sample points in each area was set up. Measurements of CO_2–C emission (FCO_2), soil temperature (T_{soil}), soil water content (WC_{soil}), soil physical (i.e. soil texture, soil bulk density, macro-porosity, micro-porosity, air-filled pore space and total pore volume) and chemical (i.e. pH, calcium, magnesium, phosphorus, potassium and cation exchange capacity) analysis were conducted at each sample point. Total emissions calculated from the area below the FCO_2 graphs were 640.7 and 440.0 kg CO_2–C ha^{-1} in the DP and MP, respectively. Soil temperature in the MP was lower (*t*-test, $p < 0.01$) throughout the experimental period when compared with the DP. This study found that the degraded pasture area released significantly more CO_2–C compared with the well-managed pasture. Therefore, the introduction of best management practices in pasture areas is an important strategy to reduce soil CO_2–C losses and promote soil C accumulation. The MP presented lower FCO_2 despite its higher soil C stock, indicating a more stable soil C condition when compared with the DP area. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: soil respiration; multivariate analysis; grazing management; geostatistics; carbon stock

INTRODUCTION

Land degradation has been a global environmental issue, and its cause includes poorly managed grazing (Palacio *et al.,* 2014). Quantitative information is needed to support policy actions for the security of food supply, water availability and development (Bai *et al.,* 2008; Mukherjee *et al.,* 2014; Zhang *et al.,* 2015). The majority of available land for increasing food production worldwide came from deforestation of tropical forests in the 1980s and 1990s (Gibbs *et al.,* 2010). To support global demand for food, fiber and bioenergy, it is important to improve the quality of pasture lands and adopt best management practices as a key strategy to avoid additional land degradation (Costa *et al.,* 2015; Papanastasis *et al.,* 2015; Smith *et al.,* 2015; Tarhouni *et al.,* 2015).

Agricultural land occupied 5,023 Mha in 2002 (FAOSTAT, 2006), with most of this area being under pasture (3,488 Mha, or 69%). Within the agricultural sector, practices that may mitigate greenhouse gas emissions include better grazing land management and pasture improvement (Smith *et al.,* 2007; Peng *et al.,* 2015). Soil organic carbon storage is a field-based soil quality indicator and a major player in climate change and nutrient cycling (Yu & Jia, 2014; Musinguzi *et al.,* 2015).

Grazing lands represent the single largest agricultural areas in Brazil, occupying more than 172 million ha, approximately 20% of the agricultural land (IBGE, 2007). In 2012, the Brazilian government launched the Plan for Mitigation and Adaptation to Climate Change to consolidation of a Low Carbon Economy in agriculture, also called ABC Plan (Low Carbon Agriculture). Within this ambitious plan, one of the main goals is to recover 15 million ha of degraded pasture by 2020 and prevent degradation of new pastures through proper management. However, limited knowledge is available regarding controlling factors and the amount of CO_2–C emission when contrasting degraded with the well-managed pasture.

Despite the large areas of degraded pasture in Brazil, scarce information exists about the variation and correlations of soil properties including nutrients and soil carbon in those pasture management systems (Cerri *et al.,* 2004; La Scala Jr. *et al.,* 2012). Such information would contribute

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to better characterization of pasture areas, providing additional information to avoid further pasture degradation, as an important strategy to face global climate change and increase food production. The appropriate management of such areas affects pasture quality, leading to the ability to support higher animal stocking rates and, consequently, achieving higher meat yields and avoiding soil degradation and further deforestation to establish new pastures.

Presenting options for offsetting global CO_2 emissions by restoration of degraded soils and intensification of world agriculture, Lal (2003) showed that the carbon (C) pool in grasslands is large and variable, and assessing the potential of soil C sequestration through changes in land use and management is an important strategy. Changes in soil C stock contrasting degraded with well-managed pasture areas in Brazil are well described (Braz *et al.,* 2013; Carvalho *et al.,* 2014); however, knowledge of the dynamic of CO_2–C losses from those systems is still limited and could contribute to identify practices that could favor soil C accumulation.

Evaluating soil C stocks under productive and degraded *Brachiaria* pastures in the Brazilian Cerrado, Braz *et al.* (2013) showed that the management of these pastures at inappropriately high stocking rates without any further addition of fertilizers leads to a reduction in the animal productivity, soil cover decreases and the areas become invaded by weeds, with the soil becoming compacted, all aspects of pasture degradation.

Even though soil CO_2–C is produced from plant and microbial respiration (Sheppard *et al.,* 1994; de Graaff *et al.,* 2015) and chemical reactions, Allaire *et al.* (2012) described that, in addition to microbial activity, soil surface CO_2–C emission could be influenced by several other properties such as soil temperature and moisture, texture, density and gas diffusion (e.g. the dynamics of gas movement inside the soil through the path defined by the free water porosity, pore connectivity and tortuosity), soil biochemical attributes (e.g. organic matter content, nitrogen (N) and C cycles), environmental conditions (e.g. rain and temperature) and crop management (e.g. fertilization, tillage and manure application).

Fearnside & Barbosa (1998) showed that pasture soils could be a net sink or a net source of CO_2–C depending on their management. Nevertheless, different aspects are still being discussed from studies concerning the potential for agricultural soils to be a sink rather than an emission source of greenhouse gases (Smith, 2004; Brevik, 2012; La Scala Jr. *et al.,* 2012; Alexander *et al.,* 2015), and additional knowledge should be obtained to better comprehend the potential of soils to avoid additional CO_2–C losses and, thus, to become a C sink. Additionally, de Moraes Sá *et al.* (2015) presenting results from soil CO_2–C depletion and strategies for its restoration showed that relatively rapid changes in the soil organic carbon (SOC) stock with no till systems (high and diversified annual C input) indicate that there is a large potential to reverse the process of soil degradation through conversion to the no till systems.

Our hypothesis is that different management practices in pasture areas result in contrasting soil C dynamics, which could lead to reduced or additional CO_2–C emission, expressed in terms of spatial–temporal variability and their correlations with physical and chemical soil properties. Hence, the objective here was to evaluate and characterize FCO_2 (CO_2 flux) in degraded and managed pasture areas located close to one another, describing their spatial–temporal variability and any correlation with possible controlling factors, aiming to identify management practices able to avoid additional CO_2–C loss by providing better conditions for soil C storage.

MATERIALS AND METHODS

Site Description

This study was carried out in two pasture areas located near Mococa city, São Paulo State, Brazil, with the same soil and climate classification. The geographic coordinates are 21°

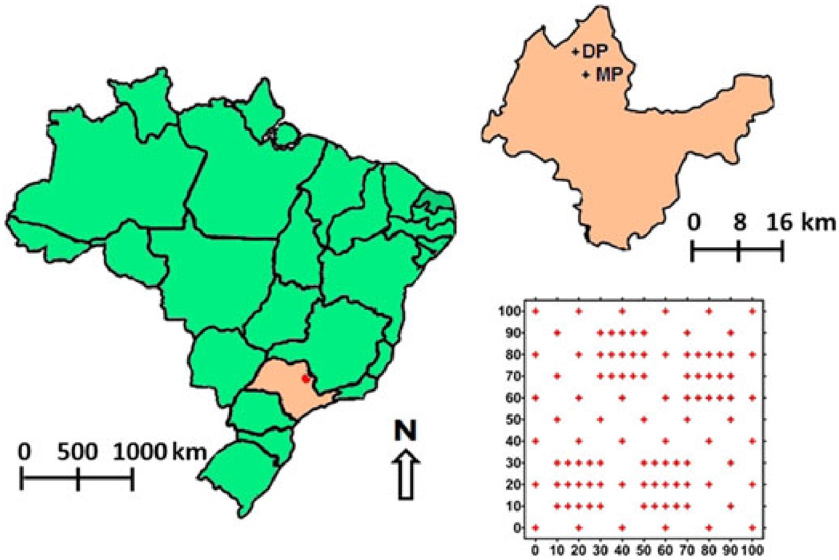

Figure 1. Schematic map indicating the location of the studied sites and both grid models in degraded (DP) and managed (MP) pasture areas. [Colour figure can be viewed at wileyonlinelibrary.com]

21′S and 47°04′W, 610 m above sea level for the managed pasture (MP) and 21°19′S and 47°05′W, 673 m above sea level for the degraded pasture (DP); these two pasture areas are 3,880 m apart (Figure 1).

The MP has been under a MP system for the last 3 years with rotational grazing, which followed a crop succession with sugarcane (*Saccharum officinarum* L.) in 2008 and maize (*Zea mays* L.) in 2009, planted in association with under-seeded *Brachiaria brizantha* (*B. brizantha* [Hochst] Stapf.) in 2009 to establish a new pasture. Of dolomite ($CaMg(CO_3)_2$), 2,000 kg ha^{-1} was applied in October 2012, approximately 4 months before the experiment started. At this time, fertilizers were applied at a rate of 150 kg N ha^{-1} year^{-1} (100 kg urea and 50 kg ammonium sulfate) and 80 kg K_2O divided among three application times (Sep/Oct/Nov/2012). The DP was characterized as *B. brizantha* pasture without any sort of amendment use or fertilizer application for the previous 5 years. According to Thornthwaite (1948), the climatic classification of both areas is B_1rB_4a, which is tropical moist with an average annual temperature of 21 °C. The mean annual precipitation is approximately 1,500 mm, and the major rainfall period is between October and March, with a relatively dry period between April and September. The soils in both areas are classified as Typic-Haplustults (USDA, Soil Taxonomy). Mean values of soil chemical–physical properties in DPs and MPs, measured at 0–30 cm depth, are presented in Table I.

FCO_2 and Soil Properties Measurements

On March 04, 2013, a grid of 100 × 100 m (1 ha) with 102 sampling points and a minimum separation distance between points of 5 m in each area (Figure 1) was set up. Measurements of soil CO_2 emission (FCO_2), soil temperature (T_{soil}) and soil water content (WC_{soil}) were conducted from March 12 until March 19, 2013, comprising a short-term period of eight measuring days to capture spatial–temporal variability. Measurements were taken in the morning between 8:00 and 12:00 with two portable LI-COR systems (LI-8100 LICOR, NE, USA) previously calibrated according to manufacturer's directions, with intervals of 90 s for each measurement and 30 s between measurements. It took 3 h and 24 min to measure both fields. The chamber was coupled to a plastic collar that was installed in the soil 24 h before the measurements took place at all 102 sampling points. Soil temperature was monitored with a 12-cm long probe (thermistor-based sensor) inserted into the soil close to the collars. The soil water content (%) was measured with a portable time domain reflectometer system (HydroSense System, Campbell Scientific, Utah, USA). Accumulated precipitation of 80 mm occurred in the period between March 10 and March 12, and 2 mm of precipitation was registered on March 13 and March 19 in the experimental areas.

Soil sample analyses (0–0.30 m depth) were performed for each measurement point of each grid, where FCO_2 was measured in the DP and MP plots to calculate soil C stock (0–30 cm depth) using Equation 1 (Bayer *et al.,* 2000), computed on an equivalent soil mass–depth basis.

$$Cstock = \frac{OC \times D_{soil} \times E}{10} \quad (1)$$

Here, *Cstock* is the soil carbon stock (Mg ha^{-1}), *OC* is the organic carbon content (g kg^{-1} = SOM/1.724) measured by the dry combustion method (Ellert & Bettany, 1995), D_{soil} is the soil bulk density (kg dm^{-3}), and *E* is the soil layer thickness (m). Soil bulk density (D_{soil}) was determined from 102 non-deformed samples collected by a suitable sampler adapted to the cylinders with an average size of 5.0-cm internal diameter and 4.0 cm in height (EMBRAPA – Empresa Brasileira de Pesquisa Agropecuária, 1997) and measured by the core method (Blake & Hartge, 1986). Total pore volume (%) was calculated using the soil bulk density values (g cm^{-3}). The micro-porosity was considered as volumetric content of water balanced in a table pressure at 60 cm water column, and the macro-porosity was calculated by the difference between the total porosity and micro-porosity, as described in Soil Analysis Methods Manual (EMBRAPA – Empresa Brasileira de Pesquisa Agropecuária, 1997). The air-filled pore space (AFPS) fraction (%) was calculated as the difference between the total pore volume (TPV; %) and the fraction of porosity filled by water [water-filled pore space (WFPS); %], which is equivalent to the soil water content.

To characterize soil chemical attributes at the 102 measurement points, 10 were randomly sampled, dried and sieved (passing through a 2-mm sieve) before being submitted to the following analyses: pH, available P, K, Ca and Mg content (Raij *et al.,* 1987). Particle size distribution (sand, silt and clay) was determined by the pipette method after dispersion of the soil by adjusting the pH to 10–11 with 1 M NaOH and sand sieving (Table I). Soil organic carbon was calculated based on a constant depth basis and expressing values as SOC stock.

Table I. Mean values of soil chemical–physical properties ± standard deviation from degraded (DP) and managed pastures (MP), measured at 0–30 cm depth

Variables	pH	Ca	Mg	P	K	CEC	Clay	Silt	Sand
MP	5.47 ± 0.1	22.78 ± 2.1	7.70 ± 0.7	17 ± 3.4	1.28 ± 0.4	52.6 ± 2.8	19.23 ± 2.64	8.90 ± 1.29	71.90 ± 2.73
DP	5.10 ± 0.05	11.6 ± 1.1	6.31 ± 0.7	8.7 ± 2.6	1.80 ± 0.3	36.3 ± 3.9	13.61 ± 2.39	6.20 ± 2.10	80.20 ± 2.62

N = 10; 0–30 cm depth. Clay, Silt and Sand (%).
pH, hydrogenic potential ($CaCl_2$); Ca, calcium (mmol$_c$ dm^{-3}); Mg, magnesium (mmol$_c$ dm^{-3}); P, available phosphorus (mg dm^{-3}); K, potassium (mmol$_c$ dm^{-3}); CEC, cation exchange capacity (mmol$_c$ dm^{-3}).

Data Analysis

For each of the two areas, descriptive statistics for FCO_2, T_{soil}, WC_{soil} and soil physico-chemical properties (SOM, soil C stock, D_{soil}, TPV, AFPS, macro-porosity and micro-porosity) were obtained to classify these variables. The significance of differences in soil properties between the management systems was determined by Student's *t*-test, observing the normality assumptions and homogeneity of variances. This analysis was performed using SAS (SAS version 9, SAS Institute, Cary, NC, USA).

For multivariate analysis, principal component analysis (PCA) was applied to the studied properties to condense the meaningful data into a smaller set of orthogonal variables (eigenvectors) composed of a linear combination of the original soil properties studied. For PCA analysis, FCO_2, T_{soil}, WC_{soil}, SOM, D_{soil}, macro-porosity and TPV were used. PCA was conducted using STATISTICA 7.0 (StatSoft. Inc., Tulsa, OK, USA).

The temporal variability of FCO_2, T_{soil} and WC_{soil} were evaluated for the MP and DP areas over the 8-day period and calculated using the means ± standard error. Linear correlation analysis was also conducted for each measurement day ($n = 102$) and along the entire measurement period considering the mean values of FCO_2, T_{soil} and WC_{soil} for each day ($n = 8$). These analyses were performed using SAS (SAS version 9, SAS Institute, Cary, NC, USA).

Spatial–temporal variability was described from daily measurements of FCO_2, T_{soil} and WC_{soil}. The spatial component was characterized by the spatial dependence between samples, which was analyzed by the variogram method. This is based on the theory of regionalized variables (Webster & Oliver, 1990) and describes the spatial continuity of the variables as a function of the distance between two locations (Equation 2):

$$\widehat{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2 \qquad (2)$$

where $\widehat{\gamma}(h)$ is the experimental semivariance for a separation distance h; $z(x_i)$ is the property value at the ith point, and $N(h)$ is the number of pairs of points separated by distance h. Plotting $\widehat{\gamma}(h)$ versus h gives the experimental variogram, which either exhibits purely random behavior or some systematic behavior described by theoretical models (spherical, exponential and Gaussian). The choice of the adjusted variogram model and its parameters was based on the sum of squared residuals and on the coefficient of determination (R^2) obtained by adjusting a theoretical model to an experimental variogram. To verify the reliability of the mathematical model, a cross-validation technique (data not shown) was used. After adjusting the model to the variogram, sites not sampled were estimated by ordinary kriging (Webster & Oliver, 1990). The variograms and interpolation through ordinary kriging were performed by GS+ software (version 9.0; Gamma Software Design, 2008), and the map interpolation edition was by Surfer (version 9.0; Golden Software, 2009).

RESULTS

Descriptive Statistics

The mean FCO_2 value observed during the 8-day period was 31.7% lower in the MP (Student's *t*-test; $p < 0.01$), 5.96 μmol m^{-2} s^{-1}, when compared with the DP, 8.73 μmol m^{-2} s^{-1} (Table II). Higher FCO_2 in the DP contrasts with its lower SC_{stock} (30,297 kg ha^{-1}) compared with the MP plot that presented lower FCO_2 and higher SC_{stock} (40,105 kg ha^{-1}) in the 0–0.30 m depth. In addition, an important aspect that can be related to the difference observed in FCO_2 pattern between the pasture systems is SOM content, which was 24.5% higher in the MP (Student's *t*-test; $p < 0.01$). Other soil properties were also significantly affected (Student's *t*-test; $p < 0.01$) by the different pasture management systems tested (Table II).

Our results showed higher values of macro-porosity in the DP compared with the MP (16.8 and 11.7%, respectively; Table II) (Student's *t*-test; $p < 0.01$), and we assume that

Table II. Descriptive statistics, mean, standard error of mean (SE), minimum (Min), maximum (Max) and coefficient of variation (CV) of FCO_2, soil temperature, soil water content and other soil physical attributes in 0–30 cm depth in managed and degraded pasture

Variables	Managed pasture						Degraded pasture					
	Mean		SE	Min	Max	CV (%)	Mean		SE	Min	Max	CV (%)
FCO_2 (μmol m^{-2} s^{-1})	5.96	a	0.20	2.71	11.37	30.7	8.73	b	0.38	2.58	15.98	32.6
T_{soil} (°C)	23.53	a	0.05	22.67	24.99	2.2	25.57	b	0.05	24.67	26.88	1.8
WC_{soil} (%)	16.90	a	0.25	12.78	27.00	14.0	13.40	b	0.21	9.78	23.89	14.7
D_{soil} (g cm^{-3})	1.52	a	0.02	1.12	1.81	10.6	1.49	a	0.01	1.14	1.77	8.7
Macro (%)	11.69	a	0.65	2.50	30.46	55.6	16.77	b	0.49	7.73	33.11	29.2
Micro (%)	30.43	a	0.42	21.21	42.51	14.0	26.73	b	0.70	8.66	44.09	26.3
SOM (g dm^{-3})	23.05	a	0.22	16.92	29.44	9.8	17.19	b	0.23	12.11	23.34	13.4
AFPS (%)	24.30	a	0.62	11.45	40.82	25.5	28.99	b	0.57	15.03	46.07	19.8
TPV (%)	42.12	a	0.56	31.25	55.93	13.4	43.50	a	0.57	30.33	60.51	13.3
SC_{stock} (Mg ha^{-1})	40,105	a	389	29,443	51,229	9.8	30,297	b	492.18	21,073	51,786	16.4

$N = 102$; means followed by the same letters on rows do not differ (Student's *t*-test; $p < 0.01$).
SE, standard error; Min, minimum value; Max, maximum value; CV, coefficient of variation; FCO_2, CO_2–C emission; T_{soil}, soil temperature; WC_{soil}, soil water content; D_{soil}, soil bulk density; Macro, macro-porosity; Micro, micro-porosity; SOM, soil organic matter; AFPS, air-filled pore space; TPV, total pore volume; SC_{stock}, soil carbon stock.

Table III. Eigenvalues and correlation coefficients between soil properties and the first two principal components

Principal components	PC1		PC2	
Eigenvalues	3.01		1.98	
Explained variance (%)	42.94		28.29	
	Eigenvector	Correlation	Eigenvectors	Correlation
FCO_2	−0.30	−0.52[a]	−0.05	−0.06
T_{soil}	−0.44	−0.77[a]	−0.28	−0.40
WC_{soil}	0.41	0.71[a]	0.31	0.44
SOM	0.42	0.73[a]	0.34	0.48
D_{soil}	0.28	0.49	−0.59	−0.82[a]
Macro	−0.46	−0.79[a]	0.20	0.27
TPV	−0.28	−0.48	0.57	0.80[a]

$N = 102$.
[a]Correlations (>0.50 in absolute value) considered in the interpretation of principal component.
FCO_2, soil CO_2–C emission; T_{soil}, soil temperature; WC_{soil}, soil water content; D_{soil}, soil bulk density; Macro, macro-porosity; SOM, soil organic matter; TPV, total pore volume.

higher macro-porosity would favor CO_2 diffusion in the DP, resulting in higher FCO_2. The same behavior was found for AFPS, which was higher in the DP (29.0%) than in the MP (24.3%).

The CV values of FCO_2 measured in both grids were quite similar, with 30.7% in MP and 32.6% in DP (high variability—CV > 24%; Warrick & Nielsen, 1980). For other soil attributes, CV in the MP varied from the lowest value of 2.2% for T_{soil} to the highest value of 55.6% for macro-porosity (Table II). Additionally, CV values in the DP showed either a low variability of 1.8% for T_{soil} and 8.7% for D_{soil} or high variability of 32.6% for FCO_2, 29% for macro-porosity and 26.3% for micro-porosity. The high variability of FCO_2 observed can lead to difficulties understanding the interrelation between those properties to better distinguish pasture management systems, thus leading to a necessarily more complex analysis such as multivariate.

Multivariate Data Analysis

The results of the main components indicated that 42.9% of the total variability was explained by the first component (PC1) and 28.3% by the second principal component (PC2), totaling 71.2% of the variability contained in the original dataset (Table III). The discriminatory behavior of each variable within the component is measured by the linear correlations between each soil property and its respective main component (Table III). In PC1, the properties that presented higher correlation coefficients in their order of significance (Table III) were macro-porosity (−0.79), T_{soil} (−0.77), SOM (0.73), WC_{soil} (0.71) and FCO_2 (−0.52). In order of significance, the properties that better related to PC2 were the variables D_{soil} (−0.82) and TPV (0.80).

Applying the so-called principal components, a bidimensional representation known as a biplot was created (Figure 2). With this analysis, it is possible to describe the structure of soil properties, which explains the maximum variability of the whole dataset of soil properties studied and possibly differentiating pasture management. The linear correlation analysis is represented by the arrow of each attribute and its projection on the biplot graphic (Figure 2). The attributes FCO_2, T_{soil}, macro-porosity and TPV presented negative correlations with PC1, particularly macro-porosity. Furthermore, T_{soil} and FCO_2 were the attributes responsible for characterizing the most points from the DP in the left region of PC1 (Figure 2). The biplot graph clearly indicates how samples from the DP are arranged at the left side of PC1, while those samples from the MP are arranged at the right side of PC1 with more extreme values for SOM and WC_{soil}. For PC2, the extreme value was TPV, showing higher sample dispersion in relation to the orthogonal axis when compared with DP samples.

Temporal Variability Analysis

FCO_2 measured in the DP was higher than in the MP during the whole period evaluated (Student's t-test; $p < 0.01$) (Figure 3). On the first study day (March 12), the emission values were 8.73 ± 0.38 and $4.47 \pm 0.21\ \mu mol\ m^{-2}\ s^{-1}$ in

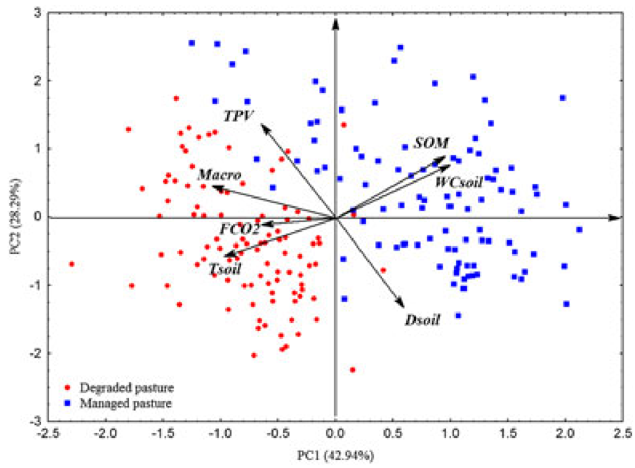

Figure 2. Biplot of the principal component (PC1 and PC2) analysis with all soil samples and variables: soil CO_2–C emission (FCO_2), soil temperature (T_{soil}), soil water content (WC_{soil}), soil bulk density (D_{soil}), total pore volume (TPV), soil organic matter (SOM) and macro-porosity (Macro). [Colour figure can be viewed at wileyonlinelibrary.com]

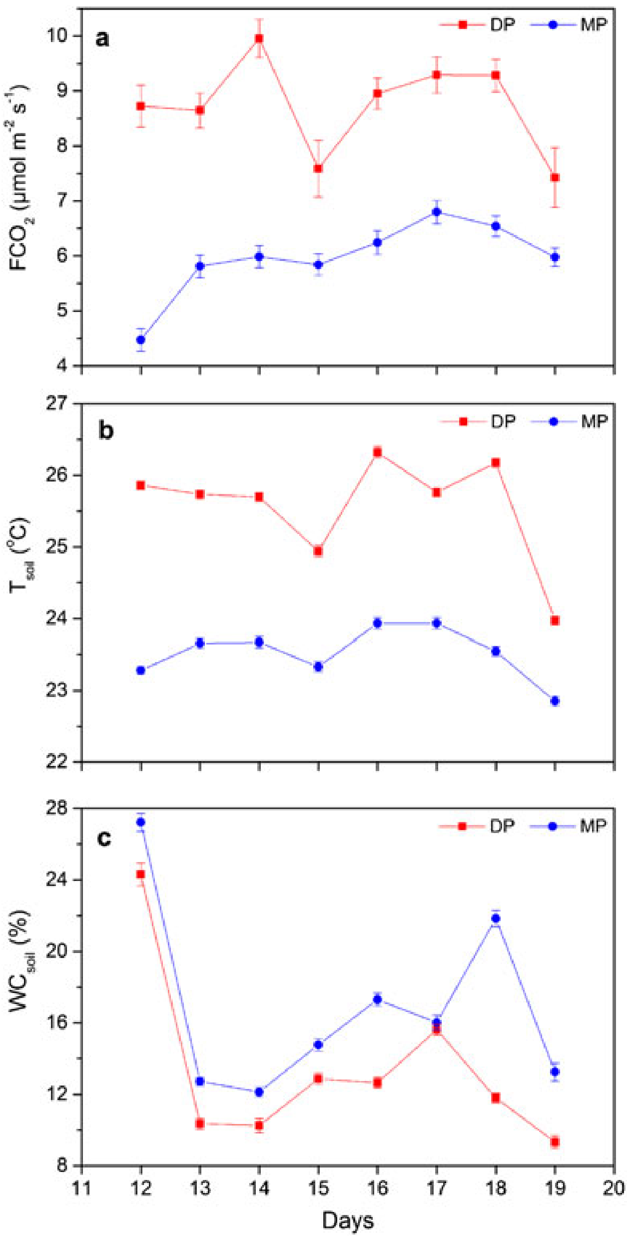

Figure 3. Temporal variability of (a) FCO_2 (μmol m^{-2} s^{-1}) ± standard error, (b) soil temperature (°C) ± standard error and (c) soil water content (%) ± standard error, in degraded (DP) and managed pasture (MP) during the study period, March 12 until March 19, 2013. [Colour figure can be viewed at wileyonlinelibrary.com]

the DP and MP, respectively. On the last study day, March 19, emissions in both areas were closer without a remarkable rain influence (7.43 ± 0.54 and 5.98 ± 0.17 μmol m^{-2} s^{-1}; Figure 3) but still significantly different (Student's *t*-test; $p < 0.01$). The difference between FCO_2 in the two areas decreased from 49% (March 12) to 20% (March 19), when the DP area presented the lowest value of WC_{soil} (9.3%). Total emissions calculated from the area below the FCO_2 graphs in Figure 3a were 640.7 and 440.0 kg CO_2–C ha^{-1} in the DP and MP, respectively, and they stand for an additional emission of 200.6 kg CO_2–C ha^{-1} from the DP in 8 days or 735.5 kg CO_2 released to the atmosphere.

Figure 3b presents changes in T_{soil} in both plots, revealing that soil temperature in the MP was lower (Student's *t*-test; $p < 0.01$) throughout the experimental period when compared with the DP. WC_{soil} was lower in the DP plot than the MP plot (Student's *t*-test; $p < 0.01$) during the entire measurement period, from the first measurement day (March 12), 24.3 and 27.2 %, respectively, to the last experimental day (March 19), 9.3 and 13.2%, respectively (Figure 3c). On March 12, after accumulated precipitation of 60 mm on March 11 and 12, AFPS in the MP presented the lowest value (14.9%), which could lead to a reduction of oxygen in soil pores, resulting in a reduction of CO_2 production and diffusion.

The diurnal relationship between FCO_2, WC_{soil} and T_{soil} was assessed by linear correlation analysis for each plot ($n = 102$), for all the study days ($n = 8$). There were no significant correlations in the MP among FCO_2, T_{soil} and WC_{soil} ($p > 0.10$). For the DP, there were positive and significant correlations ($p < 0.10$) between FCO_2 and T_{soil} on March 14 ($r = 0.19$) and March 15 ($r = 0.18$) and between FCO_2 and WC_{soil} on March 12 ($r = 0.35$), March 14 ($r = 0.20$), March 15 ($r = 0.14$) and March 16 ($r = 0.17$). Evaluating temporal correlations among FCO_2, T_{soil} and WC_{soil} along the measurement period ($n = 8$), a significant correlation in the DP was observed only between FCO_2 and T_{soil} ($r = 0.81$, $p < 0.05$).

Spatial–Temporal Variability

The adjusted variogram models for diurnal FCO_2, T_{soil} and WC_{soil} in the MP and DP are shown in Table IV. Nugget effect values (C_0, the sum of two components of measurement error: the sampling error and the error because of the short-scale variability) express the spatial variability of FCO_2, WC_{soil} and T_{soil} at small scales (Table IV). In the MP, all the study days presented similar C_0 values with a minimum value of 1.105 and a maximum of 2.081. In contrast, the variation of this parameter was high in the DP area (from 0.730 to 6.630). The spatial variability structure is expressed by C_1 values (Table IV), and we observed that higher and more variable C_1 values were found in the DP, in agreement with the standard error bars (Figure 4).

The range values (*a*) of FCO_2 observed in the adjusted variograms for the MP show small changes during the experimental period when compared with the DP area (Table IV). Despite the different ranges of spatial autocorrelation observed in the experimental areas, the range values show a similar tendency in both areas.

DISCUSSION

Descriptive Statistics

In the MP, lower FCO_2 contrasts with the dolomite and urea application 4 months before the measurements took place, which promoted the release of high amounts of CO_2–C because of their application on soil by stimulating the microbial activity (IPCC, 2006). The DP showed higher FCO_2 without any amendment or synthetic fertilizer applications for the last 5 years, indicating that MP presents lower FCO_2 even under intensive management. Feigl *et al.*

Table IV. Models and estimated parameters of experimental variograms obtained for soil CO_2 emission (FCO_2): managed and degraded pasture

	FCO_2							Soil temperature							Soil water content						
Day	Model	C_0	C_0+C_1	a	SSR	R^2	DSD	Model	C_0	C_0+C_1	a	SSR	R^2	DSD	Model	C_0	C_0+C_1	a	SSR	R^2	DSD
Managed pasture																					
12	Sph	1.99	3.32	30.3	0.33	0.73	0.60	Sph	0.18	0.36	40.5	0.012	0.67	0.50	Exp	5.33	28.22	52.5	29.5	0.90	0.19
13	Sph	1.98	3.31	23.7	0.82	0.67	0.60	Sph	0.09	0.48	32.1	0.022	0.82	0.19	Sph	0.76	4.09	17.5	0.76	0.80	0.19
14	Sph	1.41	4.23	16.2	0.92	0.71	0.33	Sph	0.00	0.66	51.8	0.026	0.94	0.00	Sph	2.76	6.45	14.1	1.96	0.58	0.43
15	Exp	1.10	3.98	23.1	0.95	0.70	0.28	Sph	0.00	0.50	41.9	0.021	0.89	0.00	Exp	1.55	14.12	10.0	5.63	0.91	0.11
16	Sph	2.08	4.71	21.7	0.10	0.97	0.44	Sph	0.03	0.68	48.2	0.034	0.91	0.05	Exp	7.13	14.60	66.3	3.96	0.89	0.49
17	Sph	1.27	4.43	18.3	0.34	0.91	0.29	Sph	0.06	0.76	58.3	0.021	0.96	0.08	Gau	6.32	26.70	88.2	13.50	0.97	0.24
18	Sph	1.66	3.64	18.6	0.40	0.78	0.46	Sph	0.07	0.45	44.7	0.010	0.92	0.16	Exp	6.79	27.15	103.5	7.48	0.97	0.25
19	Sph	1.19	2.94	20.0	0.37	0.76	0.40	Sph	0.00	0.50	43.6	0.004	0.98	0.00	Gau	11.30	44.30	116.0	34.30	0.95	0.26
Degraded pasture																					
12	Sph	6.6	15.2	90.2	5.51	0.92	0.44	Sph	0.11	0.39	31.8	0.006	0.88	0.30	Gau	9.60	81.30	117.8	243	0.96	0.12
13	Exp	5.0	10.0	61.2	12.60	0.56	0.50	Exp	0.02	0.27	19.2	0.004	0.75	0.08	Gau	2.15	15.30	105.8	5.21	0.98	0.14
14	Sph	5.2	13.0	42.5	16.40	0.74	0.40	Gau	0.05	0.46	41.4	0.005	0.97	0.10	Gau	3.18	27.00	95.3	9.37	0.98	0.12
15	Exp	0.7	5.2	15.3	1.62	0.58	0.14	Gau	0.12	0.85	52.1	0.032	0.95	0.14	Sph	3.13	8.06	20.7	2.55	0.79	0.39
16	Sph	4.8	7.4	23.0	1.36	0.64	0.64	Sph	0.04	0.56	35.8	0.051	0.77	0.07	Exp	0.99	5.98	18.6	2.95	0.61	0.17
17	Exp	2.5	6.6	35.7	0.39	0.94	0.38	Sph	0.01	0.44	43.2	0.006	0.96	0.01	PNE	5.04	5.04	—	—	—	1.00
18	Exp	4.2	8.4	46.8	1.72	0.82	0.50	Sph	0.20	0.48	33.5	0.025	0.67	0.41	Gau	0.03	0.06	68.2	0.46	0.89	0.53
19	Exp	1.8	3.6	49.5	0.17	0.90	0.50	Sph	0.17	0.36	57.1	0.004	0.92	0.46	Gau	4.14	17.14	29.7	3.40	0.98	0.24

$N = 102$; a = range (m) $= C_0 / (C_0 + C_1)$, strong for values smaller than 0.25, moderate for values between 0.25 and 0.75, and weak for values higher than 0.75 (Cambardella *et al.*, 1994).
DSD, degree of spatial dependence; SSR, sum-square residue; Exp, exponential; Sph, spherical; Gau, Gaussian; PNE, pure nugget effect.

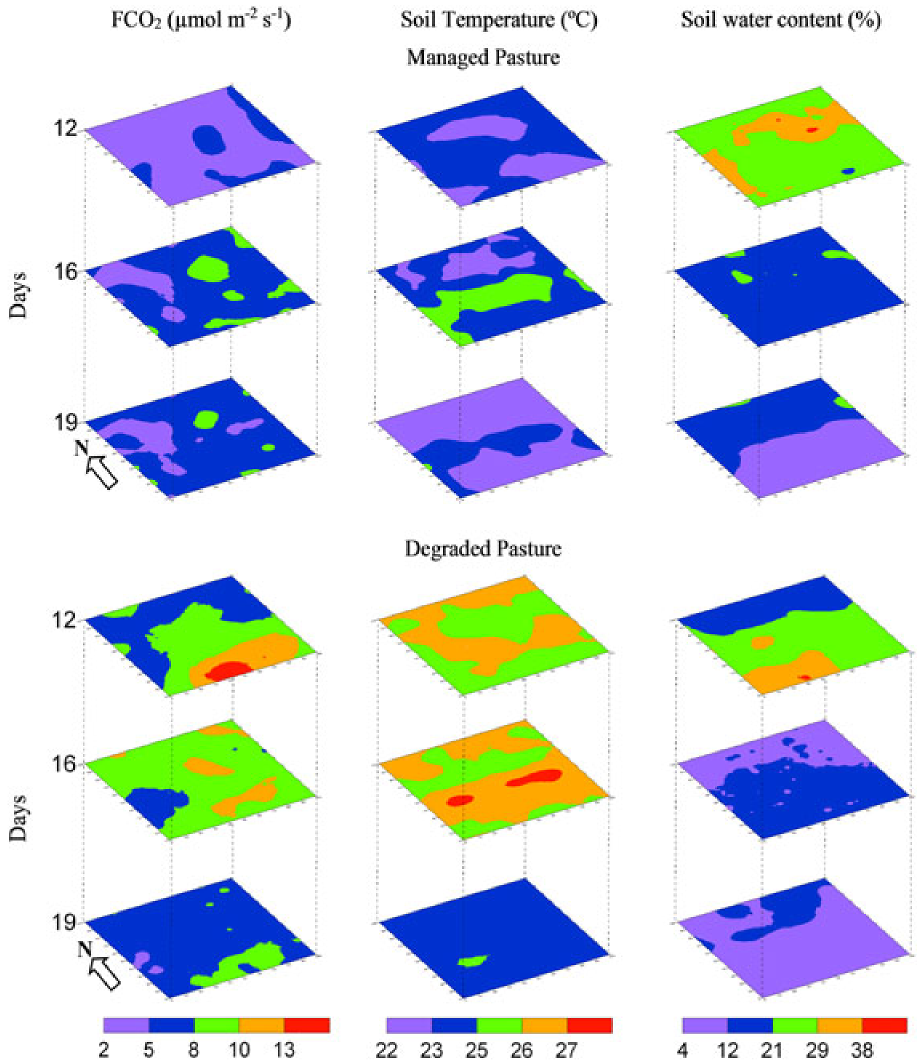

Figure 4. Maps of spatial patterns for FCO_2 ($\mu mol\,m^{-2}\,s^{-1}$), soil temperature (°C) and soil water content (%) in managed (MP) and degraded pasture (DP) areas for March 12, 16 and 19. [Colour figure can be viewed at wileyonlinelibrary.com]

(1995) showed that the major sources of CO_2–C emitted from pasture soil are the litter, SOM mineralization and plant root respiration, and that it is a difficult task to separate each individual contribution. However, based on our findings, improved pasture management can prevent additional CO_2–C loss from pasture areas, probably as a result of lower SOM mineralization and litter decomposition, influenced by lower soil temperature (Billings *et al.,* 2015), which could be a process that enables higher potential for soil C sequestration.

In this study, even when higher SOC and higher SC_{stock} were measured in the MP, this area presented lower FCO_2 than the DP area, which had lower SC_{stock}, lower SOC and higher FCO_2 (Table II). This showed that a better pasture management system can result in lower FCO_2, probably as a result of more stable C in this site. Corroborating our results, Conant *et al.* (2001) presented results from 115 studies containing over 300 data points and concluded that grasslands can act as a significant C sink with the implementation of improved management. Complementarily, Pulido-Fernández *et al.* (2013) found that overgrazing fosters thinning can promote the appearance of large bare soil areas hence reducing the SC_{stock} over the long term. A similar condition could be occurring in our DP area.

Multivariate Data Analysis

The results of multivariate analysis suggest that different pasture management practices could significantly change the spatial distribution of soil biological and physical properties, affecting values of FCO_2, WC_{soil}, T_{soil}, SOM and macro-porosity in pasture areas. The definition and characterization of degraded pasture is variable, with authors defining those areas mainly as pasture with unfavorable physical, biological and chemical soil properties, resulting in low grass and cattle yield.

Aiming to characterize pasture biophysical properties and the impact of grazing intensity in Brazil, Numata *et al.* (2007) measured quantitative parameters and their change in space and time because of pasture degradation in the Amazon, reporting that our knowledge about the characteristics of grazed pastures is very limited. Our multivariate analysis results (Figure 2) contribute to show how variables as FCO_2, T_{soil}, WC_{soil}, SOM and macro-porosity (PC1) can differentiate changes in biophysical properties in DP and MP. Studying the impact of organic amendments on soil hydrology, structure and microbial respiration, Yazdanpanah *et al.* (2016) found that greater microbial respiration resulted in more macro-porosity, emphasizing the importance of microbial respiration as a biological activity in controlling soil structural characteristics.

Results of eigenvectors, or coefficients, indicate that the PC1 component expresses WC_{soil} and SOM in contrast to T_{soil} and macro-porosity (Figure 2); therefore, 42.9% of the dataset's variation was related to this difference (Table III). An explanation for this could be that high values of WC_{soil} combined with high SOM in the MP led to low values of T_{soil}, probably influenced by higher vegetal soil covering. Complementarily, SOM is strictly related to WC_{soil}, and this effect could be explained by direct relationships established for changes in water holding capacity as a function of net increases in SOM (Khaleel *et al.,* 1981). Furthermore, Haynes & Naidu (1998) concluded that increasing SOM content results in increased water holding capacity, soil porosity and infiltration capacity, supporting our results.

Temporal Variability Analysis

Soil respiration is a combination of plant and microbial metabolism, each of which may respond differently to the temperature and soil water content (Davidson *et al.,* 2000). Higher FCO_2 found in the DP compared with the MP from March 12 until the last measurement day could be explained because the relationship between rain exposure and CO_2 is positive, with FCO_2 greater for soil under rainfall. The mechanism that produces this effect may be the physical alteration of soil aggregates because of raindrop impact, which may increase soil FCO_2 in uncovered soil conditions such as DP (Novara *et al.,* 2012).

Another explanation for the lowest FCO_2 found in the MP on March 12 could be that this site presented the highest WC_{soil} (24.4%) with the saturated soil reducing CO_2–C production because of unfavorable aerobic conditions. Xu & Qi (2001) showed that soil water content (in particular WFPS) is another variable that affects the rate of respiration. Moreover, Smith *et al.* (2003) demonstrated that methane is formed in soil by the microbial breakdown of organic compounds in strictly anaerobic conditions, perhaps the same conditions observed at the MP site on March 12.

The additional amount of FCO_2 found in the DP compared with MP (200.6 kg CO_2–C ha^{-1}) corresponds to around one half of the annual potential for soil C sequestration in pasture (0.44 Mg C ha^{-1} $year^{-1}$) according to Carvalho *et al.* (2010), who measured soil C stock changes in well-managed *B. brizantha* pastures.

The lower soil temperatures found in the MP could be attributed to the greater soil vegetable covering at this plot, which was estimated with almost all the plants having a height close to 0.5 m, as opposed to the DP management that had sparse plant cover approximately 0.10 m in height. Under DP conditions, the soil certainly receives higher direct solar radiation, leading to higher soil temperature. Studying the impacts of livestock grazing in Australia, Yates *et al.* (2000) showed that soil temperature presented the most dramatic differences between grazed and rarely grazed/ungrazed sites. Significant correlation found in the DP, between FCO_2 and T_{soil}, is worrying because a large percentage of pastures in the central-north region of Brazil are under some degradation process (Peron & Evangelista, 2004). According to the IPCC (2014), the projected near-term (2016–2035) mean surface temperature increase is 0.9–1.3 °C, which may cause additional soil CO_2–C losses in the DP environment.

Higher WC_{soil} in the MP could be attributed to the same influence that caused lower T_{soil} in this plot, higher vegetative cover of the soil and lower incidence of direct solar radiation on the soil. Perennial vegetation cover is important because it protects the soil surface from raindrop splashing and surface sealing effects, causing the soil to have improved physical properties (Yates *et al.,* 2000). Therefore, better pasture management allowing for an ideal plant height would probably promote greater pasture yields as a result of higher water availability. Additionally, Brito *et al.* (2015) showed that CO_2–C emissions were lower with increasing pasture height as a result of *Brachiaria* pasture management.

Spatial–Temporal Variability

Most of the adjusted models had a high coefficient of determination as presented by their R^2 values. According to Isaaks & Srivastava (1989), the exponential and spherical models describe variables that present semivariograms with linear behavior near to the origin and the exponential model is better adjusted to erratic phenomena at closer distance than the spherical model. Most of the spatial variability models for FCO_2 have been described using spherical models (Teixeira *et al.,* 2012) or changes in models between spherical and exponential (Brito *et al.,* 2010; Teixeira *et al.,* 2013).

The soil FCO_2 and other soil attributes presented great variability in space and time. By analyzing these attributes through geostatistics, it was possible to characterize their behavior in space and thus observe other relationships beyond those verified by conventional statistics. This information is of fundamental importance in the case of an intervention aimed at reducing these emissions.

Observing FCO_2 spatial patterns in the MP for March 12, 16 and 19 (Figure 4), we noted that this pattern was similar for all the study days, with higher emissions located in the center, indicating a greater temporal homogeneity of variables that controls the FCO_2 in this area. Studying spatial variability of soil organic C in a Mediterranean grazed area, Costa *et al.* (2015) showed the same uniform spatial patterns for SOC, which could be a variable that controls the FCO_2 spatial pattern. On the other hand, in the DP area, the spatial variability patterns were not as similar over time as observed in MP, indicating a higher temporal variability of the factors that control the FCO_2 in the DP area.

CONCLUSIONS

This study points out that the degraded pasture area released significantly more CO_2–C comparing with the well-managed pasture. This indicates that the introduction of best management practices in pasture areas is an important strategy to reduce additional soil CO_2–C losses and contribute to soil C accumulation in those areas. After 3 years adopting intensive management practices, the managed pasture area presented lower FCO_2 despite its higher soil C stock, indicating a more stable soil C condition when compared with the degraded pasture. The results of multivariate analysis can contribute to pasture system characterization. The rate and mechanism of CO_2–C loss from pasture soils related to changes in soil biophysical properties and respective management can affect the potential for soil C sequestration, with the soil functioning as either an atmospheric CO_2–C sink or an emission source.

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