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# Soil greenhouse gases emissions in a goat production system in the Brazilian semiarid region[1]

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## ABSTRACT

In the climate change scenario, studying greenhouse gases (GHG) emissions and measures of mitigation in the Caatinga biome are strategic and may provide a basis for mitigation plans. This study aimed to evaluate the soil $CO_2$, $CH_4$ and $N_2O$ fluxes, as well as determining an annual baseline for GHG emissions, in a reference site of silvopastoral production system in the Brazilian semiarid region, in order to provide subsidies for future studies on GHG emissions mitigation. The GHG fluxes were monitored over one year, in a buffel grass pasture and in grazed and native Caatinga areas, which are components of a long-term silvopastoral system. The $CO_2$ fluxes ranged from -19.98 to 179.12 mg $m^{-2}$ $h^{-1}$ of $CO_2$-C, $CH_4$ fluxes from -76.21 to 113.87 µg $m^{-2}$ $h^{-1}$ of $CH_4$-C, $N_2O$ fluxes from -1,043.12 to 471.37 µg $m^{-2}$ $h^{-1}$ of $N_2O$-N and the soil moisture was the main factor limiting the GHG fluxes. The total emissions converted to $CO_2$-equivalent in the anthropized areas were lower than in the native area (65 % for the buffel grass pasture and 741 % for the grazed Caatinga). Therefore, it is possible to affirm that the GHG soil emissions from grazed areas in the Caatinga biome are not as high as in the native Caatinga, what is an important indication of the environmental sustainability of the evaluated silvopastoral system.

KEYWORDS: *Cenchrus ciliaris* L., carbon dioxide, nitrous oxide, methane, silvopastoral system.

## RESUMO

### Emissões de gases do efeito estufa do solo em sistema de produção de caprinos no semiárido brasileiro

No cenário das mudanças climáticas, o estudo das emissões de gases do efeito estufa (GEE) e de medidas de mitigação na Caatinga são estratégicos e podem fornecer a base para planos de mitigação. Objetivou-se avaliar os fluxos de $CO_2$, $CH_4$ e $N_2O$ do solo, bem como determinar uma linha de base anual para as emissões de GEE, em um sistema de produção silvipastoril de referência no semiárido brasileiro, a fim de fornecer subsídios para estudos futuros de mitigação das emissões de GEE. Os fluxos de GEE foram monitorados durante um ano, em pastagem de capim buffel e em área de Caatinga pastejada e nativa, as quais são componentes de um sistema silvipastoril de longa duração. Os fluxos de $CO_2$ variaram de -19,98 a 179,12 mg $m^{-2}$ $h^{-1}$ de C-$CO_2$, os de $CH_4$ de -76,21 a 113,87 µg $m^{-2}$ $h^{-1}$ de C-$CH_4$, os de $N_2O$ de -1.043,12 a 471,37 µg $m^{-2}$ $h^{-1}$ de N-$N_2O$ e a umidade do solo foi o principal fator limitante para os fluxos de GEE. As emissões totais convertidas para $CO_2$-equivalente nas áreas antropizadas foram menores que na área de vegetação nativa (65 % para o capim buffel e 741 % para a Caatinga pastejada). Portanto, pode-se afirmar que as emissões de GEE nas áreas pastejadas no bioma Caatinga não são tão altas quanto na Caatinga nativa, o que é um importante indicador da sustentabilidade ambiental do sistema silvipastoril avaliado.

PALAVRAS-CHAVE: *Cenchrus ciliaris* L., dióxido de carbono, óxido nitroso, metano, sistema silvipastoril.

## INTRODUCTION

The Brazilian Northeast region comprises the most populated semiarid area in the world (Assad et al. 2013) and is characterized by a semiarid climate, with a negative water balance. The native vegetation of this region is Caatinga, the largest continuous nucleus of the seasonally dry tropical forest and woodland biome in South America (Fernandes et al. 2020). Caatinga presents a high floristic diversity, with 3,347 species and 962 genera, of which 526 species and 29 genera are endemic (Fernandes et al. 2020). Historically, the Caatinga vegetation is used as an energy source, both in the form of firewood and charcoal, and as animal

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feed for goats and sheep, especially during the rainy season. Rainfall seasonality substantially affects water resources, agriculture and livestock farming, even in years in which the total rainfall volume is high (Moura et al. 2019).

As in other semiarid regions of the world, livestock farming, especially of goats and sheep, is the main activity in the rural area of the region, in which there are 7.2 million goat heads, 8.6 million sheep heads and 14.2 million cattle heads, i.e., 8.2, 87.4 and 62.5 % of the national herd, respectively (IBGE 2017). Livestock is based on the grazing of Caatinga native pastures. During the rainy period, the Caatinga phytomass is diverse at all strata, normally decreasing in the drought period, when the animals graze cultivated forage such as buffel grass (*Cenchrus ciliaris* L.) (Rangel et al. 2020). However, the expansion in agriculture and livestock in the Caatinga biome is frequently associated with land degradation (Silva et al. 2020).

The concentration of the main greenhouse gases (GHG) in the Earth atmosphere are currently on the order of 410 ppm of $CO_2$, 1,866 ppb of $CH_4$ and 332 ppb of $N_2O$ (IPCC 2021). The Brazilian national GHG emissions are approximately 1,305 million tons of $CO_2$-equivalent, and the agriculture and energy sectors are the main responsible for these emissions (34 and 32 %, respectively) (Brasil 2020). In the Brazilian agriculture sector, most emissions come from livestock farming, particularly due to the enteric fermentation of ruminants (56.5 % of the national emissions) and agricultural soils (36 % of the national emissions) (Brasil 2020). In global terms, livestock farming is estimated to contribute with approximately 20 % of the anthropic emissions of GHG (IPCC 2014).

Despite this, few representative studies have been conducted to evaluate the GHG emissions in the Brazilian semiarid and also in the Caatinga biome. Ribeiro et al. (2016) evaluated $CO_2$, $CH_4$ and $N_2O$ fluxes from soils in areas of native Caatinga and cultivated pasture (*Brachiaria* ssp.), during the dry and rainy seasons of 2013 and 2014, and claimed that the GHG emissions in the Caatinga are lower than in other Brazilian biomes. However, this information needs to be supported by other studies, also considering the diversity existing within the semiarid environment. In addition, in the context of climate change, it is estimated that, in the future, regions around the world will face an increase in the number of consecutive days of drought (Marengo et al. 2009), what makes the data on agricultural production systems in semiarid regions strategic for the development of measures of coexistence with climate change for other regions. Moreover, realistic and relatively easy-to-adopt farming management practices, such as improved livestock care management and rotational grazing, are important tools to mitigate GHG emissions per product sold in semiarid farms (Nieto et al. 2018).

Thus, this study aimed to evaluate $CO_2$, $CH_4$ and $N_2O$ fluxes from soil and determine an annual baseline of soil GHG emissions in a reference site of silvopastoral production system in the Brazilian semiarid region, in order to provide subsidies for future studies on GHG emissions mitigation.

## MATERIAL AND METHODS

The study was conducted at the Caatinga experimental field of the Embrapa Semiárido, in Petrolina, Pernambuco state, Brazil (09º03'S, 40º19'W and altitude of 389 m). The system is a silvopastoral reference site in the Caatinga and is called Caatinga-Buffel-Legumes (CBL). This system was developed by the Embrapa Semiárido and is widely disseminated in the semiarid region, with a potential to be used in 62 % of Brazilian semiarid areas (Rangel et al. 2020).

The meat goat production system is conducted in a 155-ha area and is divided into cultivated buffel grass pasture (*C. ciliaris* L.) (35-ha) and grazed Caatinga (120-ha) (Figure 1). The buffel grass is 50+ years old non-fertilized pasture. The grazed Caatinga is composed of native vegetation, rich in forage plants, divided into four paddocks of approximately 30 ha each, which are used under rotational grazing. In the experimental field, there is also a 160-ha area of never grazed, preserved Caatinga, which was evaluated as a reference site. In this silvopastoral system, during the dry season, the animals receive roughage and concentrate supplementation and graze on the buffel grass pasture. During the rainy season, they graze in the Caatinga area. Mineral supplementation occurs both in the rainy and dry seasons. A comprehensive list of Caatinga species is provided by Fernandes et al. (2020). This biome is characterized by negative water balance, rainfalls lower than 800 mm concentrated from December to April, average insolation of 2,800 h year$^{-1}$, average

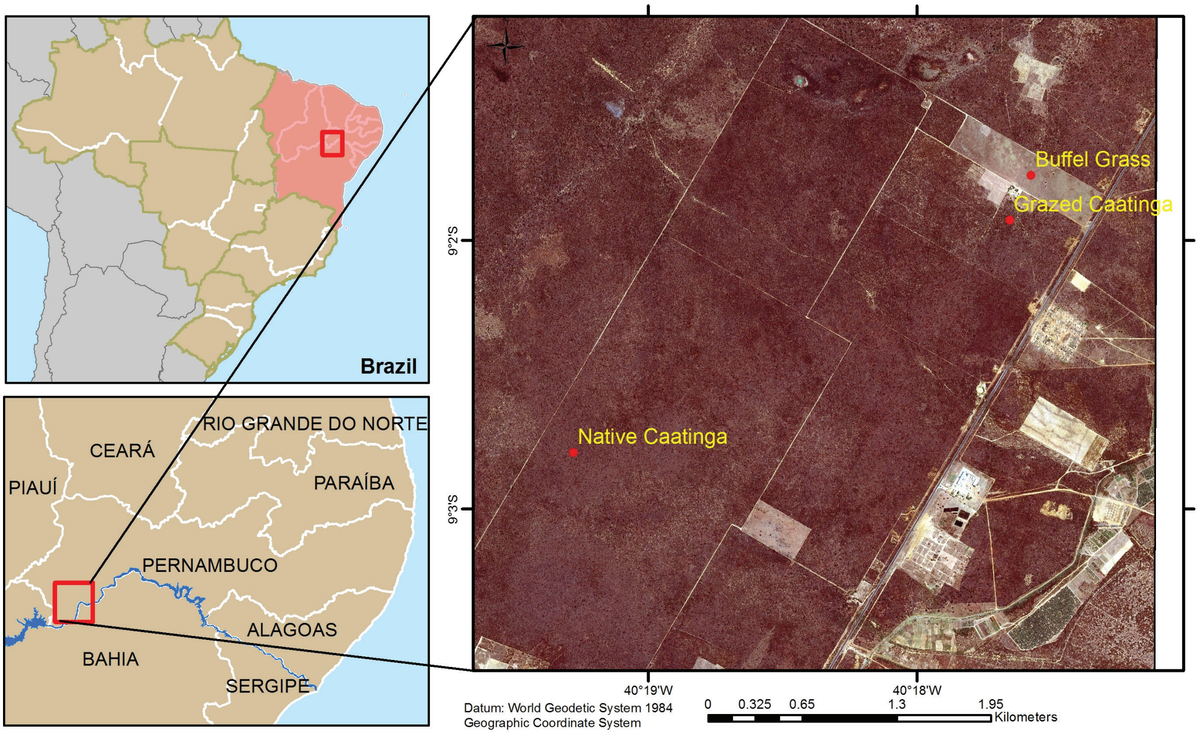

Figure 1. Experimental sites with native Caatinga, grazed Caatinga and buffel grass pasture (Petrolina, Pernambuco state, Brazil).

annual temperatures between 23 and 27 ºC, relative air humidity of approximately 50 % and evaporation rate of approximately 2,000 mm year$^{-1}$ (Moura et al. 2019).

The soil in the experimental field is Argissolo Vermelho-Amarelo (Santos et al. 2018) or Ultisol (USDA 2014). For the buffel grass pasture, the soil chemical and physical attributes are presented in Table 1.

The average temperature and rainfall in Petrolina (1981-2010) are 26.9 ºC and 482.6 mm, respectively, with rainfall concentrating from November to April (Brasil 2018). The region's climate is BSwh', according to the Köppen classification, which characterizes a hot semiarid region. Climatic conditions during the experimental period are shown in Figure 2.

Table 1. Soil attributes in native Caatinga, grazed Caatinga and buffel grass, in a Ultisol in the Brazilian semiarid.

| Soil attribute | Buffel grass pasture | Grazed Caatinga | Native Caatinga |
|---|---|---|---|
| pH | 5.30 | 5.00 | 6.00 |
| Electrical conductivity (mS cm$^{-1}$) | 0.52 | 1.08 | 0.20 |
| Organic matter (g kg$^{-1}$) | 8.48 | 5.70 | 14.30 |
| Available P (mg dm$^{-3}$) | 1.22 | 14.10 | 3.72 |
| K+ (cmol$_c$ dm$^{-3}$) | 0.27 | 0.20 | 0.20 |
| Na+ (cmol$_c$ dm$^{-3}$) | 0.06 | 0.10 | 0.00 |
| Ca++ (cmol$_c$ dm$^{-3}$) | 2.50 | 3.00 | 1.00 |
| Mg++ (cmol$_c$ dm$^{-3}$) | 0.50 | 1.00 | 1.00 |
| Al+++ (cmol$_c$ dm$^{-3}$) | 0.05 | 0.10 | 0.00 |
| H + Al (cmol$_c$ dm$^{-3}$) | 1.70 | 2.20 | 2.60 |
| Sum of bases (cmol$_c$ dm$^{-3}$) | 3.30 | 4.00 | 2.00 |
| Cation exchange capacity (cmol$_c$ dm$^{-3}$) | 5.00 | 6.20 | 4.60 |
| Sand (g kg$^{-1}$) | 789.40 | 649.50 | 679.10 |
| Silt (g kg$^{-1}$) | 111.60 | 205.90 | 242.80 |
| Clay (g kg$^{-1}$) | 99.00 | 144.60 | 78.20 |

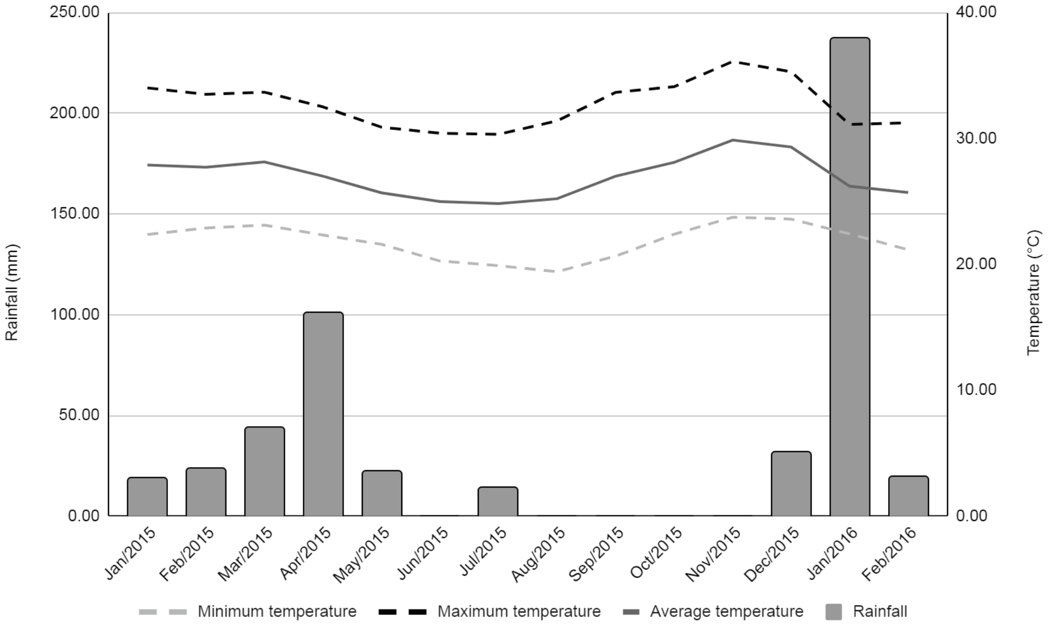

Figure 2. Monthly rainfall and maximum, average and minimum air temperature at a Caatinga experimental field in Petrolina (Pernambuco state, Brazil), during evaluations between February 2015 and February 2016.

The evaluations of GHG ($CO_2$, $CH_4$ and $N_2O$) emitted by the soil were conducted from February 2015 to February 2016, in the three areas (buffel grass, grazed Caatinga and native Caatinga). The gases were collected using static chambers, consisting of two parts: a base and a lid (Rochette & Eriksen-Hamel 2008). Rectangular galvanized-steel bases (60 cm long x 40 cm wide) and galvanized-steel lids shaped as a frustum of a rectangular pyramid were used, with a total volume of 74 L, covered by aluminized polyethylene foam insulation (2-mm thick). Each chamber has one hole on its upper end to collect the gas samples and another to attach a digital thermometer. Four bases were installed in each area and maintained at the same site until the end of the evaluation period. At one week before the first gas collection, the bases were installed in the soil, at a depth of 0.05 m, and the lid was fitted onto the base during the collections only.

The GHG samples were collected monthly during the dry season and weekly during the wet season. During the collection, the lid was fitted onto the base and the gas samples were collected at four times: closure of the chamber (time zero) and at 10, 20 and 40 min after the chamber was closed. The samples were collected in 25-mL polypropylene syringes and transferred to glass vials closed with a rubber septum, manually sealed and previously evacuated (-80 KPa). The gas collections were always carried out in the morning (Alves et al. 2012), and the lids were removed from the bases which were kept open until the next collection.

The samples were sent to the laboratory to determine the concentrations of $CO_2$, $CH_4$ and $N_2O$ by gas chromatography. The equipment used is an Agilent 7890A gas chromatograph, with injection oven working at 60 ºC. A FID detector (120 ºC) was used to determine the $CO_2$ and $CH_4$ concentrations in the gases samples and a μECD detector (300 ºC) was used to determine the concentrations of $N_2O$. The calibration curve was done with four certified standard gases of known concentration (standard 1: 250 ppb $N_2O$, 0.5 ppm $CH_4$, 250 ppm $CO_2$; standard 2: 500 ppb $N_2O$, 1 ppm $CH_4$, 500 ppm $CO_2$; standard 3: 1,000 ppb $N_2O$, 3 ppm $CH_4$, 1,000 ppm $CO_2$; standard 4: 2,000 ppb $N_2O$, 5 ppm $CH_4$, 2,000 ppm $CO_2$).

For each day of evaluation, the $CO_2$, $CH_4$ and $N_2O$ concentrations in the samples were used to calculate the fluxes of these three gases in each chamber, using the following equation: $F(\mu g\ N_2O\text{-}N/CO_2\text{-}C/CH_4\text{-}C\ m^{-2}\ h^{-1}) = (\Delta C/\Delta t).(m/Vm).V/A$, where, $\Delta C/\Delta t$ is the variation rate of the gas inside the chamber at a certain time (ppm $h^{-1}$); m the molecular mass of each gas (g); Vm the molecular volume of the gas (1 mol occupies 22.4 L under normal conditions of temperature and pressure); V the chamber volume

(L); and A the chamber area ($m^2$). The molecular volume of the gases was corrected according to the temperature inside the chamber during the sampling, by multiplying 22.4 by (273 + T /273), where T is the average temperature inside the chamber (ºC) during the sampling. During all collections, the temperature was measured in the soil, in the air inside the chamber and in the air outside the chamber, using digital thermometers.

The GHG fluxes were tabulated onto a spreadsheet. As the studied areas do not constitute an experiment, but an observational study, with four replications within each of the three areas under evaluation, parametric statistics are not an adequate tool for our data analysis. Therefore, the results are presented with their descriptive statistics, with mean and standard error of the mean. The cumulative emissions along the evaluation period were calculated by mathematical integration of daily fluxes (Signor et al. 2013). Cumulative emissions of $CH_4$ and $N_2O$ along the experimental period were converted to the $CO_2$-equivalent unit and summed to $CO_2$ accumulated emissions to estimate the total emissions of GHG in each of the three areas.

## RESULTS AND DISCUSSION

The $CO_2$ fluxes varied from -19.98 to 179.12 mg $m^{-2}$ $h^{-1}$ of $CO_2$-C and were different (means ± standard error) among the areas only on January 26, 2016 (Figure 3). In all areas, the highest $CO_2$ fluxes were observed in January and February, reflecting the increase in soil respiration due to the occurrence of rainfall events in the region (Figure 3).

The $CH_4$ fluxes varied from -76.21 to 113.87 µg $m^{-2}$ $h^{-1}$ of $CH_4$-C (Figure 3). Differences between the evaluated areas were observed on April 7 and May 27 (2015) and February 11 (2016). The native Caatinga often showed higher $CH_4$ fluxes than other areas. The lowest $CH_4$ fluxes were observed in the grazed Caatinga in February 2016, whereas, in the native Caatinga and buffel grass pasture, the lowest fluxes of this gas occurred in the driest months of the period (Figure 3).

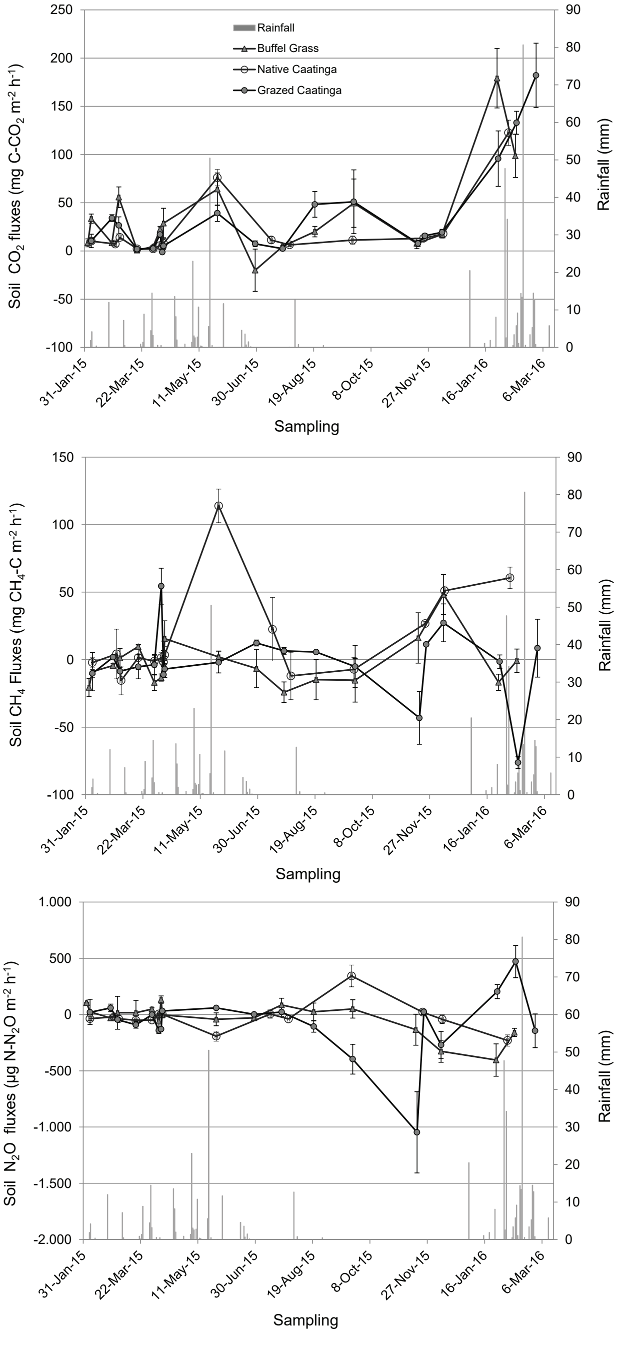

Figure 3. $CO_2$, $CH_4$ and $N_2O$ fluxes (lines) and rainfall events (bars) in native Caatinga, grazed Caatinga and buffel grass in the Brazilian semiarid. For each gas, bars represent the standard error of the means (n = 4).

The highest $CO_2$ fluxes and the lowest $CH_4$ fluxes associated with the highest rainfall events observed in this study suggest that, in this region, the soil moisture is the main limiting factor for decomposition, in agreement with Sharkhuu et al. (2016). After the rainfall events, since the soil is well-drained, the decomposition of carbon compounds occurs through aerobic pathway with emission mainly of $CO_2$. Brito et al. (2015) evaluated soil $CO_2$ emissions in pastures and also observed higher emissions in the rainy and hot summers, when compared to the dry and cold winters, and those higher emissions were directly related to variations in the rainfall and soil temperature. According to these authors, during a rainy summer, precipitation events increase the soil moisture, enhancing the root respiration and microbial processes involved in the decay of soil labile organic matter, what favors the $CO_2$ production and emission.

A similarity for $CO_2$ fluxes among the studied areas, as well as the highest fluxes in the rainy season, as reported by Brito et al. (2015), were also observed by Ribeiro et al. (2016), when comparing another site of native Caatinga with a brachiaria grazed field. Lima et al. (2020) studied a native Caatinga and a degraded pasture in a Luvisol in the Pernambuco state and also reported a seasonal variation in the soil $CO_2$ emissions, with higher emissions in the wet season. However, these authors observed higher soil respiration rates in the Caatinga than in degraded pasture, due to the higher soil carbon content and lower soil temperature in the native area. Grazing is frequently associated with increased soil $CO_2$ emissions, because it stimulates the root development and microbial activity in the rhizosphere, increasing the soil respiration, as observed by Sharkhuu et al. (2016) in the semiarid region of Mongolia. The exclusion of grazing reduces the soil respiration mainly due to the increase of moisture and reduction of soil temperature (Chen et al. 2016).

The $CH_4$ formation in soils occurs mainly under anaerobic conditions, when organic matter is anaerobically digested by methanogenic microorganisms, and, in the presence of oxygen, it is directly decomposed to $CO_2$ by methanotrofic microorganisms (Le Mer & Roger 2001). Factors such as soil moisture, soil and air temperatures, besides factors related to the management system and carbon availability in the soil, affect the soil $CH_4$ production (Wu et al. 2010). Despite the observed $CO_2$ fluxes were higher than the $CH_4$ fluxes, some positive $CH_4$ fluxes from the soil in native Caatinga occurred in the present study (Figure 3). This may, at first, seems strange in a semiarid environment, where the soil remains under aerobic conditions most of the time. In native Caatinga areas, almost all the aboveground biomass material produced by plants during the rainy season is added to the soil as litter, i.e., it is not consumed by animals, as in the grazed Caatinga and buffel grass pasture areas. In both these grazed sites, part of the grazed material returns to the soil as urine or feces, although a significant amount of waste is deposited outside the grazing area, in the pen where the animals stay in the late afternoon and at night. Thus, the amount of organic material supplied to the soil every year in the native Caatinga is much larger than in those grazed areas. The peak litterfall in the Caatinga happens at the end of the rainy season and beginning of the dry season, and the litter production falls between 1,500 and 3,000 kg $ha^{-1}$ $year^{-1}$, on a dry matter basis (Lima et al. 2015, Holanda et al. 2017). These residues are accumulated on the soil surface and are slowly decomposed throughout the dry season, because water is the main limiting factor for this process in this environment, reducing the microbial population and thus the soil organic matter decomposition (Lima et al. 2020). In the next rainy season, plant residues from the litter present in the native Caatinga, mainly composed of leaves (76.5 %, according to Lima et al. 2015), are readily decomposed by soil microorganisms, leading to the formation of many anaerobic sites in the soil. Under anaerobic conditions, carbon may be used as an electron acceptor, leading to the formation of $CH_4$, what may explain the highest fluxes in the native Caatinga in some periods of the year, once in the grazed Caatinga and buffel grass pasture areas the availability of residues on the soil would be lower precisely because of the material removal by grazing.

Assouma et al. (2017), studying soil GHG emissions in a silvopastoral system in Ferlo, Senegal, also observed the occurrence of positive $CH_4$ fluxes in grazed native area. The edaphoclimatic characteristics and rainfall distribution in the region of Ferlo are similar to those observed in the present study. In that study, the $CH_4$ fluxes in the grazed native area were equivalent to $0.45 \pm 0.3$ mg $m^{-2}$ $day^{-1}$ of $CH_4$-C, and the average flux of this gas in all areas comprising the silvopastoral system was 3.56 μg $m^{-2}$ $h^{-1}$ of $CH_4$-C. Converting to the same unit, the fluxes observed in the present study were 0.09 mg $m^{-2}$ $day^{-1}$ of $CH_4$-C, i.e., 43 % lower than that observed by Assouma et al. (2017) under similar edaphoclimatic conditions.

During the studied period, the $N_2O$ fluxes varied from -1,043.12 to 471.37 μg $m^{-2}$ $h^{-1}$ of $N_2O$-N (Figure 3), and differences were observed among the areas after September 2016. In the dry season, the grazed Caatinga showed the lowest $N_2O$ fluxes, while, in the wet season, the grazed Caatinga presented the highest and positive $N_2O$ fluxes, while the other areas presented negative fluxes (Figure 2). The $N_2O$ fluxes were similar along the evaluation period for the native Caatinga and buffel grass pasture. Differences among the sampling dates occurred only in grazed Caatinga, with the lowest fluxes between September and December 2015 and the highest fluxes between January and February 2016, months with the largest volumes of cumulative rainfall during the studied period (Figure 2). In drylands, $N_2O$ fluxes are generally constant in the dry season and significantly increase with rainfall or irrigation events, and this pulse in $N_2O$ fluxes in a short period of the year may account for the majority of the $N_2O$ emissions of the year, making the drylands $N_2O$ emissions unique (Hu et al. 2017).

$N_2O$ is formed in the soil mainly by the anaerobic biological process of denitrification, and, even in aerated soils, there are always some anaerobic sites where $N_2O$ may be produced (Signor & Cerri 2013). In dryland ecosystems, these biological processes are subjected to specific climatic conditions, such as scarcity of water and nutrients during the dry season and a pulse of water and nutrients in the wet season following rainfall, which may selectively favor some specific microbial groups like fungi (Hu et al. 2017). There are some evidences that fungal denitrification may be a key mediator of $N_2O$ emissions during the dry seasons in drylands, while classic heterotrophic bacterial denitrification in anaerobic microsites is the main $N_2O$ source during the wet seasons (Hu et al. 2017). Moreover, according to these authors, the nitrification process (the ammonia oxidation pathway and nitrifier denitrification pathway) is also an important source of $N_2O$ emissions in drylands.

Despite the episodes of rains, the $N_2O$ fluxes remained negative in the buffel grass pasture and native Caatinga in January and February 2016. Ribeiro et al. (2016) also observed that $N_2O$ fluxes are similar between areas and negative or close to zero in native Caatinga and in brachiaria cultivated pasture during the rainy season, a fact that they associated to the low N content in the soil in both areas, what is consistent with the results of the present study.

Soil can consume or emit $N_2O$ to the atmosphere, and this consumption depends on its potential to reduce $N_2O$ to $N_2$, diffusion of $N_2O$ inside the soil profile and its capacity of dissolution in water within the soil (Chapuis-Lardy et al. 2007). The negative $N_2O$ fluxes observed in the present study, and also reported by Ribeiro et al. (2016), even when rainfall events occurred in the Caatinga biome, may be related to the fast increase in the microbial activity due to the increment in soil moisture, because water is the main limiting factor for decomposition in semiarid regions (Sharkhuu et al. 2016). This intense microbial activity consumes $CO_2$ and promotes the formation of some anaerobic sites in the soil, where the complete process of denitrification is favored and leads to higher emissions of $N_2$ than $N_2O$. Moreover, C/N and C/P ratios of Caatinga litter (33 and 431, respectively) are higher and may explain the low litter decomposition rates and the N immobilization in the soil during decomposition in this biome (Souto et al. 2009), what is another possibility to explain the small $N_2O$ fluxes in the Caatinga.

Moreover, in February 2016, negative $CH_4$ fluxes and positive $N_2O$ fluxes were observed in the grazed Caatinga (Figure 2). Similar results were reported by Pan et al. (2021), in a grazed site in Mongolia. According to Le Mer & Roger (2001), the methane consumption in the soil occurs through methanotrophic microorganisms, and it also significantly contributes to nitrification in the rhizosphere.

Therefore, the results of the present study suggest that soil moisture is the main factor limiting the GHG emissions in the Brazilian semiarid region. Thus, when rainfalls occur, under favorable moisture conditions, the residue decomposition by soil microorganisms occurs very intensely, and compounds containing C are decomposed through the aerobic pathway, emitting $CO_2$ to the atmosphere. This $CO_2$ fast production consumes soil $O_2$, leading to the formation of anaerobic sites, which, with moisture still favorable to microbial reactions, allow the formation of $CH_4$ and complete denitrification (higher emission of $N_2$ to the detriment of $N_2O$), even in the well-drained soil of the studied area.

The total $CO_2$ emissions during the evaluated period were similar in all areas, while the native Caatinga showed the highest $CH_4$ and $N_2O$ emissions (Table 2). In the present study, similar $CO_2$ fluxes between the uses in most parts of the year and the increase in the fluxes due to the occurrence of rainfall (Figure 3), as well as the total similar emissions among the areas (Table 2), confirm that, in this region, the soil moisture is more important for soil respiration than the amount of material available for decomposition. This was also reported by Lima et al. (2020), who highlighted that the soil $CO_2$ emissions in the Brazilian semiarid region are similar to those in other semiarid areas of the world and vary mainly

Table 2. Cumulative emissions of $CO_2$, $CH_4$ and $N_2O$, between February 2015 and February 2016, in native Caatinga, grazed Caatinga and buffel grass pasture in the Brazilian semiarid.

| Area | Cumulative emissions | | |
|---|---|---|---|
| | $CO_2$ (g $m^{-2}$ $CO_2$-C) | $CH_4$ (mg $m^{-2}$ $CH_4$-C) | $N_2O$ (mg $m^{-2}$ $N_2O$-N) |
| Native Caatinga | 192.72 ± 35.07 | 192.73 ± 53.45 | 95.38 ± 83.48 |
| Grazed Caatinga | 296.89 ± 41.64 | -33.07 ± 25.04 | -1,303.10 ± 428.71 |
| Buffel grass | 306.75 ± 55.39 | -1.91 ± 39.37 | -591.66 ± 225.32 |

due to soil organic carbon contents, soil temperature and soil moisture.

For the total $CH_4$ emissions, the difference between native Caatinga and the anthropized areas was equivalent to 210.22 mg $m^{-2}$ of $CH_4$-C. The total $N_2O$ emissions were 1,398.48 mg $m^{-2}$ of $N_2O$-N higher in the native Caatinga than in the grazed Caatinga, during the same time. In addition, the highest cumulative $N_2O$ emissions observed in the native Caatinga (Table 2) may indicate that the $N_2O$ emissions in this area are caused by formation processes different from those observed in grazed areas, as suggested by Hu et al. (2017). According to Lima et al. (2015), the litterfall in the Caatinga contributes with almost 93 kg $ha^{-1}$ $year^{-1}$ of N, which can be available to plants and soil microorganisms to be denitrified and emitted to the atmosphere as $N_2O$ or $N_2$.

The total emissions converted to $CO_2$-equivalent in the anthropized areas were lower than those observed in the native area (Table 3). The buffel grass pasture area emitted 65 % less GHG than the native area, while the grazed Caatinga showed a reduction of 741 % in the soil GHG emissions in this period. Even if considered together, the anthropized sites showed lower GHG emissions than the native area. However, for the interpretation of total emissions, it is important to take into account that GHG emissions from the soil are dependent on soil organic matter content, and that the higher total emissions in the native Caatinga may also be explained by its higher soil organic matter content (Table 1). Despite the fact that the soil bulk density was not measured and that it was not possible to calculate the soil C stocks in the evaluated areas, it was possible to compare the soil organic matter content in these areas. Then, the native Caatinga soil organic matter content is 1.68 times higher than for buffel grass pasture and 2.50 times higher than for grazed Caatinga soil.

Therefore, the data of the present study suggest that the GHG soil emissions from grazed areas in the Caatinga biome are not higher than in the native Caatinga, what is an important indication of the environmental sustainability of the evaluated agrosilvopastoral system. However, the C balance of this silvopastoral system must also consider the C stocks in the soil and the enteric $CH_4$ emissions by the goats in the area. These aspects were not addressed in the present study, but should be considered in the future. Additionally, it is very important to take into account the GHG emissions in the pen where the goats spend the night, which is an important point for future investigation and represents a differential for the Caatinga goat production system, in comparison with other animal production systems practiced in other Brazilian regions, in which the animals usually feed and spend the night in the same paddock.

Finally, Caatinga is a large and very diverse biome, in terms of floristic composition and edaphoclimatic conditions, and, as highlighted by Silva

Table 3. Cumulative emissions ($CO_2$-equivalent) of $CO_2$, $CH_4$ and $N_2O$, between February 2015 and February 2016, in native Caatinga, grazed Caatinga and buffel grass pasture in the Brazilian semiarid.

| Area | Cumulative emissions | | | Total emissions (g $m^{-2}$ $CO_2$-C-eq) | Total (Mg $ha^{-2}$ $CO_2$-C-eq) |
|---|---|---|---|---|---|
| | $CO_2$ | $CH_4$ | $N_2O$ | | |
| | g $m^{-2}$ $CO_2$-C-eq | | | | |
| Native Caatinga | 192.72 | 6.42 | 46.46 | 52.89 | 0.53 |
| Grazed Caatinga | 296.89 | -1.10 | -634.80 | -339.01 | -3.39 |
| Buffel grass | 306.75 | -0.06 | -288.22 | 18.46 | 0.18 |

Conversion used: $CO_2$-equivalent = 25 * ($CH_4$ * 16/12); $CO_2$-equivalent = 310 * ($N_2O$ * 44/28).

et al. (2020), it presents low resilience in periods of severe droughts. This diversity should be considered in future studies on GHG emissions both in native areas and in agroecosystems, and also in the development of mitigation practices, which have to be observed in order to avoid land degradation and desertification.

## CONCLUSIONS

1. Rainfall events in the Caatinga biome are associated with higher $CO_2$ fluxes, lower $CH_4$ fluxes and increments in $N_2O$ fluxes, and are the main factor limiting greenhouse gases (GHG) emissions in the Brazilian semiarid region;
2. $CO_2$ emissions are similar among native Caatinga, grazed Caatinga and buffel grass. Rain increments the $N_2O$ fluxes, but not sufficiently to make them positive in anthropized areas. Negative $CH_4$ emissions are also observed in soils of grazed areas;
3. For the Caatinga, areas under grazing (grazed Caatinga and buffel grass pasture) show lower GHG fluxes, when compared to the native Caatinga, being an important indication of the environmental sustainability of the silvopastoral activities in this biome.

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