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GREENHOUSE GAS EMISSIONS AND CHEMICAL AND PHYSICAL SOIL ATTRIBUTES OF OFF-SEASON AGRICULTURAL PRODUCTION SYSTEMS IN THE SAVANNAH OF MARANHÃO STATE, BRAZIL

Lucélia de C. R. de Brito[1*], Henrique A. de Souza[2], Diana S. Deon[3], Ivanderlete M. de Souza[4], Smaiello F. da C. B. dos Santos[1], Amanda H. S. Sobral[1]

[1*]Corresponding author. Federal University of Piauí/Teresina - PI, Brazil.
E-mail: lucelia_cassia@yahoo.com.br | ORCID ID: https://orcid.org/0000.0001.5137.9610

KEYWORDS

Cerrado, Carbon dioxide, Methane, Nitrous oxide.

ABSTRACT

Management of agricultural production systems interferes with greenhouse gases (GHG) emissions, thereby altering physical, chemical, and biological attributes of soil; therefore, it is important to understand the relationship between soil attributes and GHG emissions. This study evaluated GHG emissions and their relationship with soil attributes in off-season soybean, maize, brachiaria and eucalyptus production systems. The experiment was carried out in Brejo, Maranhão, Brazil, with soybean (*Glycine max*), maize (*Zea mays*), brachiaria (*Urochloa ruzizienses*), and eucalyptus (*Eucalyptus grandis*). Fluxes of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) were evaluated using air samples analyzed by gas chromatography. Soil attributes were ammonium and nitrate contents, total organic carbon, moisture, pH, density, total porosity, and water-filled pore space. N_2O flux was 287.1 µg m^{-2} h^{-1} for eucalyptus cultivation, while areas cultivated with soybeans, maize and brachiaria had influxes of 46.7, 7.2, and 13.17 µg m^{-2} h^{-1}, respectively. In the off-season, the highest emissions of N_2O and CO_2 were measured in eucalyptus areas due to soil moisture and porosity conditions provided by accumulation of litter on the soil surface.

INTRODUCTION

The adoption of agricultural systems using technologies such as (i) crop rotation, succession planting and intercropping, (ii) no-till farming or (iii) crop-livestock-forest integration are sustainable forms of land use with high potential for mitigating greenhouse gas (GHG) emissions of carbon dioxide (CO_2), nitrous oxide (N_2O), and methane gas (CH_4) (Oliveira et al., 2019).

Integrated systems have recently become one of the most widespread technologies in the Brazilian Savannah (Cerrado), specifically in the Mid-North region, which is formed by the states of Piauí and Maranhão. Integrated systems use concepts of crop rotation, succession planting, and intercropping, and trees may be a key component of such systems (Teixeira Neto et al., 2019).

Agricultural systems interfere with GHG balance by affecting multiple simultaneous processes occurring in the soil-plant relationship (Vieira, 2017). Agricultural activities change soil attributes, including porosity, water retention capacity (Santos et al. al., 2016; Smith, 2017), O_2 content, pH, and N content (Hickman et al., 2015; Carvalho et al., 2017).

Nitrification is the process of oxidizing ammonium (NH_4^+) (ammonia-NH_3, in terms of substrate) to nitrite and subsequently to nitrate (NO_3^-) while denitrification is the microbiological reduction of NO_3^- to nitrous oxide (N_2O) or molecular N (N_2). These are simultaneous processes responsible for N_2O production (Vieira, 2017) and sensitive

[1] Federal University of Piauí/Teresina - PI, Brazil.
[2] Embrapa Meio-Norte/Teresina - PI, Brazil.
[3] Embrapa Semiárido/Petrolina - PE, Brazil.
[4] State University Vale do Acarau/Sobral - CE, Brazil.

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to management and application timing, as the processes are highly dependent on C oxidizable and soil moisture.

Although the influence of soil management on GHG emissions has been widely studied (Araújo et al., 2022; Lopes et al., 2018; Oliveira Filho et al., 2020), there is little information on how GHG emissions relate to different integrated system components (crop, forage, and tree) in Cerrado biome of Maranhão state, a region considered an agricultural frontier (Lustosa Filho et al., 2021). Such information is especially important in off-season crop production, when water becomes limiting due to climatic conditions, making it difficult for plant residues to remain on the soil surface.

The hypothesis was that different agricultural systems can interfere with GHG emissions due to changes in physical and chemical attributes of soil in an agricultural frontier region. Thus, the objective was to evaluate greenhouse gas emissions, soil chemical and physical characteristics in soybean, maize, brachiaria and eucalyptus production systems over the off-season in a Cerrado biome of eastern Maranhão state, Brazil.

MATERIAL AND METHODS

The study was carried out at Barbosa farm, located in the municipality of Brejo, in the eastern region of the state of Maranhão, Brazil (03 º 37' S and 43 º 35' W). Evaluations took place in the 2018 crop season, following grain harvest and the beginning of the off-season.

The climate in the region, according to the Köppen-Gerger classification, is type Aw (tropical climate, with dry winter season), with average annual temperature above 27 °C and average annual rainfall of 1,613 mm. From January to May, there is water surplus, followed to water deficit from June to December (Passos et al., 2016). Climate data for the year of the experiment are shown in Figure 1.

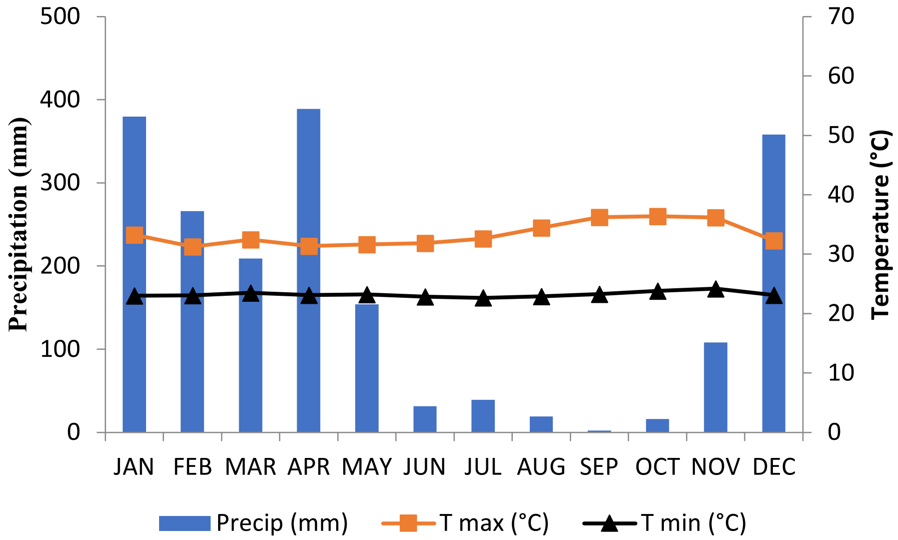

FIGURE 1. Climatic data of air temperature and rainfall recorded in the year the study was conducted. Brejo, Maranhão, 2018. Source: Inmet for air temperature and Barbosa farm for rainfall.

Average altitude of the experimental area is 95 m, with smooth relief and low slope (0.2%). The soil is classified as dystrocohesive Yellow Argisol (Dantas et al., 2014; Resende et al., 2014; Santos et al., 2018). Before setting up the experiment, the experimental area was subsoiled (30 cm) and 1.6 t ha $^{-1}$ of dolomitic limestone was applied. After 40 days, soil samples were collected for chemical and granulometry testing (Table 1).

TABLE 1. Chemical and physical characteristics of the soil before setting up the experiment. Brejo, Maranhão, 2017.

Depth	pH	OM	P	K	Na	Ca	Mg	Al	H+Al	SB	CEC	BS
cm	(H_2O)	g kg^{-1}	mg dm^{-3}	---------------------- cmol$_c$ dm^{-3} --------------------								%
0-20	5.6	29	17	0.31	0.09	8.7	1.3	0.08	7.8	10.31	18.1	57
20-40	5.4	32	11	0.28	0.09	8.1	1.1	0.10	8.9	9.48	18.4	52

	Cu	Fe	Mn	Zn	Coarse Sand	Fine Sand	Clay	Silt	Classification
	----- mg dm^{-3} ----				-------------------- % ------------------				
0-20	0.2	22.3	6.9	0.6	25.0	36.1	18.6	20.4	Sandy loam
20-40	0.3	34.0	5.2	0.6	26.4	25.0	20.6	28.1	

OM: organic matter. P: phosphorus. K: potassium. Ca: calcium. Mg: magnesium. Na: sodium. H + Al: potential acidity. Al: aluminium. SB: sum of bases. CEC: cationic exchange capacity. BS: base saturation. Cu: copper. Fe: iron. Mn: manganese. Zn: zinc. Methods: pH(H_2O) was determined at a soil: solution ratio of 1:2.5; OM was determined according to the Walkley-Black method; P, K, Na, Cu, Fe, Mn, and Zn were extracted with Mehlich-1; Ca, Mg and Al were extracted by KCl 1 mol L−1 ; H + Al were extracted by Ca acetate; clay, silt and sand were extracted by pipette method.

The study was carried out in four management areas: soybean (*Glycine max*), maize (*Zea mays*), brachiaria (*Urochloa ruzizienses*), and eucalyptus (*Eucalyptus grandis*) (Table 2). The areas have been similarly used until 2016. All areas were deforested in 2004 and, in the following year, upland rice was cultivated. From 2006 to 2010, soybean was grown in a no-till system with soil fertility management based on soil chemical analysis each year. From 2011, *Urochloa brizantha* cv. Marandu was overseeded on soybean crop (*Glycine max* L.). After soybean harvest and adequate forage development, cattle were let loose in the area (stocking rate of 2.0 AU ha^{-1}). Around 30 days before soybean planting for the next crop, forage was desiccated for straw under no-till farming. From 2017, different managements were applied to each area, as described in table 2.

TABLE 2. Description and management history of areas under soybean, maize, brachiaria and eucalyptus. Brejo, Maranhão, 2018.

Management history and description
Soybean (*Glycine max*)
In 2017, maize (*Zea mays*) was intercropped with brachiaria (*Urochloa ruziziensis*). The forage was broadcasted at the rate of 5 kg ha^{-1}. Basal fertilization consisted of 260 kg ha^{-1} of 13-33-08 applied to planting furrows and 280 kg ha^{-1} of 08-00-36 as topdressing when maize plants had four leaves (four-leaf stage) and 150 kg ha^{-1} of polymerized urea, also as topdressing, at eight-leaf stage. After maize harvest, brachiaria plants remained in the area until desiccation in January 2018 for soybean sowing at a spacing of 0.5 m between plant rows for a population of 200,000 plants ha^{-1} (cultivar AN 83022 SC Conventional). Following soybean harvest (May 2018), pearl millet seeds were broadcasted at rate of 20 kg ha^{-1} of seeds. Basal fertilization in soybeans consisted of 165 kg ha^{-1} of 09-46-00 (monoammonium phosphate) and 300 kg ha^{-1} of 10-00-30 as topdressing (30 days after planting).
Maize (*Zea mays*)
In 2017, the area was cultivated with sorghum (*Sorghum bicolor*) with basal fertilization consisting of 260 kg ha^{-1} of 13-33-08 applied to planting furrows and 280 kg ha^{-1} of 08-00-36 as topdressing at four-leaf stage and 150 kg ha^{-1} of polymerized urea also as topdressing at eight-leaf stage. After harvesting, crop residues were used as straw for the following harvest. In 2018, maize was sown with rows spaced at 0.5 m apart for a stand of 60,000 plants ha^{-1}. At sowing, 280 kg ha^{-1} of NPK 13-33-08 were used, and the first topdressing fertilization was performed at four-leaf stage by applying 280 kg ha^{-1} of 10-00-30. The second topdressing fertilization was carried out at four-leaf stage, applying 100 kg ha^{-1} of polymerized urea. Maize harvest took place in June 2018.
Brachiaria (*Urochloa ruzizienses*)
In 2017, the area was cultivated with sorghum (*Sorghum bicolor*) and basal fertilization consisted of 260 kg ha^{-1} of 13-33-08 in planting furrows and 280 kg ha^{-1} of 08-00-36 as topdressing at four-leaf stage and 150 kg ha^{-1} of polymerized urea as topdressing at eight-leaf stage. In January 2018, desiccant was applied to plants growing on the area. Approximately 20 days after desiccant application, brachiaria was broadcasted using 8 kg ha^{-1} of seeds at a cultural value of 30%, without fertilization.
Eucalyptus (*Eucalyptus grandis*)
Eucalyptus seedlings were transplanted in January 2017, in triple rows (4 m between rows and 3 m between plants), in the East-West direction. The spacing between rows was 28 m and the row length was 150 m. Between tree rows, soybeans and maize were cultivated. Eucalyptus implantation was accompanied by soil amendment and fertilizer application following recommendations by Sousa and Lobato (2004).

Greenhouse gas (GHG) emissions were measured on July 25, 2018, using terrestrial static chambers (Steudler et al., 1991). Four sampling units were used for each system (repetitions), thus totaling 16 sampling units. When gases were collected in the areas, soybean and maize crops had already been harvested, brachiaria showed abundant biomass (7,866 kg ha^{-1} of dry mass) completely covering the soil surface, and eucalyptus was in its second year of development.

The chambers were made of a rectangular galvanized steel base partially buried in the ground (approximately 5 cm deep) and a rectangular plastic cover coated with aluminized thermal blanket to maintain the temperature inside the chamber. The bases were installed in soil 24 hours before the start of gas collection and remained in the field throughout the evaluation period (Steudler et al. 1991). At the time of collection, the cover was placed on the base and rested on a channel located on the outer edge of the base. The sealing between the cover and the base was carried out with a small amount of water inside the channel. The upper end of each chamber had a valve for collecting gas samples and an orifice for measuring the internal temperature with a digital thermometer during collection. After closing the chamber, gas samples emitted by the soil were collected at four intervals: when the cover was fitted onto the base (time zero), and at 10, 30 and 45 minutes after closing the chamber. Samples were collected in 50 mL polypropylene syringes and immediately transferred to glass vials (serum vials) with absence of gases inside (80 Kpa) and sealed with a rubber septum.

The determination of the concentrations of CO_2, CH_4 and N_2O in the samples was performed by gas chromatography, in the chromatography laboratory of Embrapa Semi-arid, in an Agilent 7890A chromatograph, equipped with a flame ionization detector (FID) to determine the concentrations of CO_2 and CH_4 in samples with a μECD detector to determine N_2O concentrations. The rate of change of gas concentration inside the chamber was used to calculate the GHG emission flux, using the formula:

$$F\ (\mu g\ C - CO_2/N - N_2O/N - CH_4\ m^{-2}\ h^{-1}) = (\Delta C/\Delta t) * (m/Vm) * V/A \quad (1)$$

where:

$\Delta C/\Delta t$ is the rate of change of the gas inside the chamber at a given time (ppm/hour);

m is the molecular mass of each gas (g);

Vm is the molecular volume of the gas (1 mol occupies 22.4 L under normal conditions of temperature and pressure);

V is the volume of the chamber (L);

A is the chamber area (m^2). The molecular volume of gases is corrected as a function of the temperature inside the chamber during sampling:

$$Vm\ (corrected) = 22.4 * (273 + T/273) \quad (2)$$

where:

T is the average temperature inside the chamber (°C).

Concomitantly with gas emission collections, soil sampling was carried out (0-0.1 m) at the four cardinal points in a 2-m radius from each chamber. The samples were homogenized to form a composite sample for the determination of ammonium (NH_4^+ - analyzed by the distillation and titration method), nitrate (NO_3^- - analyzed by the distillation and titration method), total organic carbon (TOC - Walkley-Black method), pH (H_2O), moisture (Moist), soil bulk density (BD - volumetric ring method), and total porosity (TP – indirect method by soil and particle density), according to Teixeira et al. (2017). Further, with the total porosity and soil moisture data, water-filled pore space (WFPS) was calculated.

The data were subjected to comparisons of means of each land use system according to Payton et al. (2000) using the confidence interval (CI) of the mean ($p<0.05$). When there was no overlapping between the upper and lower limits of the confidence interval, the difference between means was significant.

The evaluate the correlation between variables, principal component analysis (PCA) was carried out using R software (R Core Team, 2018). Variables were standardized for multivariate tests (Manly, 2008).

Pearson's correlation analysis was also performed. Classification was based on correlation coefficients (r): insignificant (0.0-0.3); low (0.31-0.50), moderate (0.51-0.70), high (0.71-0.90), and very high (0.91-1.0) (Mukaka, 2012). Analyses were performed using the R software (R Core Team, 2018).

RESULTS AND DISCUSSION

The efflux (emission) of N-N_2O was 287.1 µg m^{-2} h^{-1} for eucalyptus cultivation, while areas cultivated with soybeans, maize and brachiaria had influxes (uptake) of 4.7; 7.2 and 13.2 ug m^{-2} h^{-1}, respectively (Figure 2).

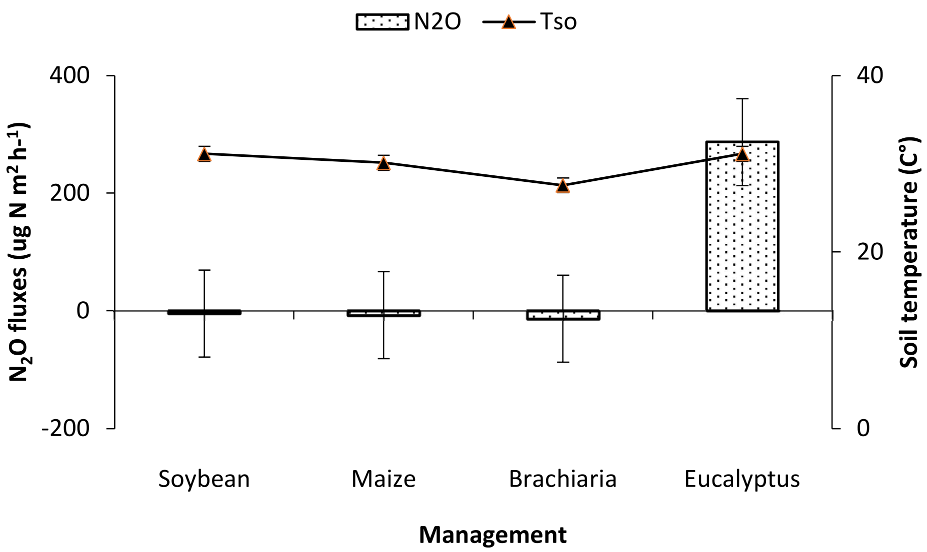

FIGURE 2. N-N_2O fluxes (µg m^{-2} h^{-1}) in areas with soybean, maize, brachiaria, and eucalyptus. Brejo, Maranhão, 2018. Tso = soil temperature.

Soybean, maize, brachiaria and eucalyptus managements showed C-CH_4 influxes and C-CO_2 effluxes (Figure 3). Soybean, eucalyptus, and maize management systems showed C-CH_4 drainage of -27.8, -15.7 and -7.0 ug m^2 .h^{-1}, respectively. The smallest influx of C-CH_4 was observed in soil cultivated with brachiaria (-5.1 ug m^2 h^{-1}).

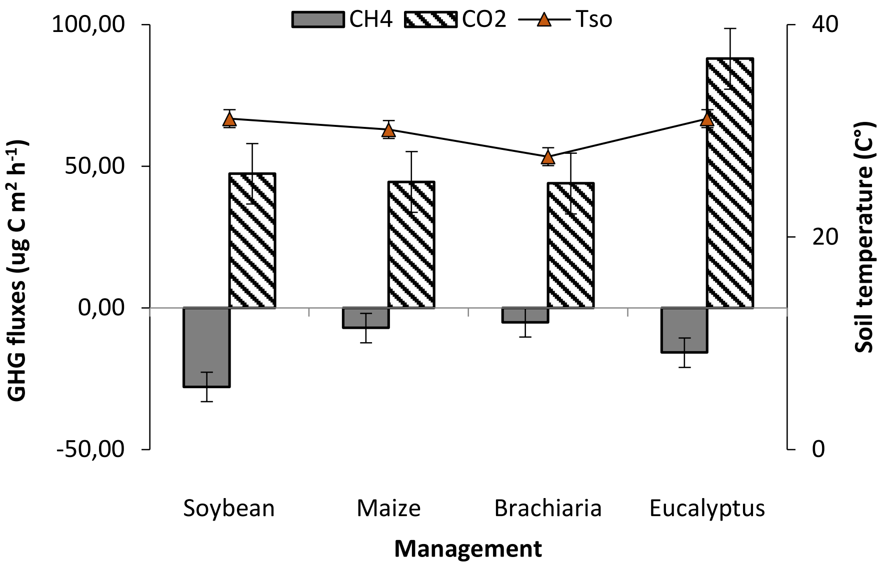

FIGURE 3. C-CH_4 (μg m^{-2} h^{-1}) and C-CO_2 (μg m^{-2} h^{-1}) fluxes and soil temperatures during gas collections in soybean, maize, brachiaria and eucalyptus management areas. Brejo, Maranhão, 2018.

Emission values were 47.4, 44.4, 44.0 and 88.0 μg m^2 h^{-1}, respectively, for soybean, maize, brachiaria and eucalyptus (Figure 3). The highest C-CO_2 emission was observed in soil under eucalyptus cultivation. Soil temperature positively influenced C-CH_4 and C-CO_2 emissions since the highest soil temperature values were verified for soybean and eucalyptus, with averages of 31°C for both managements, while soil temperature in brachiaria and maize areas were 28 and 30 °C, respectively.

The confidence interval for nitrate (Figure 4A), ammonium (Figure 4B), pH (Figure 4D), soil moisture (Figure 4E) and total porosity (Figure 4F) revealed an overlap between areas; however, for total organic carbon (Figure 4C), soybean had the highest value in relation to maize, but both did not differ from brachiaria and eucalyptus areas.

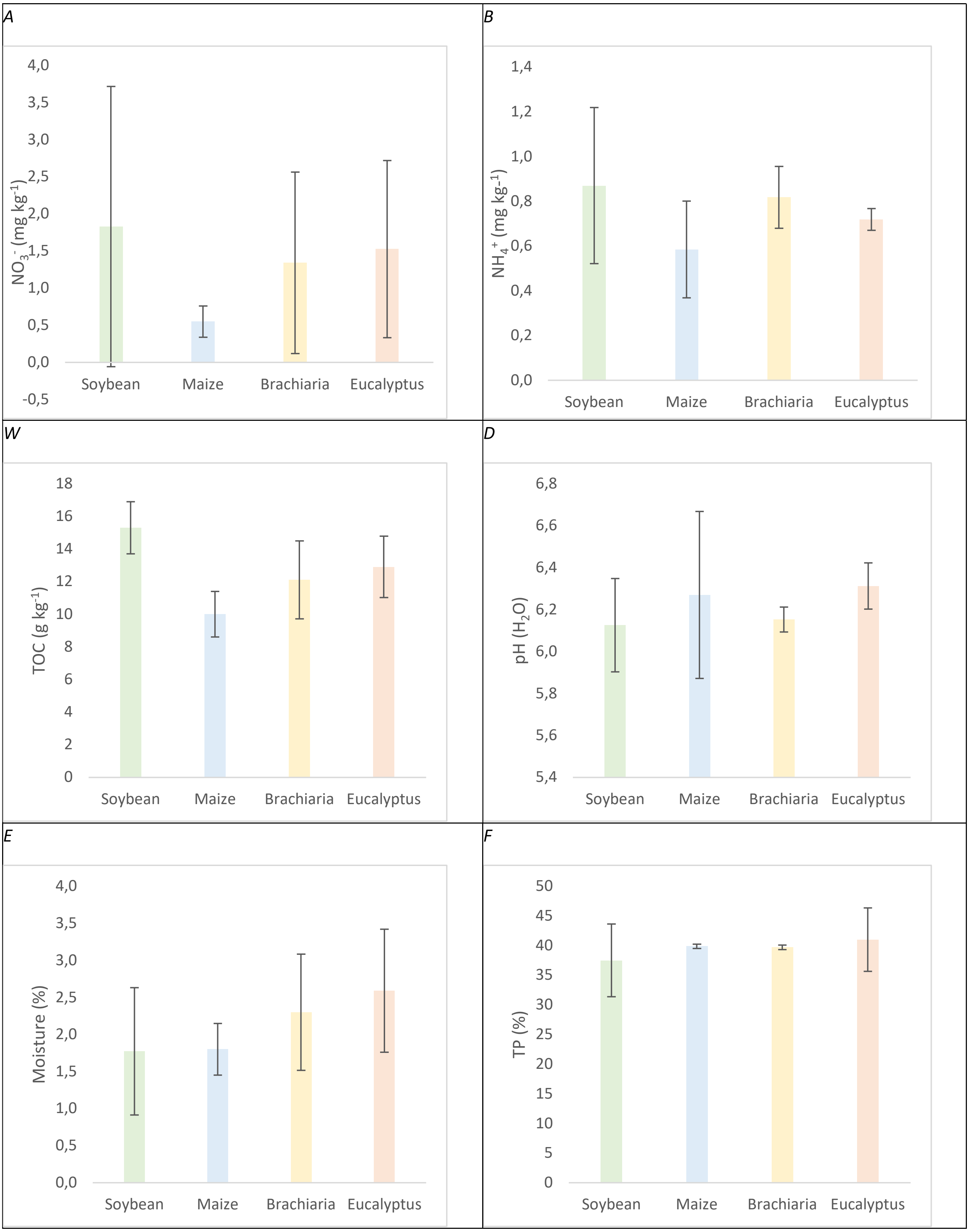

FIGURE 4. Mean values and confidence interval ($p<0.05$) for nitrate (A), ammonium (B), total organic carbon (C), pH (D), moisture (E) and total porosity (F) in 0-0.1 m soil layer in soybean, maize, brachiaria and eucalyptus managements. Brejo, Maranhão, 2018.

Regarding water-filled pore space (Figure 5A) and soil bulk density (Figure 5B), there was an overlap between the confidence intervals; however, for air temperature, the maize area showed higher values than those of the other areas (Figure 5C); conversely, for the temperature inside the chamber (Figure 5D) and in soil (Figure 5E), the brachiaria area showed the lowest values in relation to the other systems.

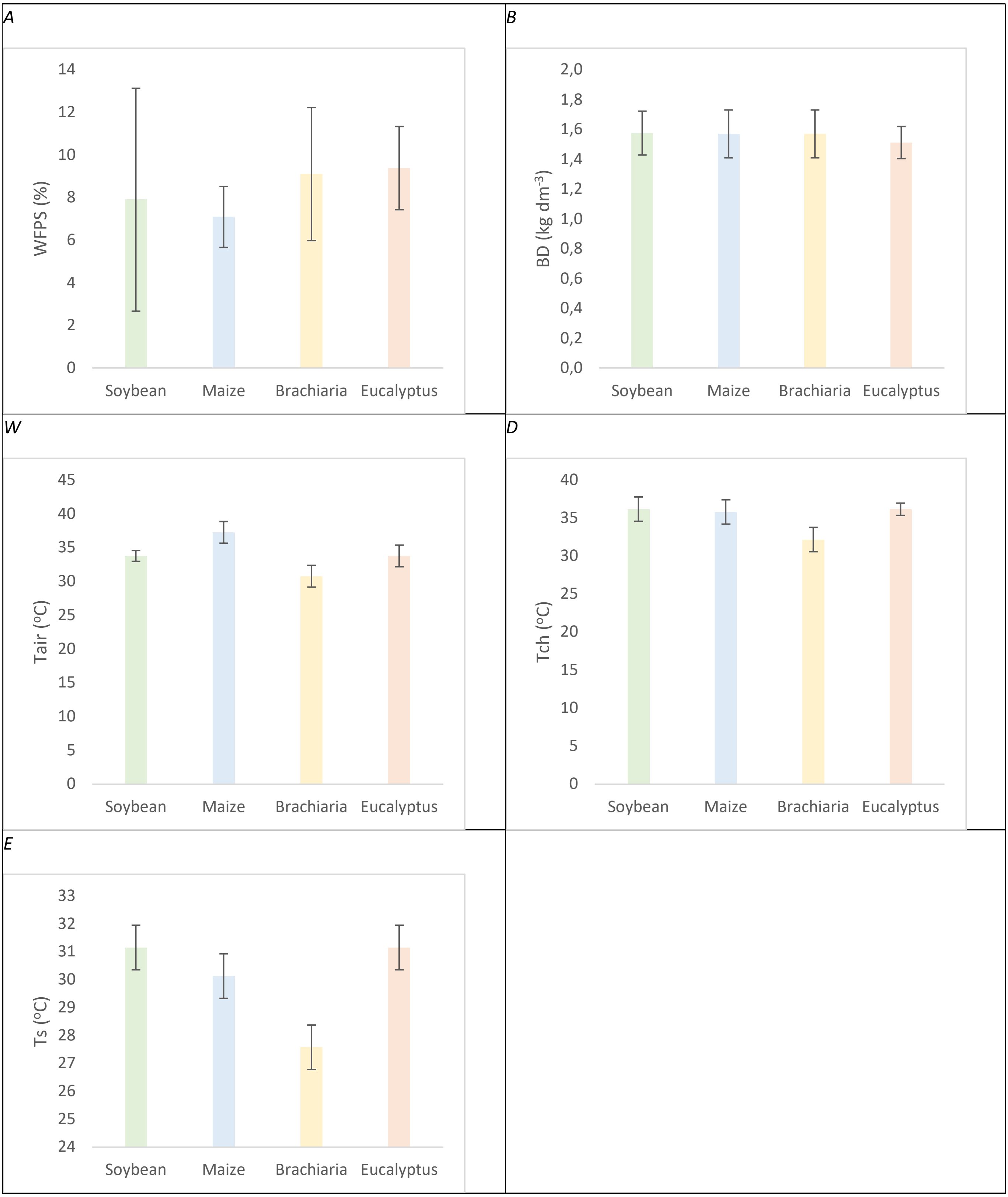

FIGURE 5. Mean values and confidence interval ($p<0.05$) for water-filled pore space (A), soil bulk density (B), air temperature (C), chamber temperature (D), and soil temperature (E) in the 0-0.1 m soil layer under soybean, maize, brachiaria and eucalyptus managements. Brejo, Maranhão, 2018.

Table 3 presents the correlations between GHG emissions and soil attributes evaluated in four managements at 0-0.1 m in depth. There was a strong significant and positive correlation between C-CO_2 and N-N_2O emissions (0.87), between chamber and soil temperatures (0.98), between WFPS and soil moisture (0.86); there was still a significant moderate and positive correlation between NH_4^+ and NO_3^- (0.61), between TOC and NH_4^+ (0.51); between air temperature and soil temperature (0.57); and there was a significant weak and positive correlation between soil moisture and C-CO_2 (0.47); and between soil temperature and C-CO_2 (0.45). Still, there was a strong negative correlation between TP and BD (-0.96); there is a moderate and negative correlation between TOC and C-CH_4 (-0.51), and between soil temperature and methane (-0.51).

TABLE 3. GHG correlation matrix, chemical and physical soil attributes in the 0-0.1 m layer in soybean, corn, brachiaria and eucalyptus managements. Brejo, Maranhão, 2018.

	N_2O	CH_4	CO_2	NO_3^-	NH_{4+}	Moist	pH	TOC	Ts	Tair	Tch	BD	TP
CH_4	0.01												
CO_2	0.87*	0.04											
NO_3^-	0.0	-0.26	0.12										
NH_4^+	-0.12	-0.15	-0.04	0.61*									
Moist	0.38	0.04	0.47*	0.03	0.22								
pH	0.35	0.19	0.33	0.13	-0.16	-0.05							
TOC	0.01	-0.51*	0.10	0.23	0.51*	0.2	-0.03						
Ts	0.38	-0.51*	0.45*	0.09	-0.06	-0.08	0.13	0.29					
Tair	-0.01	-0.02	-0.02	-0.25	-0.38	-0.24	0.19	-0.33	0.57*				
Tch	0.32	-0.44	0.38	0.02	-0.15	-0.12	0.15	0.17	0.98*	0.72			
BD	-0.35	0.39	-0.17	-0.34	-0.35	-0.24	-0.3	-0.12	-0.12	0.01	-0.10		
TP	0.29	-0.26	0.06	0.29	0.24	0.25	0.28	-0.11	-0.05	0.02	-0.04	-0.96*	
WFPS	0.16	0.16	0.39	-0.04	0.15	0.86*	-0.16	0.27	-0.07	-0.24	-0.12	0.24	-0.25

N_2O = nitrous oxide; CH_4 = methane; CO_2 = carbon dioxide; NO_3^- = nitrate; NH_4^+ = ammonium; Moist = soil moisture; TOC = total organic carbon; Ts = soil temperature; Tair = air temperature; Tch= chamber temperature; BD = soil bulk density; TP = total porosity; WFPS= water-filled pore space. *Significant at 5% probability.

Principal component analysis showed two components explained 73.4% of the total data variability (Table 4). Regarding the correlation between variables and principal components, those with weight coefficients greater than 0.3 were considered relevant.

TABLE 4. Weight coefficients (eigenvectors), eigenvalues and variance explained by each principal component (PC1 and PC2) for greenhouse gas fluxes and soil chemical and physical attributes in soybean, maize, brachiaria and eucalyptus managements. Brejo, Maranhão, 2018.

Attributes	PC1	PC2
N_2O	**0.40**	0.13
CH_4	0.11	-0.29
CO_2	**0.37**	0.19
NO_3^-	-0.06	**0.46**
NH_4^+	-0.21	**0.40**
Moist	**0.33**	0.20
pH	**0.38**	-0.18
TOC	-0.13	**0.41**
Ts	0.11	0.08
Tair	0.05	**-0.33**
Tch	0.10	-0.02
BD	**-0.40**	-0.15
TP	**0.38**	-0.12
WFPS	0.21	**0.32**
Eigenvalues	5.62	4.64
Total variance (%)	40.2	33.2
Accumulated variance (%)	40.2	73.4

Note: N_2O = nitrous oxide; CH_4 = methane; CO_2 = carbon dioxide; NO_3^- = nitrate; NH_4^+ = ammonium; Moist = soil moisture; TOC = total organic carbon; Ts = soil temperature; Tair = air temperature; Tch = chamber temperature; BD= soil bulk density; TP = total porosity; WFPS = water-filled pore space.

Principal components analysis revealed that the eucalyptus area was positively correlated with the highest values of N_2O, CO_2, soil moisture and water-filled pore space (even in the off-season) (Figure 6). Furthermore, the eucalyptus area was dissociated from high values of soil density (negative scores for PC1 and PC2), probably due to the management of the eucalyptus area which, unlike maize and soybean areas, is not affected by machinery traffic (planting, spraying, and harvesting). Soybean and brachiaria management were correlated with attributes with positive scores for PC2 and negative for PC1, associating the highest concentrations of NO_3^-, NH_4^+ and TOC (Figure 6). Maize area correlated with variables that presented negative scores for PC2 and positive scores for PC1 such as Tair and CH_4 (Figure 6).

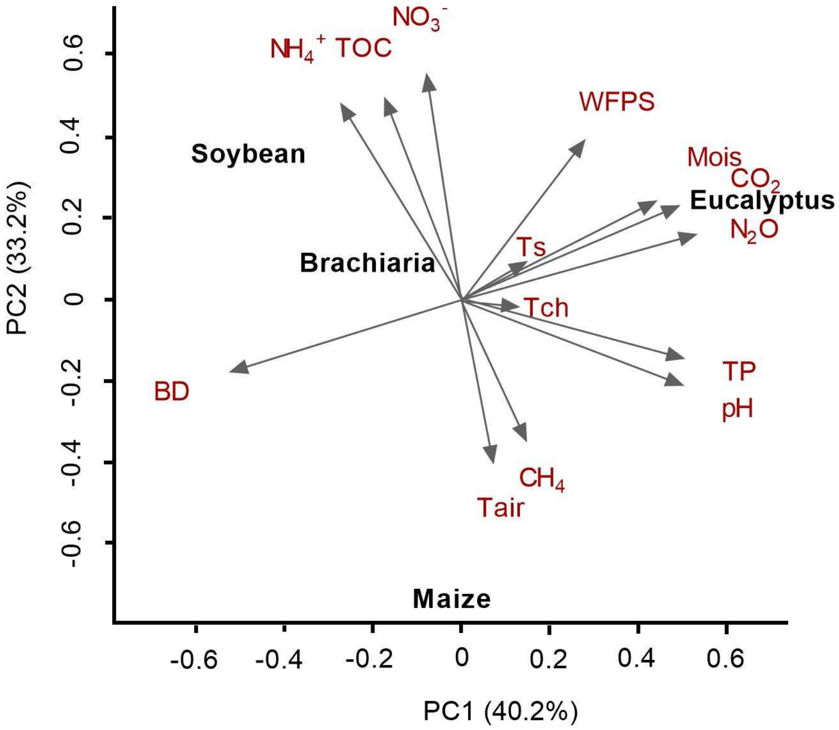

FIGURE 6. Biplot showing the relationship between greenhouse gases and soil chemical and physical attributes in soybean, maize, brachiaria and eucalyptus managements for two principal components (PC1 and PC2). Brejo, Maranhão, 2018.

The highest emission of $N\text{-}N_2O$ observed in soil with eucalyptus cultivation is related to soil moisture and WFPS when evaluating the gases (Figure 6), since litter deposited on soil surface contributes to an increase in soil moisture. This result is reinforced by the lower soil density observed in this management and the inverse relationship (-0.35) between $N\text{-}N_2O$ and BD (Table 3). The lower soil density in eucalyptus can be explained by the lower traffic of machines and implements, by tree roots, and constant deposition of thin branches and leaves on soil surface, which acted as a physical barrier partially preventing soil from drying the dry season and formed a protective layer reducing the effects of machine load (Melo et al., 2022).

The conditions in the eucalyptus area mentioned above (soil moisture, plant residues, soil aeration) are highly favorable to the process of N_2O synthesis via the process of aerobic oxidation of ammonium to nitrate (nitrification), carried out by chemoautotrophic bacteria and regulated by several soil properties, including moisture, high soil temperature, and presence of O_2 (Carvalho et al., 2017).

Considering that the present study was carried out only in the dry season, we could not determine whether there is an annual analysis of variation between dry and rainy seasons on GHG emissions due to the absence of precipitation (Passos et al., 2016), so that the balance of GHGs can be associated with area management and the residues on soil surface of the different agricultural systems. Another highlight is that soybean and maize areas are cultivated in a no-till farming system, a relatively recent management in the area that has not yet changed the soil structure, as verified by BD. Therefore, in these areas, more accumulation of soil organic matter with a lower degree of stabilization and more exposed to mineralization was observed, which is more easily accessible to decomposers, thereby generating greater fluxes of CO_2 and N_2O from the soil matrix to the atmosphere (Oliveira et al., 2019). Van Kessel et al. (2013), in a large meta-analysis study, showed that no-till and reduced tillage systems are associated with negative fluxes of $N\text{-}N_2O$ from soil to the atmosphere, but that this behavior only occurs in systems already consolidated, with more than 10 years of implementation. In the first years of no-till cultivation, $N\text{-}N_2O$ emissions are positive, especially in dry environments.

$C\text{-}CH_4$ influxes are related to the activity of methanotrophic bacterial communities, which use $C\text{-}CH_4$ as the sole source of C and energy (Cardoso & Andreote, 2016). In this reaction, methane is partially oxidized, resulting in organic compounds such as methanol or acetate, which are subsequently used for denitrification producing $C\text{-}CO_2$ and $N\text{-}N_2O$ (Corrêa et al., 2021). In light of these considerations, an emission pattern between C-CH_4 and C-CO_2 can be observed for soybeans and eucalyptus (Figure 3), which showed higher C-CH_4 influxes in soybeans (-27.8 μg m^{-2} h^{-1}) and eucalyptus (-15.7 μg m^{-2} h^{-1}) and higher values of C-CO_2 in soybean (47.4 μg m^{-2} h^{-1}) and eucalyptus (87.9 μg m^{-2} h^{-1}).

The higher CO_2 emissions observed in eucalyptus management may be the combined result of methane consumption and litter deposition, which, due to decomposition, stimulates the production of CO_2 as a result of the multiplication of microorganisms, increased metabolic activity, and root respiration. This consideration is reinforced by the correlation between CO_2 emissions and N_2O (0.87) (Table 4).

The deposition of eucalyptus litter and processes of respiration and decomposition explain the relationships between soil moisture, WFPS, TP, BD and GHG emissions observed in this study. The metabolic processes and decomposition performed by microorganisms are extremely dependent on soil and plant management. Thus, a plausible explanation for the results lies in the relationships between systems management, soil attributes, and local climatic conditions, which culminated in increased C-CO_2 and N-N_2O emissions. For example, the deposition of litter provides the availability of N, an important element in the synthesis of N-N_2O, which also affects the WFPS, as there is better moisture retention in soils with plant residues; and higher values of WFPS promote anaerobiosis sites, determinants in the formation of N-N_2O.

C-CO_2 emissions showed a significant relationship with soil temperature ($r = 0.45$) (Figure 6) and soil moisture ($r = 0.47$). These results, once again, demonstrate that soil GHG production and emission processes were influenced by management systems, as these played a direct role in soil temperature and moisture. Other research results corroborate the influence of soil temperature and moisture on C-CO_2 emissions (Silva et al., 2019; Ray et al., 2020; Zhang et al., 2021).

Higher soil temperatures in soybeans, maize and eucalyptus were accompanied by C-CO_2 emissions. It is worth pointing out that the relationship between Ts and C-CO_2 emissions is explained by the sensitivity of microorganisms responsible for the oxidation of soil organic matter to variations in soil temperature, whose range from 30 ºC to 45 ºC is considered ideal for the carbon cycle state at which the mineralization of organic substrates and the transfer of C-CO_2 to the atmosphere occur (Pulrolnik, 2009).

The correlation observed for TOC, CO_2 and N_2O (Table 3) is explained by the relationship between these gases and the metabolic activity of decomposing microorganisms. The results of C-CO_2 and N-N_2O emissions in eucalyptus management help to understand the strong correlation between the emission of these gases. According to Signor et al. (2014), C-CO_2 emissions come from the metabolism of bacteria during the process of mineralization of organic compounds. Thus, it is understood that the addition of organic material from the deposition of eucalyptus litter on soil provided a favorable environment for microbial activity. The entry of plant material into the system may have stimulated nitrification, the process responsible for the synthesis of N oxides, and the production of C-CO_2, as a result of the metabolic microbial activities during oxidation (Maul et al., 2019).

The strong correlation of water-filled pore space with soil moisture is an expected result by its very definition. In managements where there is a contribution of plant residues to soil, these physical parameters tend to be strongly influenced, and these attributes are often studied in the evaluation of different soil management systems (Freitas et al., 2017; Oliveira et al., 2021; Melo et al., 2022)

Soil moisture and temperature strongly correlated with C-CO_2 emissions due to their interference with the metabolic activity of soil organisms (Vieira 2017). Thus, the results of higher CO_2 emissions in managements resulting in higher soil temperature are consistent, as observed in the management of soybeans, maize, and eucalyptus (Figure 5E).

The correlation between temperature and CH_4 indicated a negative relationship between the variables. Overall, the increase in temperature accelerates the chemical reactions and metabolism of microorganisms (Vieira, 2017), positively influencing the availability of NH_4^+ in soil. NH_4^+ is an inhibitor of CH_4 oxidation in soil by competing for monooxygenase enzyme, which catalyzes the oxidation of CH_4 (Majumdar & Mitra, 2004). Conversely, the availability of ammonium and the increase in temperature may favor nitrification in the systems. In this process, intermediate compounds such as hydroxylamine (NH_2OH) and nitrite (NO_2^-) are produced, which have a toxic effect on methanotrophic bacteria (Shrestha et al., 2015), explaining the negative correlation between Tso and CH_4. This explanation is reinforced by the moderate and negative correlation between TOC and CH_4 (-0.51), since, in this study, TOC may be linked to nitrification. At last, the moderate and negative correlation between soil temperature and methane (-0.51) validates the aforementioned justification.

Considering that the results obtained come from the off-season in an agricultural frontier region, characterized by low straw production due to low rainfall over a period in the year, it is assumed that the adoption of some agricultural systems can contribute to the increase of GHG emissions; however, the positive or negative balance of GHG emissions over a period of one year must be carried out to understand the balance and to adopt management measures or adjustments for possible compensations.

Understanding whether a given management increases or decreases GHG emissions becomes paramount in agricultural frontier regions due to the need to adapt and select more conservation systems because sandier soils are exploited under climate conditions different from more traditional regions of cultivation (Donagemma et al., 2016).

CONCLUSIONS

Greenhouse gas emissions were different between the agricultural systems evaluated in the off-season.

In the off-season, the highest emissions of N-N_2O and C-CO_2 were associated with crops that have less machinery traffic, constant input of litter and consequent higher soil moisture, such as the eucalyptus forest component.

The highest emissions of N-N_2O and C-CO_2 were associated with soil moisture and water-filled pore space.

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