Revista Brasileira de Ciência do Solo

Division - Soil Processes and Properties | Commission – Soil Physics

Impacts of land-use changes on soil respiration in the semi-arid region of Brazil

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Received: May 21, 2020

Approved: September 02, 2020

How to cite: Lima JRS, Souza RMS, Santos ES, Souza ES, Oliveira JES, Medeiros EV, Pessoa LGM, Antonino ACD, Hammecker C. Impacts of land use changes on soil respiration in the semi-arid region of Brazil. Rev Bras Cienc Solo. 2020;44:e0200092.
https://doi.org/10.36783/18069657rbcs20200092

ABSTRACT: Soil respiration represents the largest flux of CO_2 emission from terrestrial ecosystems, being affected by land-use changes and soil properties. There are few studies investigating the response of soil respiration to land-use changes in the Caatinga biome. This study aimed to measure soil respiration from Caatinga vegetation and degraded pasture, to verify the effect of land-use changes on soil respiration. Measurements of soil respiration were performed using the infrared gas analyzer method over nine months (in rainy and dry seasons), in Caatinga and degraded pasture in the semi-arid region of Pernambuco. The soil moisture, soil temperature, soil organic carbon (SOC), Normalized Difference Vegetation Index (NDVI), and climatic variables were also measured. Soil organic carbon and NDVI were higher in Caatinga than in degraded pasture, while the inverse occurred with soil temperature. The soil respiration showed a clear seasonal variation, with the highest values occurring in the wet season, being positively correlated with soil moisture and negatively with soil temperature. Soil respiration was significantly higher in the Caatinga (8.0 ton ha^{-1} yr^{-1} of C) than in degraded pasture (3.7 ton ha^{-1} yr^{-1} of C). These higher values of soil respiration in Caatinga were due to lower soil temperature and higher SOC, and can be seen as indicators of good environmental quality.

Keywords: Caatinga, degraded pasture, soil moisture, soil temperature, soil organic carbon.

INTRODUCTION

The CO_2 emission from the soil surface, commonly referred to as soil CO_2 efflux (ECO_2) or soil respiration (SR), is the sum of processes that include the production of CO_2 by roots, micro-organisms, and soil fauna throughout the soil profile, and the subsequent diffusion of CO_2 to the soil surface (Bond-Lamberty and Thomson, 2010; Ferreira et al., 2018). This flux has great importance for the global carbon balance, returning from 80 to 98 Pg of C to the atmosphere each year (Raich et al., 2002; Bond-Lamberty and Thomson, 2010), which is more than 11 times that CO_2 emission from fossil fuel combustion (Peng et al., 2009; Xu and Shang, 2016). Therefore, measuring the soil respiration is important to establish sustainable land-use models and to estimate global fluxes of carbon, affecting climatic change (Ferreira et al., 2018).

Small changes in the magnitude of SR could have a large influence on atmospheric CO_2 concentration and accurate estimates of SR from different ecosystems can help to quantify terrestrial carbon storage. Several studies have quantified the SR in various ecosystems and climate zones (Davidson et al., 2006; Deng et al., 2012; Chen et al., 2014; Huang et al., 2016; Liu et al., 2016; Figueiredo et al., 2017; Duan et al., 2019). However, although the arid and semi-arid ecosystems cover a substantial fraction of the earth surface (Wang et al., 2014) and significantly contribute to the carbon cycle (Tucker and Reed, 2016), SR in these ecosystems has been less intensively investigated than in others (Rey et al., 2011; Lai et al., 2012; Oyonarte et al., 2012; Zhang et al., 2015). Arid and semiarid ecosystems may dominate the trajectory of biosphere-to-atmosphere carbon (C) exchange, and understanding SR in these ecosystems is important for C cycling at the global scale and to ensure the accurate representation in large-scale carbon models (Wang et al., 2014; Tucker and Reed, 2016).

Land-use changes (LUC) are a large anthropogenic source of greenhouse gas emissions, and for the period 1990–2005, the net LUC CO_2 emissions were 1.5 ± 0.7 Pg yr^{-1} of C, which corresponds to 8-12 % of the total fluxes of CO_2 to the atmosphere (Le Quéré et al., 2009), mainly due to deforestation in the tropical and subtropical regions (Don et al., 2011). Understanding the effects of different LUC on the variation of SR can provide important information for ecosystem management practices (Liu et al., 2016). Several studies found that SR was influenced by LUC (Liu et al., 2016; Wang et al., 2017), due to changes occurred in the soil properties that control SR such as moisture content, temperature, organic carbon and nitrogen content, etc. Soil respiration also is influenced by other factors like substrate amount and quality and the pH-value of the soil (Reth et al., 2005), whereas soil temperature and soil moisture are most important (Lloyd and Taylor, 1994; Raich et al., 2002; Gaumont-Guay et al., 2006; Lellei-Kovács et al., 2011), as they influence directly soil biological activity and decomposition of organic matter.

In the semi-arid region of Brazil, severe drought events thoroughly affect plant growth and have a substantial social and economic impact on the population (Ribeiro et al., 2016). In the Caatinga region of the semi-arid Brazil, rain is scarce and usually restricted to three to four months rainy season, causing a negative water balance and high aridity index (Giulietti et al., 2004; Souza et al., 2016). In this region, the most common LUC consists in converting the seasonally dry forests, called Caatinga, to croplands and grasslands (Ribeiro et al., 2016) and often leads to degradation of the soil (Leite et al., 2018), with reduction of the soil organic carbon, carbon stocks, microbial biomass (Santos et al., 2019) and enzymatic activities (Silva et al., 2019), increases of the air temperature and decreases of the evapotranspiration (Silva et al., 2017).

The knowledge of the effects of the LUC on the SR and the drivers that control this flux in the semi-arid ecosystems of Brazil are limited. To date, only one research (Ribeiro et al., 2016) quantified the effect of LUC in SR in semi-arid of Brazil. These authors did not find significant differences in annual soil CO_2 emission between Caatinga and grassland and found that soil CO_2 emissions presented a negative correlation with soil temperature and a positive one with soil moisture. However, the study of these authors was performed in the municipality of São João, in the Agreste region of Pernambuco State, in sandy soils, with low water retention, and with more rainfall than in the semiarid region of Pernambuco. The Agreste is a transition region that presents a diverse climate, varying from dry to humid tropical, with vegetation of Atlantic forest and Caatinga (Ribeiro et al., 2016; Ferreira et al., 2018). In the semiarid region, the climate is hotter and dryer than in the Agreste region, therefore land-use changes will promote an ecological disequilibrium in the ecosystem.

Understanding the effects caused by land-use changes on soil properties, as organic carbon, soil moisture, and soil temperature is essential for predicting changes in soil respiration. Thus, we hypothesized that the Caatinga has higher SR than degraded pasture, because forest soils generally have the best quality due to the development of climax vegetation, with higher soil organic carbon contents.

We conducted an experiment in the Caatinga vegetation and in a degraded pasture in the northeastern region of Brazil to improve the current understanding of SR in these two ecosystems. The main objective of this study was to quantify and compare the seasonal variations of SR over the Caatinga and degraded pasture. Another contribution is related to the LUC (conversion of Caatinga to grassland areas) and its effect on the SR. We also aimed to verify whether soil moisture or soil temperature controls mostly the seasonal variations of SR, and which biome will be most affected. Our results can contribute to a better understanding of the implication of replacing Caatinga with degraded pasture on ecosystem carbon balance.

MATERIALS AND METHODS

Location, soil, and climate

The study was conducted in a dry tropical forest known as Caatinga, in an area within the municipality of Serra Talhada (07° 56’ 50” S and 38° 23’ 29” W), state of Pernambuco, Brazil (Figure 1). According to Köppen’s classification system, the climate is BShw’ semi-arid, hot and dry, with precipitation occurring between December and May, with the

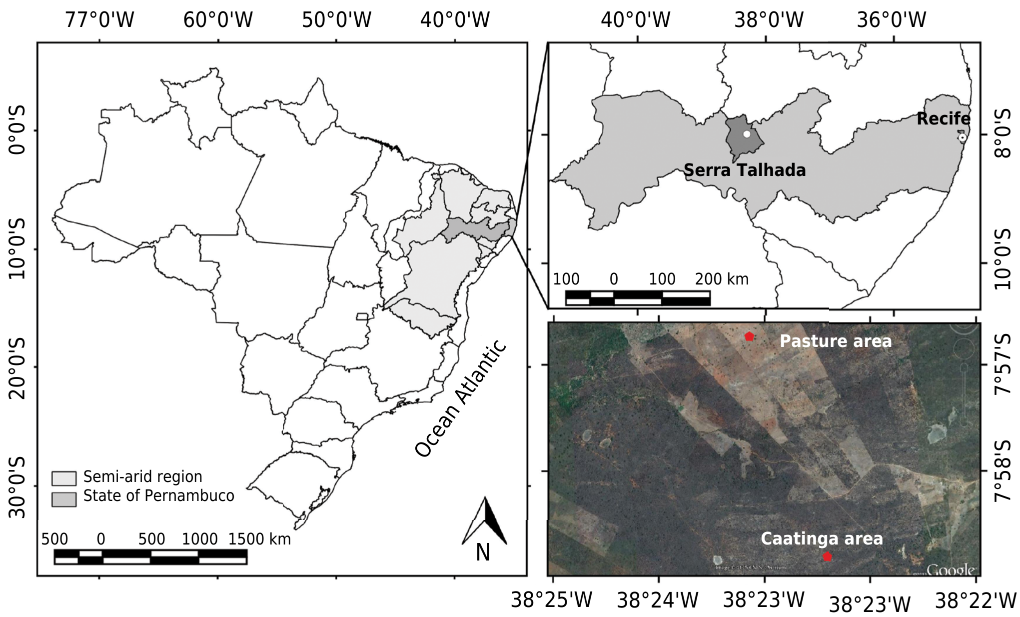

Figure 1. Location of experimental fields of Caatinga and degraded pasture in the semi-arid region of Brazil.

highest values occurring in March and an annual average of 642 mm (Souza et al., 2016). The experiment was carried out between September 2016 and May 2017.

The predominant soils for both areas are *Luvissolo Crômico* (Santos et al., 2018), which corresponds to Luvisol, according to World Reference Base (IUSS Working Group WRB, 2015). The soil properties of the studied sites were determined according to Donagemma et al. (2011), and are shown in table 1. The soil texture, particle density, porosity, and soil organic matter content were measured in a laboratory, while soil bulk density, saturated hydraulic conductivity, and infiltration capacity were measured in the field. The soil texture of the studied sites is sandy loam (Souza et al., 2016) and according to Leite et al. (2018), the two areas have different infiltration capacities and potential runoff and erosion susceptibility. These differences are mainly due to the management applied in the degraded pasture area.

The pasture area (7° 56’ 50.4’’ S, 38° 23’ 29’’ W) was introduced in 1995 (Souza et al., 2015) with two C4 types of grasses (via photosynthetic Hatch-Slack), buffel and urochloa grasses (*Cenchus cilicares* L. and *Urochloa mosambicensis* Hack. Dandy), maintained until nowadays. However, due to the recent drought events (five consecutive years), the pasture was degraded, presenting exposed soil and invasive pasture type vegetation (*Senna obtusifolia* L.).

The Caatinga area (7° 58’ 5.2” S, 38° 23’ 2.62” W) has a rich diversity of tree species such as *Parapiptadenia r*igida, *Cammiphora leptophloeos*, *Cordia oncocalyx*, *Poincianella bracteosa, Mimosa tenuiflora* Benth, among others (Leite et al., 2018). These trees cover between 80 and 90 % of the ground surface and contribute with approximately 1 kg m^{-2} to plant litter annually (Santos et al., 2019). These sites are part of the National Observatory of Water and Carbon Dynamics in the Caatinga Biome (NOWCDCB) network.

Soil respiration, temperature, and moisture measurements

The SR was measured with a portable infrared gas analyzer (LI-6400, LI-COR, Lincoln, NE, USA) equipped with a soil respiration chamber (model LI- 6400-09, LI-COR, Lincoln, NE, USA) with an internal volume of 991 cm^3 and sampled area of 71.6 cm^2. The CO_2 concentration was read every five seconds during a 90 to 120 s time interval, and three cycles of readings were taken in each ring. The field measurements were taken between 09:00 a.m. to 02:00 p.m.

Table 1. Soil surface properties of Caatinga and degraded pasture areas

Soil properties	Land use	
	Degraded pasture	Caatinga
Sand (g kg^{-1})	666.4 ± 25.2	716.5 ± 30.3
Silt (g kg^{-1})	166.3 ± 24.7	172.4 ± 16.7
Clay (g kg^{-1})	167.3 ± 10.3	111.1 ± 20.8
ρb (Mg m^{-3})	1.44 ± 0.04	1.39 ± 0.05
ρp (Mg m^{-3})	2.64 ± 0.02	2.59 ± 0.02
f (m^3 m^{-3})	0.455 ± 0.03	0.463 ± 0.04
Ks (mm h^{-1})	36 ± 26	214 ± 146
Infiltration capacity	Low	High
SOC (g kg^{-1})	8.44 ± 1.5	18.13 ± 2.3

ρb: bulk density; ρp: particle density; f: porosity; Ks: saturated hydraulic conductivity; SOC: organic carbon content, data from Silva et al. (2019). Mean ± standard deviation. Adapted from Leite et al. (2018). Soil texture was determined by the hydrometer method; ρb was determined by the core method; ρp was determined by the pycnometer method; f was determined by the relationship between ρb and ρp [f = 1-(ρb/ρp)]; Ks and was measured by Beerkan method (Souza et al., 2008); SOC was determined by Walkley and Black method.

For the SR measurements, the infrared gas analyzer (IRGA) was placed within PVC rings (10.3 cm internal diameter × 4.4 cm high), and 4 rings per area were permanently allocated to a depth of approximately 1.4 cm in the soil, separated of each other by 20 cm. The IRGA was placed 1 cm above the soil surface and the first reading started 13 days after the installation of the rings. Before each SR measurement, the IRGA was calibrated to the reference CO_2 (ambient CO_2) near the measurement site. As IRGA was 1 cm above the soil surface, the total volume of the chamber was recalculated automatically to 1,091 cm^3.

The soil temperature (Ts) was measured with the sensor integrated to LI-COR 6400-09. It consisted of a rod of 0.20 m, which was inserted into the ground, perpendicular to the surface, next to the flow chamber at a depth of 0.10 m. After the SR and Ts readings, soil samples were collected at a depth of 0.10 m in four replicates at a distance of 0.2 m from the PVC collars to determine soil moisture, by the gravimetric method. The samples were stored in aluminum cans and then weighed to determine the wet mass. The samples were then oven-dried at 105 °C for 24 h to determine the dry mass. Gravimetric soil water content was calculated and transformed to volumetric soil moisture (θv), by multiplying by the respective bulk soil densities of each experimental area (Table 1). Readings were made on 13 dates, with four repetitions, totaling 52 measurements of each soil properties (soil respiration, soil moisture, and soil temperature).

Soil respiration models

To evaluate the effects of soil moisture and soil temperature on soil respiration, we fitted seven empirical models commonly used for this propose (Lloyd and Taylor, 1994; Li et al., 2008; Lai et al., 2012), considering both soil moisture and soil temperature together and separately, as well as, linear and non-linear models. The combination of the seven models resulted in ten fittings for each area since the equations 1, 2, and 3 can be fitted considering soil moisture or soil temperature.

$$Rs(X) = aX^{b} \qquad \text{Eq. 1}$$

$$Rs(X) = ae^{(bX)} \qquad \text{Eq. 2}$$

$$Rs(X) = a + bX + cX^{2} \qquad \text{Eq. 3}$$

$$Rs(X,Y) = aX^{b}\,Y^{c} \qquad \text{Eq. 4}$$

$$Rs(X,Y) = ae^{(bX)}\,e^{(cY)} \qquad \text{Eq. 5}$$

$$Rs(X,Y) = a + b(XY) \qquad \text{Eq. 6}$$

$$Rs(X,Y) = a + bX + cY \qquad \text{Eq. 7}$$

in which: a, b, and c are the fitted constants; X in equations 1, 2, and 3 can be soil moisture or soil temperature; X and Y in equations 4, 5, 6, and 7 are, respectively, the soil moisture and soil temperature. Two statistical indicators, R^2 and AIC (Akaike information criterion) were used to compare the performance of these models in estimating soil respiration.

Climatological variables and NDVI

Precipitation and air temperature measurements were conducted from a 10 m tall tower in the Caatinga and 2 m tall in the degraded pasture. Data were recorded every minute and an average air temperature and total precipitation values were stored every 30 min in a data logger (CR1000, Campbell Scientific Inc.) (Silva et al., 2017). The NDVI data were obtained from moderate-resolution imaging spectroradiometer (MODIS) images, with a spatial resolution of 250 m recorded at 16-day intervals. We used the Google Earth Engine platform to download one-pixel for each area. For this study, we collected 18 images over time in the same coordinates for each area.

Data analysis

We first compute the average of the variables (soil moisture, temperature, and respiration) for each measurement over time (dates) and in the wet and dry seasons. After that, the confidence interval at 95 % (CI95%) level for the average was calculated using the bootstrap technique. The averages were considered statistically different when there was no overlap between the average and the bootstrapped CI95% (Zanella de Arruda et al., 2016). The fitted model performance was compared using the Akaike information criterion (AIC), and for the cases that there was no difference in AIC, the model was chosen based on the shape of the curve. All statistical analysis, model fitting, and graphics were realized with R (R Development Core Team, 2019).

RESULTS

Climatic and environmental factors

The precipitation presented a seasonal trend, clearly differentiating the dry season (from September 2016 to January 2017) from the rainy season (February-May 2017). The cumulative rainfall during the rainy season was 362.4 mm, and only 38.6 mm during the dry season. The highest rainfall events were recorded in March (157.5 mm) and April 2017 (122 mm). These two months accounted for 70 % of the total rainfall in the studied period. During the 273-days monitoring, daily rainfall greater than 5.0 and 10 mm only occurred on 23 and 12 days, respectively. Daily rainfall higher than 20 mm occurred on 07 dates (2/20/2017; 3/9/2017; 3/17/2017; 3/31/2017; 4/2/2017; 4/11/2017; and 5/31/2017) and accounted for 50 % of the total rainfall in the studied period (Figure 2).

Air temperature in the Caatinga and the degraded pasture areas followed a seasonal pattern, with higher values (above 25 °C) occurring in the dry season and the lowest in the rainy season. The air temperature in the Caatinga area ranged from 22.8 to 32.3 °C, while in the degraded pasture area ranged from 20.3 to 33.3 °C (Figure 2).

The seasonality of NDVI in both areas also followed precipitation variations. In the dry season from September 2016 to January 2017, the NDVI was stable, around 0.2 in the degraded pasture and 0.3 in the Caatinga. With the beginning of the rainy season, in February 2017, an increase of NDVI began to occur, reaching maximum values, above 0.6 in the Caatinga and 0.4 in the pasture, in May 2017 (Figure 2). The NDVI of the Caatinga was higher than in degraded pasture, whereas the averages for the degraded pasture and Caatinga were 0.33 and 0.46, respectively.

Soil moisture, soil temperature, and soil respiration

Volumetric soil moisture, θv, in the Caatinga area ranged from 0.01 to 0.16 $cm^3\ cm^{-3}$, with a mean of 0.06 $cm^3\ cm^{-3}$; while in the degraded pasture area θv ranged from 0.03 to 0.20 $cm^3\ cm^{-3}$ with a mean of 0.09 $cm^3\ cm^{-3}$. In both areas, θv followed seasonal variations (Figure 3).

Soil temperature (Ts) in both land-uses also followed seasonal variations, with higher values (above 30 °C) occurring in the dry season and lower (below 25 °C) in the wet season. In the Caatinga, Ts varied from 25.6 to 40.4 °C with a mean of 32.9 °C, while in the degraded pasture these values varied from 31.4 to 47.3 °C and the mean was 39.2 °C

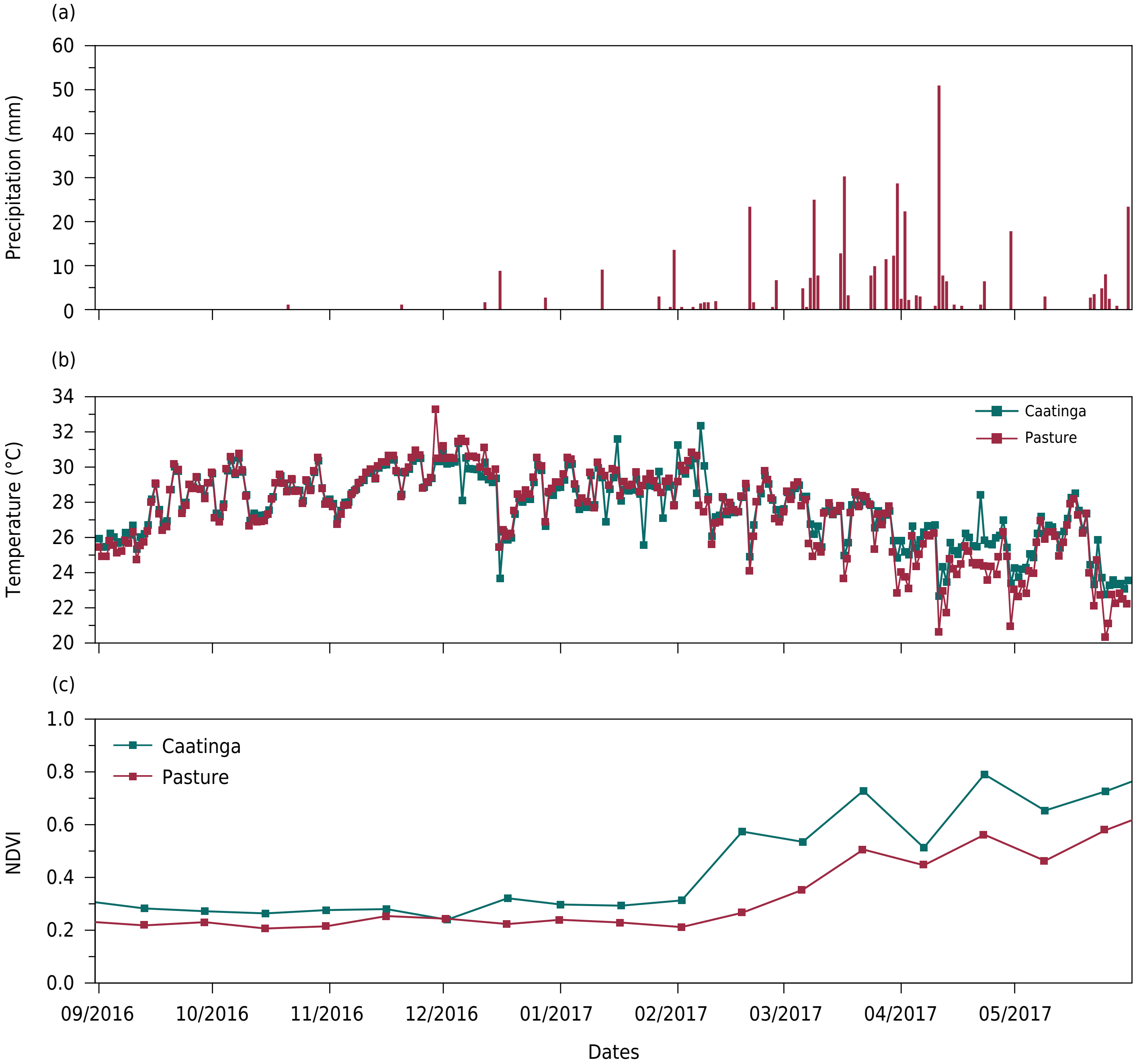

Figure 2. Temporal variation of precipitation, air temperature, and NDVI in Caatinga and degraded pasture areas.

(Figure 3). Soil temperature and θv presented a negative correlation in both land-uses (r = -0.725 for Caatinga and r = -0.716 for degraded pasture; $p<0.05$) (Table 2), i.e., with increases of θv occur decreases of soil temperature and vice versa.

Soil respiration (SR) showed a clear seasonal variation, with the highest values (above 2.0 μmol m^{-2} s^{-1}) occurring in the wet season and the lowest in the dry season, regardless of the land use type. The Rs ranged from 0.42 to 5.87 μmol m^{-2} s^{-1}, with a mean of 2.10 μmol m^{-2} s^{-1} in the Caatinga and from 0.18 to 3.10 μmol m^{-2} s^{-1}, mean of 0.97 μmol m^{-2} s^{-1}, in the degraded pasture (Figure 3).

Soil respiration showed significant differences ($p<0.05$) between seasons, with a mean value of 0.46 and 5.01 μmol m^{-2} s^{-1} in the Caatinga, in the dry and wet seasons, respectively. In the degraded pasture, SR was 0.20 μmol m^{-2} s^{-1} in the dry season and 2.44 μmol m^{-2} s^{-1} in the wet season. Soil respiration also had significant differences ($p<0.05$) between land-uses, independently of season. The SR in Caatinga was higher

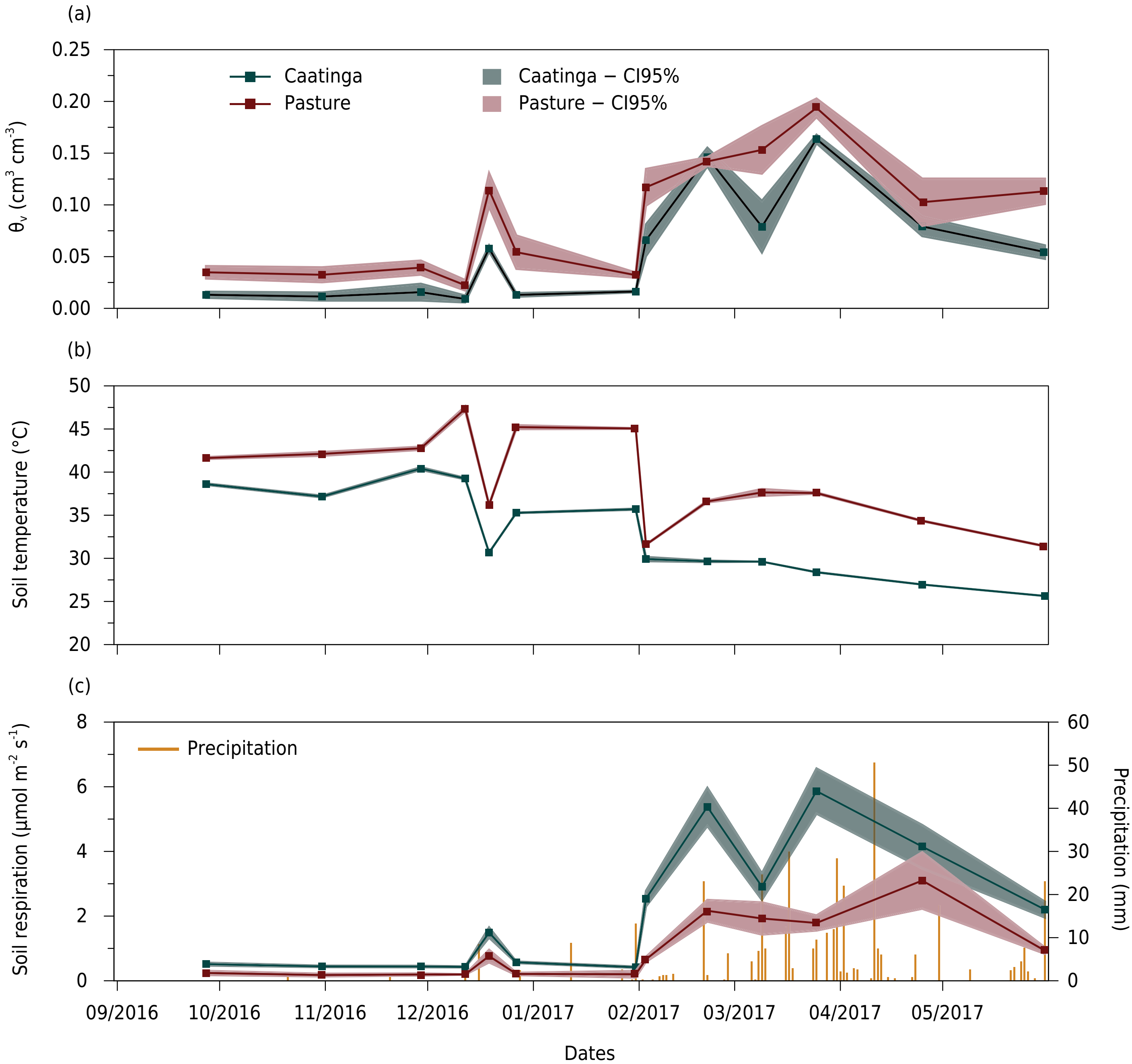

Figure 3. Soil volumetric moisture (θv), soil temperature (Ts), and soil respiration (SR) of the Caatinga and degraded pasture areas over experimental time. The shaded area represents the mean intervals at a confidence level of 95 % (CI95%) calculated bootstrapping the samples for each measurement over the time.

Table 2. Correlations between soil respiration (SR), soil moisture (θv), and soil temperature (Ts) in Caatinga and degraded pasture areas

Land-use	Property	Rs	θv	Tsoil
Caatinga	Rs	1		
	*θ*v	0.978 (p<0.05)	1	
	Tsoil	-0.763 (p<0.05)	-0.725 (p<0.05)	1
Degraded pasture	Rs	1		
	*θ*v	0.785 (p<0.05)	1	
	Tsoil	-0.595 (p<0.05)	-0.716 (p<0.05)	1

($p<0.05$) than that recorded for the degraded pasture regardless of the season (dry or wet) (Figure 4).

During the wet season, the SR was higher ($p<0.05$) in Caatinga (5.01 μmol m^{-2} s^{-1}) than degraded pasture (2.44 μmol m^{-2} s^{-1}), the θv was similar (0.121 cm^3 cm^{-3} in Caatinga and 0.148 cm^3 cm^{-3} in degraded pasture), and Ts was lower ($p<0.05$) in Caatinga (27.7 °C) than degraded pasture (35.9 °C); while in dry season the SR also was higher ($p<0.05$) in Caatinga (0.46 μmol m^{-2} s^{-1}) than degraded pasture (0.20 μmol m^{-2} s^{-1}), with θv higher ($p<0.05$) in degraded pasture (0.032 cm^3 cm^{-3}) than Caatinga (0.012 cm^3 cm^{-3}) and Ts higher in degraded pasture (43.5 °C) than Caatinga (38.9 °C) (Figure 4).

The results of models used to estimate soil respiration in function of soil moisture and/or soil temperature are shown in table 3. The Caatinga presented more variability in model performance based on AIC and R^2. When estimating SR in Caatinga using θv or Ts, the best performance was found using equations 1 (power function) and 3 (quadratic function) for θv and the models using only Ts showed the poorest performance. However, when combining these two variables, the best performance was found by fitting equations 4 (power function) and 7 (linear function). On the other hand, the 10 fits performed for the degraded pasture had similar performance with AIC around 34 and R^2 around 0.45. Despite that, equations 1 (power function) and 3 (quadratic function) seem to be the best options to estimate SR in the degraded pasture when using θv. The models using only Ts showed the poorest performance. In addition, combining θv with Ts did not increase the model performance to estimate SR in the degraded pasture, differently from Caatinga.

There was a negative relationship between Ts and SR and a positive relationship between θv and SR (Table 2 and Figure 5) for both land-uses. The correlation (Table 2) between SR and Ts in Caatinga (-0.763) was higher than in degraded pasture (-0.595), the same occurring with the correlation between SR and θv in Caatinga (0.978) and degraded pasture (0.785). In both land-uses the soil moisture was a better predictor of soil respiration than soil temperature (Table 3 and Figure 5).

DISCUSSION

Environmental factors

The precipitation distribution recorded from September 2016 to May 2017 followed the general pattern of this semi-arid region, showing high variability in terms of timing and

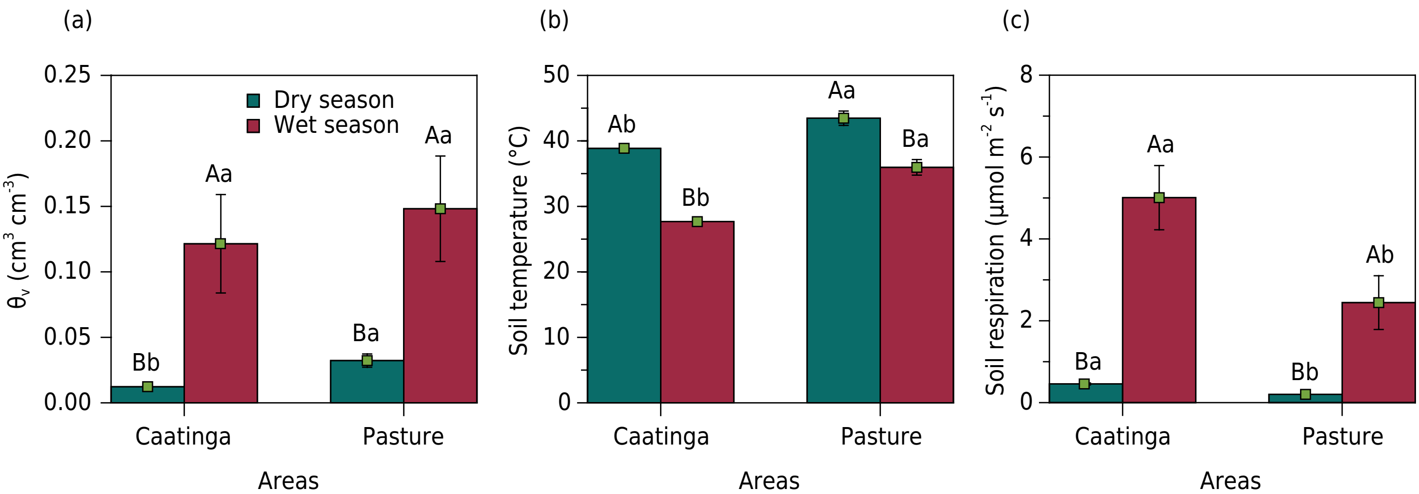

Figure 4. Comparison of soil water content, temperature, and soil respiration between seasons (dry and wet) and between areas. Uppercase letters compare the same area between seasons (dry and wet) while lowercase letters compare the different areas to the same season. Equal letters do not differ statistically at the 95 % confidence level according to the bootstrap.

Table 3. Akaike criterion information (AIC) and coefficient of determination (R^2) for the models fitted to estimate soil respiration in Caatinga and degraded pasture. Bold values show the best-fitting performance

Fit	Model	Caatinga		Degraded pasture	
		AIC	R^2	AIC	R^2
1	Eq. 1 (θv)	**18.49**	**0.957**	**31.53**	**0.520**
2	Eq. 2 (θv)	34.24	0.862	33.71	0.436
3	Eq. 3 (θv)	**19.60**	**0.960**	**32.59**	**0.550**
4	Eq. 1 (Ts)	50.92	0.492	37.75	0.229
5	Eq. 2 (Ts)	50.07	0.523	37.28	0.257
6	Eq. 3 (Ts)	50.04	0.583	35.40	0.441
7	Eq. 4	**14.82**	**0.972**	33.49	0.521
8	Eq. 5	23.82	0.946	34.83	0.472
9	Eq. 6	24.14	0.934	31.92	0.501
10	Eq. 7	**18.80**	**0.962**	33.14	0.530

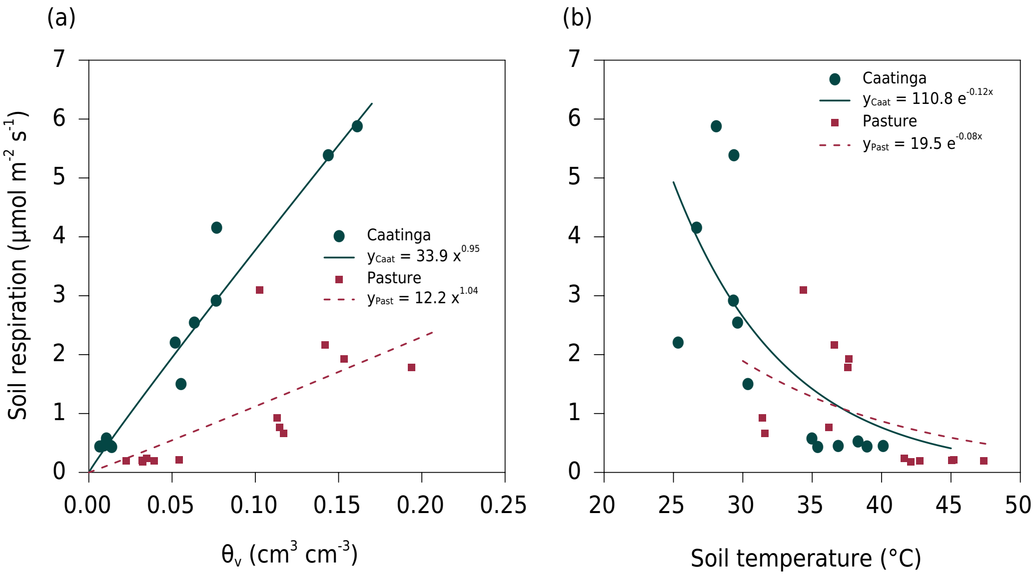

Figure 5. Relationship between soil respiration and soil moisture (a) and soil temperature (b) in Caatinga and degraded pasture.

volume (Souza et al., 2016; Silva et al., 2017). The mean air temperature in Caatinga (28.4 °C) and degraded pasture (29.3 °C) was higher in the dry season than in the wet season (26.8 °C in Caatinga and 26.0 °C in degraded pasture), due to higher solar radiation in the dry season and also due to the low water availability, most of the energy is converted into sensible heat flux. The higher mean value of the air temperature in the degraded pasture area is due, probably to the higher sensible heat flux. Silva et al. (2017) found that the sensible heat flux was higher in a degraded pasture (5.2 MJ m^{-2} day^{-1}) than in the Caatinga vegetation (4.5 MJ m^{-2} day^{-1}), corroborating our results. The sensible heat flux is the main consumer of the net radiation in semi-arid areas (Teixeira et al., 2008; Silva et al., 2017; Campos et al., 2019) and this occurs because, during the dry season, the air above the vegetation receives more heat than water vapor, resulting in warmer air layers (Teixeira et al., 2008).

The degraded pasture canopy is lower than the Caatinga vegetation, as inferred by NDVI. The NDVI is an often applied vegetation index related to the leaf area index (Miranda et al., 2020), and primary production (Wang et al., 2005). Besides that, NDVI can be also used to correlate changes in phenology and activity of vegetation with the ecosystem energy and carbon fluxes (Nagler et al., 2007; Qun and Huizhi, 2013). The NDVI in both areas ranged between the minimum during the dry season and reached its peak during or after the peak of the rain season (Souza et al., 2015; Silva et al., 2017). The higher NDVI in Caatinga is due to the buffering capacity of the ecosystem that accumulates enough reserves and biomass and the litterfall is slower in Caatinga (Souza et al., 2016) than in degraded pasture. In Caatinga, Silva et al. (2017) and Campos et al. (2019) also found higher NDVI in the wet season and lower in the dry season, with values varying from 0.3 (dry season) to 0.8 (wet season).

After the wet season, there is a soil moisture deficit and both Caatinga and degraded pasture enter in dormancy, and NDVI represents the bare soil and tree branches. This behavior has been reported for several seasonal ecosystems (natural or planted), such as temperate semi-arid grasslands in Semi-arid Arizona, USA (Krishnan et al., 2012). All of the above-mentioned environmental variables (rainfall, air temperature, and NDVI) followed a marked seasonal cycle. This seasonal variation was also reported by other authors (Meirelles et al., 2011; Gondim et al., 2015; Silva et al., 2017; Campos et al., 2019) who measured these environmental variables in pastures and Caatinga areas in Brazil.

Soil moisture, soil temperature, and soil respiration in the Caatinga biome

Overall, the θv was higher in the degraded pasture area (Figures 3 and 4), probably due to lower soil cover, since the pasture was degraded, causing more rain to reach the soil directly. The Caatinga area also has a larger canopy and therefore greater interception of precipitation, decreasing the water infiltration into the soil. Although there are few publications about water partition measuring most components, canopy interception in Caatinga can account for about from 10.3 to 13 % of the rainfall (Medeiros et al., 2009; Queiroz et al., 2020), and most of this water does not contribute to the soil moisture since it returns to the atmosphere as evaporation in a few hours after rain events.

On the other hand, as the hydraulic conductivity (Ks) for the degraded pasture was lower than for the Caatinga (Table 1), it may increase runoff, reduce infiltration rate and, thereby, decrease θv. However, θv was higher in degraded pasture than in Caatinga. As the soil bulk density and total porosity were similar in both land uses (Table 1), the highest infiltration capacity in Caatinga can be due to root-induced macropore flow, which is higher in a forest than in open areas (Tobella et al., 2014). Kellner and Hubbart (2016) measured θv in a forest and an agriculture field and found that θv was higher in the agriculture field and it was attributed to plant water use and preferential flow paths in the forest.

In addition, the lower θv in Caatinga can be associated with a higher water uptake due the its structure and demand, and also with a deeper root system compared with grassland. According to Pinheiro et al. (2013), the effective root depth of Caatinga ranged from 0.60 to 0.78 m. Similar results were found by Silva et al. (2017), who measured θv in Caatinga and pasture areas and found lower soil moisture in the Caatinga area. The values of θv found in our study are within the range reported by other authors in Caatinga and pastures areas in the Brazilian semi-arid region (Silva et al., 2014; Souza et al., 2015; Silva et al., 2017; Brito et al., 2020).

The Ts was higher in degraded pasture than in Caatinga vegetation, because of lower soil cover in the degraded pasture, causing more incoming solar radiation to reach the soil directly, which contributes to soil heat flux (G) increasing and, consequently, Ts. Soil heat flux is the amount of thermal energy that moves through an area of soil in a unit of time, indicating the ability of a soil to conduct heat and determines how fast its temperature changes and, generally, represents 5 % of net radiation in the forest and between 20 and 40 % in partially covered surface (Kustas et al., 2000). Silva et al. (2017) measured energy balance in pasture and Caatinga in the same area of our study and found higher G in the pasture (0.47 MJ m^{-2} day^{-1}), than in Caatinga (0.34 MJ m^{-2} day^{-1}), corroborating our results.

The different land-uses caused changes in θv, Ts (Figures 3 and 4), and SOC (Table 1), consequently affected SR, with Caatinga emitting more CO_2 to the atmosphere than degraded pasture. However, converting SOC into soil C stocks using soil bulk density, we found that the relation between SR and C stocks was similar in both areas (31.6 % in Caatinga and 30.5 % in degraded pasture). The lower SR in degraded pasture was due probably to lower SOC; while the higher values of SR in Caatinga were associated with higher SOC, besides of θv is at the adequate level.

Concerning SOC, Santos et al. (2019) assessed the effect of land-use changes in SOC stocks (TCS) and microbial biomass carbon (MBC) in semi-arid Brazilian, and found that the conversion of forest (Caatinga) into successional areas can decrease by up to 44 % TCS and 68 % MBC, affecting, thus, the SR and corroborating with our results. The SOC values in both land-uses (8.44 and 18.13 g kg^{-1} in degraded pasture and Caatinga, respectively) are within the range reported by other authors (Medeiros et al., 2017; Santana et al., 2019) in the semi-arid region of Brazil.

Concerning soil moisture, the marked seasonality of rainfall (Figure 2) explains the higher values in the wet season, in both land-uses (Figure 4). In semi-arid areas, soil moisture is largely conditioned by rainfall, which can cause a positive relationship between rainfall and soil respiration. For example, on 12/12/2016 soil respiration was 0.46 and 0.20 μmol m^{-2} s^{-1} in Caatinga and degraded pasture respectively, and increased to 1.5 μmol m^{-2} s^{-1} in Caatinga and to 0.8 μmol m^{-2} s^{-1} in the degraded pasture on 12/19/2016, after of a precipitation pulse of 8.5 mm occurred on 12/16/2016 (Figure 3). The pulse of soil respiration following wetting of dry soils is called "Birch effect" and can be due to the infiltration of rainwater, which may displace CO_2 that accumulated in soil pore spaces during dry periods (Liu et al., 2019).

Soil respiration was high in the rainy season when the soil held the highest soil moisture and lowest soil temperature (Figure 4). According to Souto et al. (2005), in the Caatinga, the soil wetting/drying cycle is quite fast, which may imply greater or lower activity and proliferation of organisms. In addition, the higher Ts in dry season also contributes to the lower microbial population and reduction in the intensity of organic matter decomposition. In this sense, several authors (Correia et al., 2015; Holanda et al., 2015; Ferreira et al., 2018) report that high Ts limits microbial activity in Caatinga soils because they reduce microbial populations and, consequently, reduce the intensity of organic residue decomposition and SR.

The lowest values of SR, in both land-uses, in the dry season are probably associated with the lowest θv in this season, as well as due to the higher values of Ts. As θv decreased (90 and 78 % for Caatinga and degraded pasture, respectively), in the dry season, the dependence of microbial and enzymatic activities on moisture in the soil became obvious (Han et al., 2019), because the low θv can inhibit soil microbial respiration (Curiel Yuste et al., 2003). Oyonarte et al. (2012), in semi-arid ecosystems of Spain, found that θv <5 % (0.05 cm^3 cm^{-3}) did not exert any control over SR. However, in our study, values of soil moisture above 0.03 cm^3 cm^{-3} exerted control over soil respiration.

In ecosystems where water is not limiting, the soil organic matter amount and quality (Reth et al., 2005), as well as the Ts are typically the dominant factors controlling the rate of SR, often explaining most of its variability (Lloyd and Taylor, 1994; Bond-Lamberty and Thomson, 2010; Lellei-Kovács et al., 2011). According to these authors, SR generally increases exponentially with Ts over a wide range of θv but becomes a function of soil water content as the soil dries out to the point that microbial activity is reduced. In the semi-arid region of Spain, Rey et al. (2011) developed a model in which, under the same environmental conditions, the effect of soil temperature on SR disappears above 20 °C. As our area is located in a semi-arid climate, there was a negative relationship between SR and Ts, i.e., an increase of Ts decreases SR. Ribeiro et al. (2016) obtained similar results and found a negative relationship between Ts and SR in Caatinga and grassland in the Northeast of Brazil.

The higher emission of CO_2 during the wet season is due to the positive relationship between SR and θv, which illustrated the key role of both rainfall and soil moisture as forcing conditions on SR (Davidson et al., 2006). The variation in θv can also affect the diffusion of soluble substrates and diffusion of oxygen, which can affect soil microbial respiration (Ribeiro et al., 2016). In addition, soil moisture and temperature may act independently or together, interdependent factors controlling soil respiration (Davidson et al., 2006). In the wet season, as the soil moisture increased, a decrease in the soil temperature occurred, with the inverse occurred in the dry season. On the semi-arid Loess Plateau of China, in the grassland area, Niu et al. (2019) found that soil temperature was negatively correlated with SR in the dry period and conversely, soil moisture was positively related to SR in both periods (wet and dry). The higher soil respiration in Caatinga than in degraded pasture may also be due to the higher diversity of plants in Caatinga area that have more diversity of inputs and quality of residues that affect the microbial diversity and density, resulting in variations in SR (Santos et al., 2019). In addition, the highest SR in Caatinga area has been associated with higher levels of SOC that influence microbial activity as observed by Notaro et al. (2014) in soils from the Brazilian semi-arid region.

Overall, the highest values of SR in Caatinga can be seen as indicators of good environmental quality due to the higher levels of SOC and ecological equilibrium of the ecosystem. On the other hand, the lower CO_2 emissions in pasture can be indicative of a degraded ecosystem with low levels of SOC. Oyonarte et al. (2012), assessing the use of SR as an indicator of ecosystem functioning of the SE of Spain, found that the higher soil CO_2 efflux is interpreted as an improvement in the ecosystem state. The root biomass of Caatinga can reach 19.6 ton ha^{-1} (Costa et al., 2014), while in pasture the root biomass is around 5.0 ton ha^{-1} (Silva et al., 2014). Thus, the root respiration in Caatinga is probably higher than in pasture, mainly, degraded pasture. This also can explain the highest soil respiration in Caatinga.

As seen previously there are only a few studies on soil respiration in the semi-arid ecosystems of Brazil (Ribeiro et al., 2016; Ferreira et al., 2018), so a comparison with these and other semi-arid ecosystems of the world are shown in table 4. The soil respiration in pastures and grasslands varied from 3.0 to 6.8 ton ha^{-1} yr^{-1} of C and was lower than in forests, savannas, and shrubland, which varied from 4.2 to 10.1 ton ha^{-1} yr^{-1} of C. It was seen also that degraded ecosystems (pasture or grassland) showed the annual lowest values of soil respiration (3.0-3.7 ton ha^{-1} yr^{-1} of C). Hence, soil CO_2 emissions in the semi-arid region of Brazil are similar to other semi-arid areas of the world and vary in function of soil organic carbon contents, soil temperature, and soil moisture.

CONCLUSIONS

We analyzed the effects of land-use change on soil respiration and how soil moisture and temperature affect soil respiration in a preserved Caatinga vegetation and a degraded pasture in the semi-arid region of Brazil. The preserved Caatinga presented higher soil respiration compared with the degraded pasture. Consequences of land-use changes from the woody Caatinga biome towards degraded pasture were observed not only to affect physical properties like soil moisture or soil temperature. Due to the shift from a multi-specific environment towards a degraded pasture, organic matter quality, and microbial activity, probably also were affected.

Table 4. Overview of annual soil respiration (SR) in grassland, pasture, shrubland, and forest ecosystems in semiarid regions

Cover	SR	Country	Reference
	ton ha^{-1} yr^{-1}		
Grassland	4.9	China	Liu et al. (2016)
Grassland	4.0	Spain	Rey et al. (2011)
Degraded grassland	3.0	Spain	Rey et al. (2011)
Pasture	6.1	Brazil	Ribeiro et al. (2016)
Pasture	6.8	Brazil	Ferreira et al. (2018)
Degraded pasture	3.7	Brazil	This study
Forest	8.4	Spain	Asensio et al. (2007)
Shrubland	10.1	China	Shi et al. (2014)
Forest	4.2	USA	Barron-Gafford et al. (2011)
Forest	6.1	Brazil	Ribeiro et al. (2016)
Forest	8.6	Brazil	Ferreira et al. (2018)
Forest	8.0	Brazil	This study

The soil respiration was strongly affected by the rainfall seasonality and both areas reach their emission peaks during the wet season. In this semi-arid region, soil moisture alone was a better predictor of the soil respiration in Caatinga, but the performance of the models can increase when they are combined with soil temperature. In the degraded pasture, the evaluated models did not perform well, but soil moisture was better than soil temperature to estimate the soil respiration under this condition. In both areas, the main driver triggering and controlling the soil respiration was the water availability.

ACKNOWLEDGMENTS

This study was performed in areas of the National Observatory of Water and Carbon Dynamics in the Caatinga Biome (INCT:NOWCBCB) and was financed by the National Council for Scientific and Technological Development (CNPq) [grants numbers 312984/2017-0, 435508/2018-0, 465764/2014-2, 448504/2014-6, 441305/2017-2, 409990/2018-3, 438596/2018-8, 307335/2017-8, 310537/2017-7]; the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) [Finance Code 001; 88881.318207/2019-01/PrInt, 88887.136369/2017-00]; the Fundação de Amparo à Ciência e Tecnologia do Estado de Pernambuco (FACEPE) (grant numbers APQ-0532-5.01/14; APQ-0498-3.07/17). In particular, we thank Homem Bom de Magalhães and José Silva for the assignment of this experimental field. We would like to thank the three anonymous reviewers whose suggestions helped improve and clarify this manuscript.

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