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Impact of Conversion of the Caatinga Forest to Different Land Uses on Soil and Root Respiration Dynamics in the Brazilian Semiarid Region

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Abstract: The Caatinga biome has been severely devastated over the years due to the replacement of native dry forests with grassland areas in the Brazilian semiarid region. Despite this, variations in key soil quality indicators still need to be fully elucidated. We evaluated soil and root respiration dynamics in grassland (GR), agroforestry (AS), and Caatinga forest (CA) areas, during dry and rainy seasons. In situ, monthly CO_2 flux (total, root, and heterotrophic respirations), soil moisture (θv), and temperature (T_{soil}) were measured. Soil samples were collected every 5 cm layer up to 20 cm depth to analyze total organic carbon (TOC) and microbial activities. The highest parameter values occurred during the rainy season. Total soil respiration was highest in AS, followed by CA and then GR, with 19.3, 13.4, and 8.4 ton C ha^{-1} yr^{-1}, respectively, and root respiration contributed 33.2 and 32.9% to total soil respiration in CA and AS, respectively. However, TOC concentrations and microbial activity were significantly higher in AS than in GR and similar to CA, more than compensating the C losses by respiration. Therefore, agroforestry systems have a high potential for semiarid lands because they preserve soil carbon and microbial activity comparable to Caatinga forests.

Keywords: dry forest; grassland; sustainable systems; soil organic carbon; environmental impact

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1. Introduction

The Caatinga biome, located in northeastern Brazil, is a dry tropical forest and considered as one of the most biodiverse ecosystems globally [1,2]. Known for its resilient flora and fauna, the Caatinga plays a crucial role in regional ecosystem stability primarily through control of soil processes [3]. However, human activities such as agricultural expansion, deforestation, and urbanization have led to significant changes in land use within the Caatinga [4]. These changes often involve converting natural Caatinga vegetation into various land uses like croplands, pastures, and urban areas, which can profoundly impact on soil properties and processes, including carbon stocks, microbial communities, and respiration [5,6].

Soil respiration is one of the terrestrial biosphere's most significant global carbon fluxes [7], accounting for up to 80% of the total terrestrial respiration [8,9] and releasing 64 to 94 Pg C yr^{-1} into the atmosphere. It results from several interrelated biogeochemical processes, being affected by climate, vegetation, land use, soil type, biota, soil moisture, and temperature [10–13]. It can be divided into autotrophic (from plant roots and their associated mycorrhizae) and heterotrophic (from soil organic C decomposition and mineralization) activities [7,14,15].

Soil moisture and temperature are considered the abiotic factors that most influence soil respiration because they control the decomposition of organic matter and the production and efflux of CO_2 [16–18]. Soil moisture, especially in arid and semiarid environments, plays a significant role in soil respiration because it influences carbon bioavailability, microbial activity, mass transport, pore-water connectivity, and oxygen access [6,16,19]. Both high and low soil moisture contents affect the rate of CO_2 production. High contents create a barrier to gaseous diffusion at the soil–atmosphere interface, while low contents restrict pore-water connectivity and decrease carbon mass transport [20,21]. Studies by Shen et al. [22] and Yang et al. [23] suggest a quadratic link between soil respiration and soil moisture, indicating limitations in both arid and wet conditions. Research has also shown that soil respiration is sensitive to changes in soil temperature, as an increase in temperature affects the metabolic activity of microorganisms [10,24]. The Q_{10} value, defined as the increase in the respiratory rate per 10°C increase in temperature, is commonly used to describe the sensitivity of soil respiration to temperature fluctuations.

Root respiration accounts for much of total soil respiration, thought to release 40–50 Pg C yr^{-1} to the atmosphere, varying with climate, ecosystems, and other factors [8,25]. Quantifying the proportion of root respiration is essential. However, is a difficult task, as direct in situ measurements of root respiration are rare, especially in semiarid ecosystems and agroecosystems, particularly in the Brazilian semiarid region. Jian et al. [25] evaluated the contribution of root respiration (R_{root}) to total soil respiration (R_{total}) and the effect of biotic and abiotic factors on this respiration ratio (RC-ratio of R_{root}:R_{total}). Their findings indicate that plant roots contribute to 42% of the R_{total}.

Analyzing the spatial and temporal variability of soil and root respiration is crucial for quantifying carbon losses in global, regional, and local ecosystems and understanding how changes in land use influence these losses [26,27]. While studies often focus on measuring total soil respiration, further improvements are needed to understand the factors governing its component fluxes [6,28–30]. In the Brazilian semiarid region, grassland progressive replacement of Caatinga landscapes has spurred research into measuring total soil respiration in these contrasting land use types [6,29].

Integrating agroforestry systems into the Caatinga biome offers a sustainable alternative for land use in the semiarid region [30]. These systems have demonstrated viability in converting Caatinga forests, leading to increased carbon stocks and microbial communities in the soil [31]. Quantifying the proportions of total soil respiration from agroforestry root systems and comparing them with Caatinga and grassland is crucial, considering that they are a carbon reservoir with relatively rapid renewal for semiarid conditions. This study aimed to evaluate soil and root respiration dynamics and their relationship with soil moisture and temperature in grassland, agroforestry, and Caatinga forest areas in the Brazilian semiarid region. It was also aimed to calculate the contribution of root respiration to total soil respiration in these systems. Our hypotheses are that 1) agroforestry systems have higher respiration than the grasslands but this carbon loss is more than compensated for by the higher organic matter input to the soil, leading to higher soil C concentrations and stocks and 2) the higher soil C dynamics leads to higher microbial activity.

2. Materials and Methods

2.1. Study Sites

The study was conducted from November 2018 to May 2021 in areas within the neighboring municipalities of Serra Talhada and Triunfo, Pernambuco state, Brazil (Figure 1).

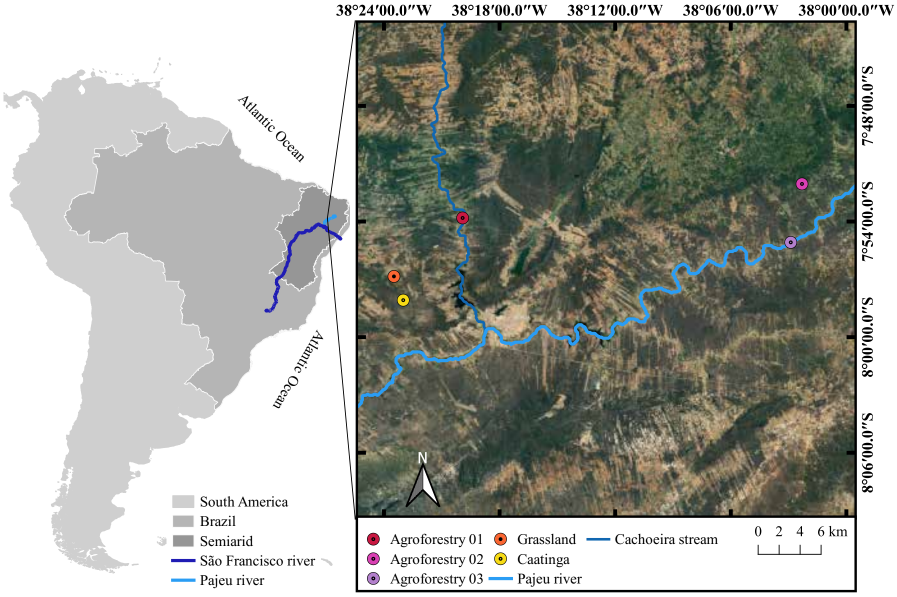

Figure 1. Overview of Brazil within South America, semiarid region, São Francisco River, Pajeu River, and experimental sites in Serra Talhada and Triunfo municipalities, Pernambuco state.

Three sites were chosen in Serra Talhada, located around 07°59′31″ South, 38°17′54″ West, and 430 m above sea level (MASL). The local climate is Bswh′ type, semiarid hot and dry, according to the Köppen classification adapted for Brazil [32], with 642 mm average annual rainfall, mainly occurring between December and May [33]. Average air temperatures range between 23.6 and 27.7 °C. Two sites were selected in the lower part of Triunfo municipality. The first site is located at approximately 07°52′03″ S latitude and 38°02′18.4″ W longitude, with an elevation of 466 MASL. The second site is situated at approximately 07°55′05″ S latitude and 38°02′54.9″ W longitude, with an elevation of 446 MASL. These sites have edaphoclimatic characteristics similar to those in the Serra Talhada sites.

In Serra Talhada, three sites were studied: (1) grassland (GR, 18 ha) established in 1995 with buffel grass (*Cenchrus ciliaris* L.) and urochloa grass (*Urochloa mosambicensis* Hack. Dandy); (2) an agroforestry system (AS, 0.5 ha) implemented at least 15 years ago for forage, organic food production, and preservation; and (3) 270 ha old-growth native dry forest stand representing the Caatinga biome (CA).

CA and GR are rainfed systems, while AS receives sporadic watering during the peak of the dry season. The bedrocks in the GR and CA sites are crystalline and impermeable, with shallow (40 cm) sandy loam soils, classified as an Entisol Orthent and an Aridisol Argid [34]. The soil in the AS site is an Entisol Fluvent [34]. In Triunfo, two agroforestry systems (AS, 0.5 ha) implemented 15 years ago, similar to those in Serra Talhada in agroecological principles and production destination, were studied. The soils in the two Triunfo sites are Entisols Fluvents and Entisols Orthents [34]. Table 1 provides information on the main physical and chemical attributes of the surface layer (0–10 cm) of these soils.

The grassland in GR is currently degraded due to inadequate management, with bare soil spots and invasive plant species caused by high animal grazing pressure considering the usual climatic conditions (high temperatures and prolonged drought periods). The AS areas consist of several plant species, including C4 plants (*Saccharum officinarum* L. and *Pennisetum purpureum* Schumach), C3 fruit (*Mangifera indica* L., *Malpighia emarginata* DC, *Punica granatum* L., and *Carica papaya* L.), and legume species (*Gliricidia sepium* (Jacq.) Kunth ex Walp and *Mimosa caesalpiniifolia* Benth.), as well as CAM fruits and forage species (*Ananas comosus* (L) Merr. and *Opuntia* spp.). CA mainly comprises tree species, including

Parapiptadenia rigida Benth Brenan, *Cammiphora leptophloeos* (Mart.) J. B. Gillet, *Cordia oncocalyx* Allemão, *Poincianella bracteosa* (Benth.) L. P. Queiroz, and *Mimosa tenuiflora* Benth.

Table 1. Soil physical and chemical attributes (means ± standard deviation) of samples from the 0–10 cm superficial layer collected from areas with three different land uses in the Brazilian semi-arid region.

	Grassland	**Agroforestry**	**Caatinga**
		Physical attributes	
Sand (g kg^{-1})	65.32 ± 2.5	59.04 ± 5.8	69.30 ± 6.4
Silt (g kg^{-1})	18.40 ± 2.8	31.60 ± 4.3	18.40 ± 3.2
Clay (g kg^{-1})	16.28 ± 1.1	9.36 ± 1.27	12.30 ± 5.2
Bulk Density (g cm^{-3})	1.61 ± 0.42	1.32 ± 0.68	1.45 ± 0.28
Particle Density (g cm^{-3})	2.61 ± 0.62	2.47 ± 0.88	2.57 ± 0.76
Total Porosity (%)	38.3 ± 2.10	46.6 ± 2.71	43.6 ± 2.01
Textural Class	Sandy Loam	Sandy Loam	Sandy Loam
		Chemical attributes	
pH (H_2O)	7.30 ± 1.21	6.81 ± 1.69	7.11 ± 1.90
P (mg dm^{-3})	2.10 ± 1.39	3.87 ± 1.91	3.95 ± 1.88
Ca^{2+} ($cmol_c$ dm^{-3})	0.60 ± 0.19	1.30 ± 0.25	1.40 ± 0.31
Mg^{2+} ($cmol_c$ dm^{-3})	0.09 ± 0.02	0.16 ± 0.06	0.15 ± 0.06
Na^{+} ($cmol_c$ dm^{-3})	0.18 ± 0.01	0.76 ± 0.03	0.09 ± 0.02
K^{+} ($cmol_c$ dm^{-3})	0.32 ± 0.11	0.76 ± 0.16	0.78 ± 0.14
H^{1+}+Al^{3+} ($cmol_c$ dm^{-3})	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00
SB ($cmol_c$ dm^{-3})	1.19 ± 0.42	2.28 ± 0.80	2.42 ± 0.82
CEC ($cmol_c$ dm^{-3})	2.19 ± 0.84	3.29 ± 1.19	3.42 ± 1.62
V (%)	54.3 ± 1.04	69.6 ± 1.23	70.7 ± 2.03
m (%)	0.0 ± 0.00	0.0 ± 0.00	0.0 ± 0.00
Organic Matter (%)	1.40 ± 0.71	3.56 ± 1.09	3.47 ± 1.29

Sum of Base (SB) = Ca^{2+} + Mg^{2+} + K^{+} + Na^{+}; Cation Exchange Capacity (CEC) = SB + (H^{1+}+ Al^{3+}); Base Saturation (V) = (SB/CEC)·100; Aluminium Saturation (m) = (Al^{3+}/CEC) · 10.

2.2. Experimental Procedures, Data Collection, and Analysis

Several sampling plots were systematically designed within each area, according to their sizes, to monitor soil respiration, soil moisture, and soil temperature. Four plots were established in GR, four in CA, and only one in each AS. The sampling plots were at least 300 m in CA and 150 m in GR. In AS, they were in the center of the area. In each sampling plot, four PVC collars, adjustable to an IRGA chamber, were inserted into the soil down to 3.0 cm depth to measure the total respiration (R_{total}) and four collars were inserted down to 30 cm depth to measure root-free soil respiration, that is, heterotrophic respiration (R_{het}) (Figure 2). These deep collars had lateral windows lined with 0.5 µm nylon mesh to allow microbial migration, and gas and water diffusion into the collar. The collars were placed in a cross distribution, facing the four cardinal directions, and separated by 2 m in the linear direction. An access tube to allow soil moisture measurements was inserted in the center of the cross distribution.

The method of root exclusion [35] was used to account for the contribution of root respiration (R_{root}) and heterotrophic soil respiration (R_{het}) for total soil respiration (R_{total}). This method assumes that, around the circumference of the plastic collars, soil root disruption reduces R_{root} to negligible levels within three months after trenching [36]. Root respiration (R_{root}) was obtained as the difference between total soil respiration (R_{total}) and heterotrophic respiration (R_{het}).

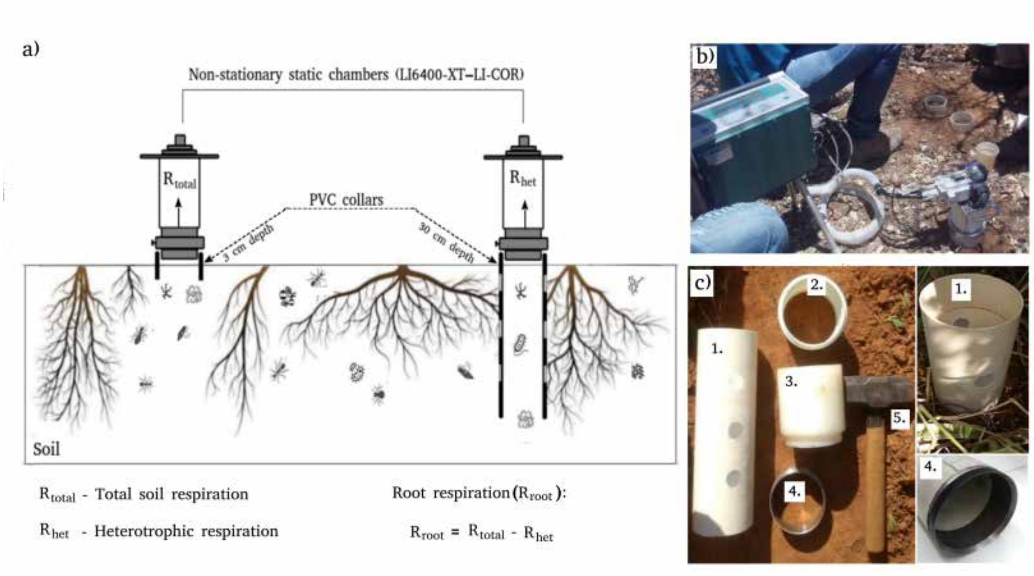

Figure 2. Installation scheme of PVC collars to monitor R_{total} and R_{het} (**a**), soil CO_2 flux system (LI-6400-09, LI-COR, Lincoln, NE, USA) (**b**), and collar at 30 cm depth with installation details. Components include (**c**), 1. collar with lateral windows lined with 0.5 µm nylon mesh; 2. PVC slip coupling with rubber ring joint gaskets for sealing; 3. polyamide nylon billet; 4. single bevel-cutting ring with a flat outer edge for sharp ground cutting; and 5. hammer.

2.2.1. Soil Respiration, Moisture, and Temperature Measurements

Measurements of CO_2 efflux were made using an infrared gas analyzer (IRGA LI6400-XT–LI-COR) coupled to a CO_2 retention chamber (LI-6400-09, LI-COR, Lincoln, NE, USA) with an internal volume of 991 cm^3 and exposed on PCV collars with a soil area of 71.6 cm^2. The measurements began after the system was equilibrated, about 15 days after installing the collars, and were repeated every 30 days. In the dry season, measurements were performed between 7:00 and 11:00 a.m., and in the rainy season between 9:00 and 11:00 a.m. Once in the dry and in the rainy seasons, on a sunny day, measurements were performed every two hours, from 7:00 a.m. to 5:00 p.m., to evaluate the behavior of CO_2 efflux on an hourly scale. Before each measurement, the IRGA was calibrated using the CO_2 of the measurement site (1 cm above the soil) as a reference. We used the height data of the CO_2 retention chamber about the soil surface and the number of readings for each PVC collar during the IRGA calibration.

Access tubes installed in the center of each experimental site monitored soil moisture at a 0–10 cm layer. Readings were taken with an FDR probe (Diviner 2000; Sentek Pty Ltd., Stepney, Australia), also known as a capacitance probe, based on a pair of electrodes or conductive metal plates arranged in parallel and separated by an insulating material. Soil temperature was measured at the surface by a portable infrared thermometer, with a temperature range between −50 and 380 °C. Both soil moisture and temperature readings were taken simultaneously with the soil respiration measurements.

2.2.2. Data Analysis

The temporal variation of soil moisture and temperature data was used to evaluate the effects of land use change on CO_2 dynamics. It also made it possible to adjust both total soil and root respiration models for the three systems studied. The standard Q_{10}, representing the soil respiration rate with an increase of 10 °C [37], was derived from the exponential model of the relationship between R_{total}, R_{het}, R_{root}, and soil temperature (T_{soil}):

$$R_X = a \cdot e^{b \cdot T_{soil}} \tag{1}$$

$$Q_{10} = e^{10 \cdot b} \tag{2}$$

where X is replaced by $total$, het, and $root$ to represent R_{total}, R_{het}, and R_{root} (in µmol CO_2 m^{-2} s^{-1}), T_{soil} is the soil surface temperature (°C), and a and b are constants fitted to the exponential model.

Linear, quadratic, and exponential functions were tested to describe the relationship between soil respiration (R_{total}, R_{het}, and R_{root}) and θv [38,39]:

$$R_X = a + b \cdot \theta v \tag{3}$$

$$R_X = a + b \cdot \theta v + c \cdot \theta v^2 \tag{4}$$

$$R_X = a \cdot e^{b \cdot \theta v} \tag{5}$$

where a, b, and c are fitted constants and θv (cm^3 cm^{-3}) is the soil moisture at the 10 cm depth layer.

2.3. Soil Carbon and Microbiological Attributes

Composite samples were taken from the 0–5, 5–10, and 10–20 cm layers to refine soil C measurements and evaluate soil biological activities. These samples were placed in thermal boxes, transported to the laboratory, and kept at 4 °C until analysis.

Total organic carbon (TOC) was determined by wet oxidation with potassium dichromate, followed by titration with ammonium ferrous sulfate [40].

Soil basal respiration (SBR) was determined by quantifying the carbon dioxide (CO_2) released during seven days of incubation from 20 g soil samples placed into hermetically closed 3 L flasks. A smaller flask containing 20 g M^{-1} NaOH captured the released CO_2, which was then determined by titration with 0.5 M HCl, after precipitation of barium carbonate formed by adding barium chloride ($BaCl_2$) aqueous solution to the NaOH solution. Phenolphthalein diluted in 100 mL ethanol (60%, v/v) was used as an indicator [41]. The analyses were performed in triplicate.

Carbon from soil microbial biomass (MBC) was obtained using the combined method of irradiation and extraction [42,43]. Two 10 g soil samples were divided into Petri dishes, and one was irradiated with microwaves and the other left untreated. These samples were mixed with a 0.5 M potassium sulfate (K_2SO_4) extraction solution in 50 mL conical bottom tubes. After shaking for 30 min, the tubes were centrifuged at 7342 rpm for 10 min and filtered through a 45 µm pore diameter paper filter. MBC contents were quantified using the colorimetric method described by Bartlett and Ross [44], with potassium permanganate as the oxidizing agent. All analyses were performed in triplicate.

The soil microbial (qMic) and metabolic (qCO_2) ratios were calculated as the MBC to TOC ratio, according to Anderson and Domsch [41], and as the ratio of basal respiration to the microbial biomass C, according to Sparling [45].

2.4. Statistical Analysis

The data underwent testing for normality and homogeneity of variances using the Shapiro–Wilk [46] and Levene [47] tests, respectively. Differences in TOC and microbiological variables among management systems (grassland, agroforestry, and Caatinga) and seasons (dry and rainy) were assessed using ANOVA , with mean comparisons conducted using the Tukey test at a 5% probability level. The analyses used R, version 3.6.3 [48].

3. Results

3.1. Soil Total, Heterotrophic, and Root Respiration Responses

As they cover most of the rainfall, the monthly intervals from March to July 2019, January to June 2020, and November to May 2021 were considered the rainy season. While the intervals with little or no rain, from August to December 2019 and July to October 2020, were considered the dry season (Figure 3A).

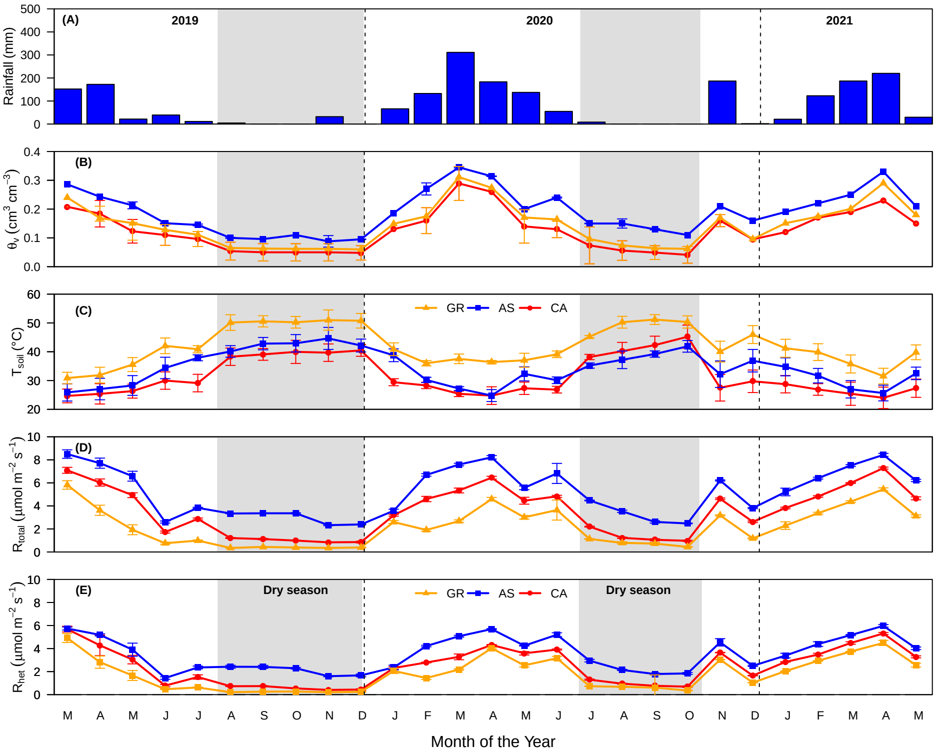

Figure 3. Dynamics of soil total (R_{total}) (**D**) and heterotrophic (R_{het}) (**E**) respirations, moisture (θ v) (**B**), and soil temperature (T_{soil}) (**C**) in grassland (GR), agroforests (AS), and native Caatinga vegetation (CA) systems in the semiarid region of Brazil. Subfigure (**A**) shows the average monthly rainfall in the region.

Soil moisture (θv), expressed at a 0-10 cm layer, followed this seasonal variation (Figure 3B), with almost parallel curves for the three land uses and higher contents in AS (mean of 0.19 cm^3 cm^{-3}), followed by the GR (0.15 cm^3 cm^{-3}) and CA (0.13 cm^3 cm^{-3}). The maximum value was 0.35 cm^3 cm^{-3} and the minimum 0.05 cm^3 cm^{-3}. Soil surface temperature (T_{soil}) also varied along the seasons (Figure 3C), but it was higher in the dry than in the rainy season, reaching a maximum of 52 °C and a minimum of 24 °C. On average, the temperature was higher in GR (42 °C) than in AS (34 °C) and CA (32 °C).

From November 2018 to February 2019, CO_2 fluxes from the deeper soil collars were consistently higher than those from the shallower collars. However, this effect was reversed in all areas based on soil respiration analyses that started in March 2019. This phenomenon could be attributed to the increase in heterotrophic respiration (R_{het}) due to the decomposition of recently cut root tissues in the soil. The seasonal variations in total soil respiration (R_{total}) followed those of the soil moisture content and were higher in the rainy than in the dry season (Figure 3D) and higher in AS (mean of 5.16 μmol CO_2 m^{-2} s^{-1}), followed by CA (3.55 μmol CO_2 m^{-2} s^{-1}) and GR (2.20 μmol CO_2 m^{-2} s^{-1}). The lowest and highest values in AS were 2.15 and 8.88 μmol CO_2 m^{-2} s^{-1}, while in CA they were 0.73 to 7.44 μmol CO_2 m^{-2} s^{-1}, and in GR 0.32 to 5.93 μmol CO_2 m^{-2} s^{-1}. Heterotrophic, that is, root-free soil respiration (R_{het}) matched very closely R_{total}, with values being from 4.4 to 54.9% lower (Figure 3E). On average, R_{het} was 3.48 μmol CO_2 m^{-2} s^{-1} in AS, 2.47 μmol CO_2 m^{-2} s^{-1} in CA, and 1.8 μmol CO_2 m^{-2} s^{-1}) in GR.

Autotrophic or root respiration (R_{root}), obtained by the difference between R_{total} and R_{het}, reflected their seasonal variations (Figure 4), being higher in AS (1.68 μmol CO_2 m^{-2} s^{-1}), followed by CA (1.10 μmol CO_2 m^{-2} s^{-1}) and GR (0.4 μmol CO_2 m^{-2} s^{-1}). However, the contributions of the roots (RC) to the total respiration had a slightly different pattern, being similar in CA and AS (global average of 33.2% and 32.9%, respectively) and both higher than in GR (22.3%).

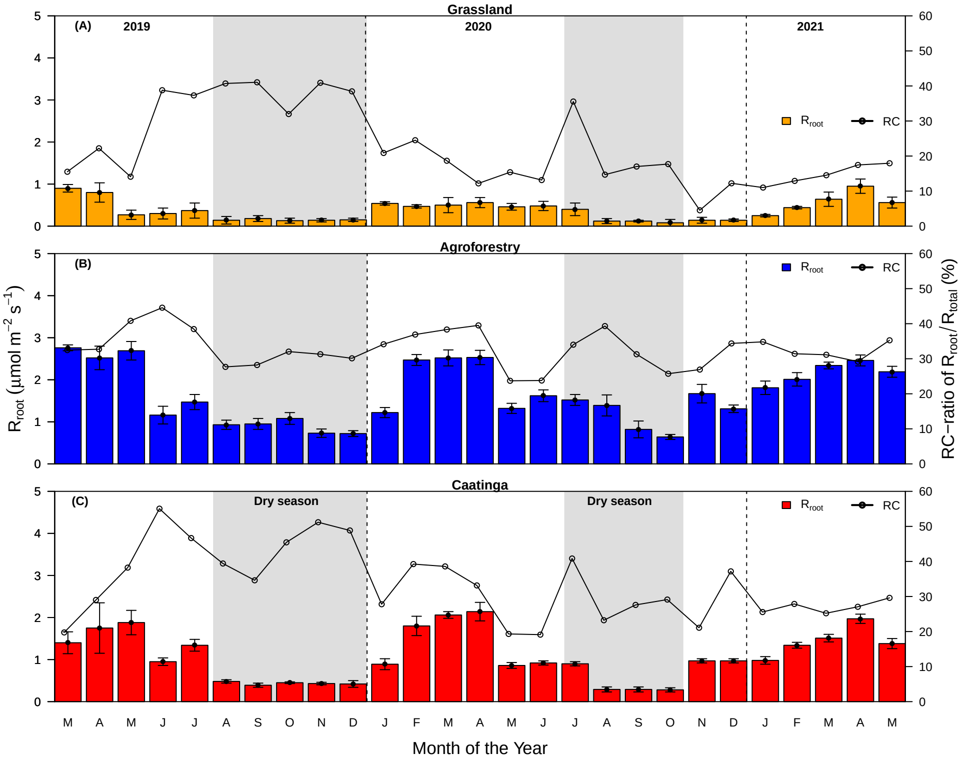

Figure 4. Seasonality of the root respiration rate (R_{root}) and its contribution to total soil respiration (RC) in grassland, agroforestry, and native Caatinga vegetation systems in the semiarid region of Brazil. Bars ± standard deviation represent R_{root}, while lines with points represent RC.

3.2. Soil Respiration and Moisture and Temperature Relationship

Soil moisture had a strong and positive correlation (mean $r > 0.80$, $p < 0.05$) with soil respiration in all the land uses (Table 2). The quadratic model (Equation (4)) fitted this relationship best between the total soil respiration (R_{total}) and its components (R_{het} and R_{hoot}), and θv was derived from the monthly measurements in each soil use (Figure 5).

All relationships were significant ($p < 0.01$), with R^2 values ranging from 0.74 to 0.86 in the three areas, except for R_{root} in grassland and agroforest ($p < 0.05$, with R^2 equal to 0.72 and 0.72). The peaks of soil respiration rates in CA were reached when the θv values were 0.265, 0.254, and 0.305 cm^3 cm^{-3} for R_{total}, R_{het}, and R_{root}, respectively, while in GR the peaks were reached with 0.323, 0.314, and 0.49 cm^3 cm^{-3}. In AS, the respiration rates increased to the highest soil moisture levels, not reaching maxima values (Figure 5).

Soil temperature showed a strong negative correlation with soil respiration across all land uses (mean $r = -0.89$; $p < 0.01$), contrasting with the relationship observed for soil moisture (Figure 6; Table 2). The negative exponential model best described this relationship, particularly for the agroforestry system (AS), which had higher R_{total} and R_{het} values than the grassland (GR).

AS also had the highest Q_{10} values, while the Caatinga (CA) had the lowest. In general, R_{root} was more responsive to changes in soil temperature (T_{soil}) than R_{het}, except for AS (Table 3).

In the dry season, respiration remained low and stable throughout the day despite variations in T_{soil} (Figure 7A–C).

Table 2. Pearson's correlation between annual total soil respiration (R_{total}), heterotrophic (R_{het}) and root respiration (R_{root}), volumetric soil moisture (θv), and surface temperature (T_{soil}) under three different land uses in the semiarid region of Pernambuco state, Brazil.

Respiration Types	Grassland		Agroforestry		Caatinga	
(μmol m^{-2} s^{-1})	θv (cm^3 cm^{-3})	T_{soil} (°C)	θv (cm^3 cm^{-3})	T_{soil} (°C)	θv (cm^3 cm^{-3})	T_{soil} (°C)
R_{total}	0.87 ***	−0.87 ***	0.93 ***	−0.95 ***	0.91 ***	−0.91 ***
R_{het}	0.86 ***	−0.85 ***	0.91 ***	−0.91 ***	0.86 ***	−0.87 ***
R_{root}	0.79 ***	−0.87 ***	0.89 ***	−0.93 ***	0.89 ***	−0.86 ***

*** correlation statistically significant to $p < 0.001$.

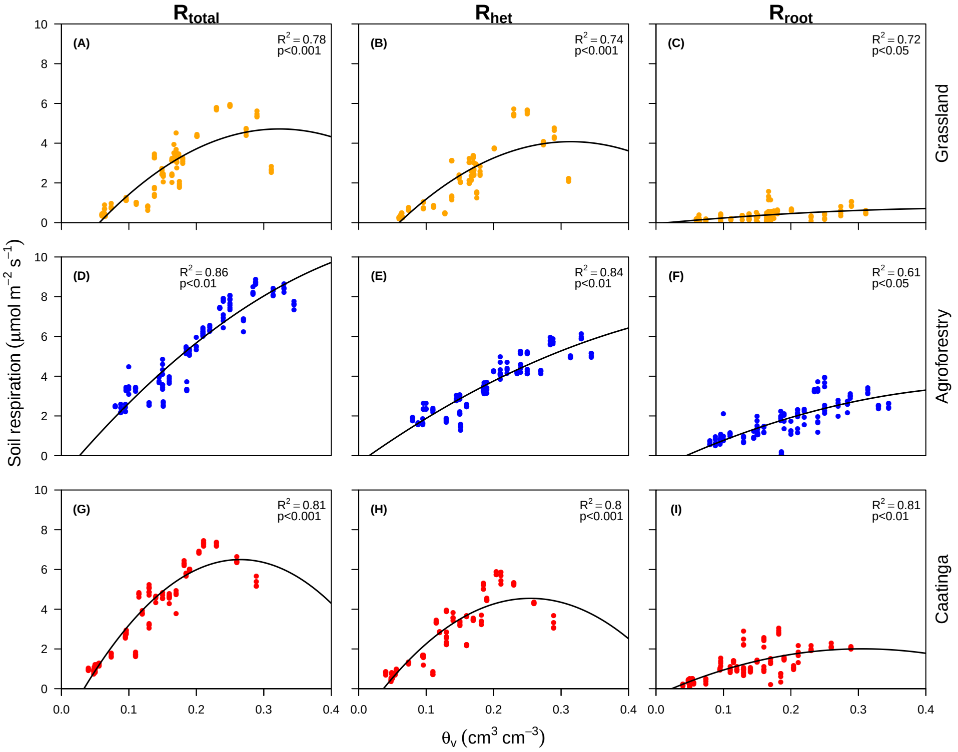

Figure 5. Quadratic relationships between soil respiration (R_{total}, R_{het}, and R_{root}) and soil moisture (θv) from March 2019 to May 2021 in grassland (GR), agroforestry (AS), and native Caatinga vegetation (CA) systems in the semiarid region of Brazil. Subfigures (**A**,**D**,**G**) illustrate the relationship between (θv) and (R_{total}, while subfigures (**B**,**E**,**H**), as well as (**C**,**F**,**I**), depict the relationships between (θv) and R_{het} and R_{root}), respectively.

Table 3. Fitted parameters of exponential models for the relationship between annual soil respiration (μmol CO_2 m^{-2} s^{-1}) and temperature (T_{soil}, °C) and Q_{10} values for the three different land uses in the semiarid region of Brazil.

Areas	Exponential Models (Equation (2))	R^2	Q_{10} (Equation (3))
Grassland	$R_{total} = 94.2 \times 10^{-0.094T_{soil}}$	0.76 ***	0.39
	$R_{het} = 93.7 \times 10^{-0.094T_{soil}}$	0.71 ***	0.37
	$R_{root} = 5.4 \times 10^{-0.070T_{soil}}$	0.31 **	0.49
Agroforestry	$R_{total} = 42.22 \times 10^{-0.063T_{soil}}$	0.94 ***	0.53
	$R_{het} = 22.6 \times 10^{-0.056T_{soil}}$	0.84 ***	0.57
	$R_{root} = 22.4 \times 10^{-0.078T_{soil}}$	0.75 ***	0.46
Caatinga	$R_{total} = 854.9 \times 10^{-0.195T_{soil}}$	0.92 ***	0.14
	$R_{het} = 851.7 \times 10^{-0.209T_{soil}}$	0.86 **	0.12
	$R_{root} = 101.86 \times 10^{-0.162T_{soil}}$	0.52 **	0.20

*** correlation statistically significant to $p < 0.001$, ** correlation statistically significant to $p < 0.01$.

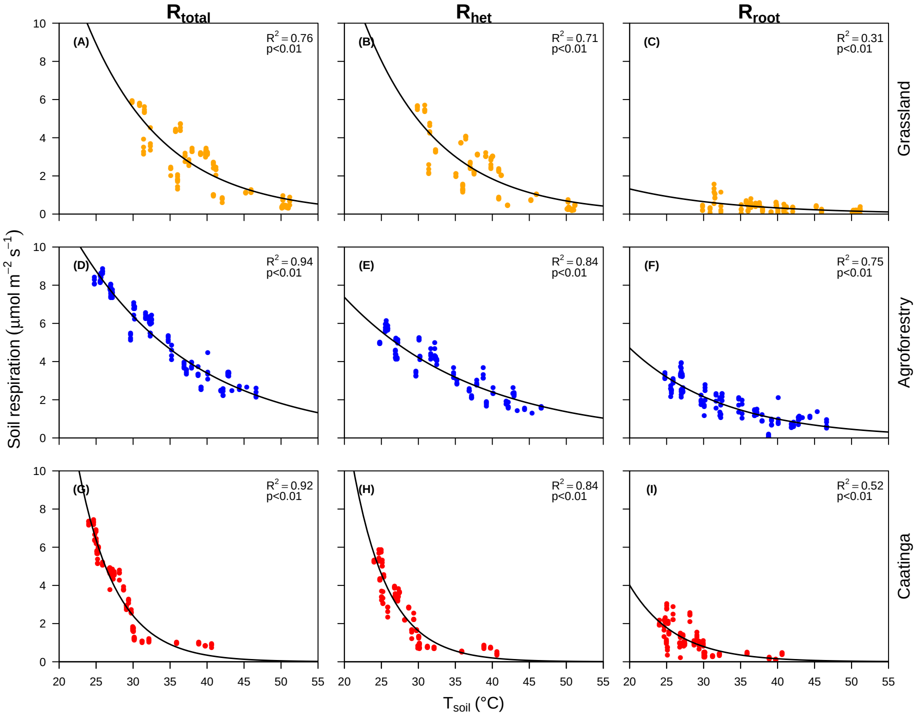

Figure 6. Relationship between total, heterotrophic, and root soil respirations (R_{total}, R_{het}, and R_{root}) and soil surface temperature (T_{soil}) from March 2019 to May 2021 in grassland (GR), agroforestry (AS), and native Caatinga vegetation (CA) systems in the semiarid region of Brazil. Subfigures (**A**,**D**,**G**) illustrate the relationship between (T_{soil}) and (R_{total}, while subfigures (**B**,**E**,**H**), as well as (**C**,**F**,**I**), depict the relationships between (T_{soil}) and R_{het} and R_{root}), respectively.

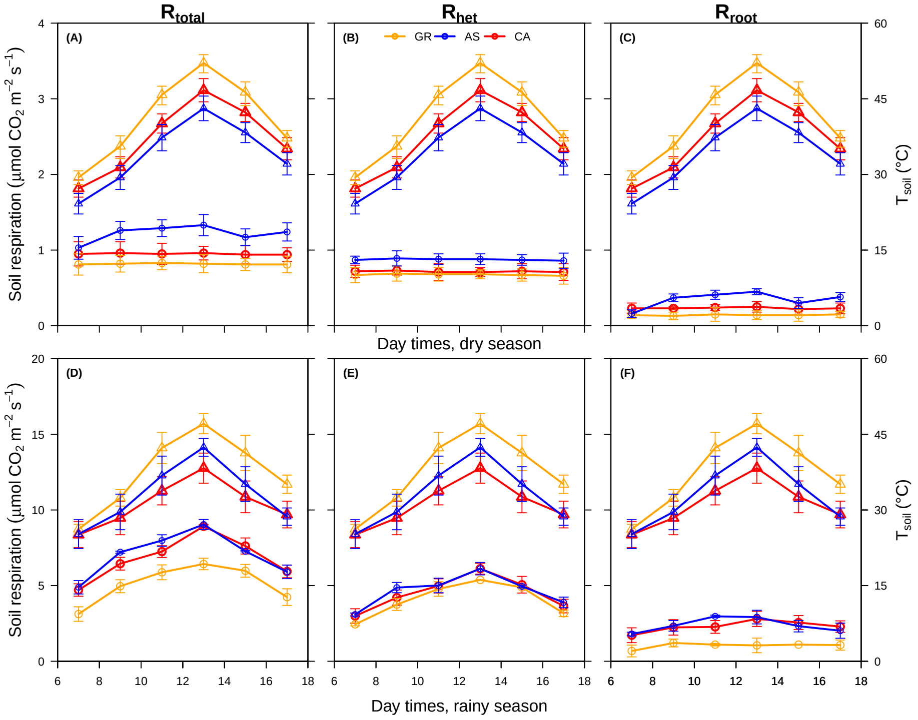

Figure 7. Diurnal variation in soil surface temperature and soil respiration (R_{total}, R_{het}, and R_{root}) from three different land uses (grassland, GR; agroforestry system, AS; and native Caatinga, CA) in the semiarid region of Brazil, during the dry (sugfigures **A**–**C**) and rainy seasons (subfigures **D**–**F**).

On the other hand, during the rainy season, respiration reached higher values, following the variation of T_{soil} throughout the day, reaching a peak at 1:00 p.m. (Figure 7D–F).

3.3. TOC and Microbiological Attributes

The AS had a slightly higher but not significantly different TOC than the CA, and both (the CA and AS) had higher contents than the GR in both rainy and dry seasons (Table 4). On average, the TOC in AS and CA was more than double that in GR (19.35 ± 3.03 and 19.23 ± 2.68 g kg^{-1} versus 7.92 ± 1.93 g kg^{-1}), and was 10 to 20% higher in the rainy than in the dry season.

Table 4. Total organic carbon (TOC), soil basal respiration (SBR), microbial biomass carbon (MBC), microbial quotient (qMic), and metabolic quotient (qCO$_2$) in the dry and rainy seasons, in areas under three different land uses in the semiarid region of Pernambuco state, Brazil.

Attributes	Layer (cm)	Grassland	Agroforestry	Caatinga
		Dry Season		
TOC (g C kg^{-1})	00–05	8.5 ± 2.11 bB	21.4 ± 2.89 aB	20.9 ± 2.51 aB
	05–10	7.8 ± 1.69 bB	18.6 ± 2.71 aB	17.7 ± 2.21 aB
	10–20	6.8 ± 1.21 bA	14.7 ± 2.80 aB	15.5 ± 2.09 aB
SBR (mg C-CO$_2$ kg^{-1} h^{-1})	00–05	0.21 ± 0.04 cB	0.52 ± 0.09 aB	0.42 ± 0.04 bB
	05–10	0.18 ± 0.02 cB	0.44 ± 0.11 aB	0.37 ± 0.06 bB
	10–20	0.14 ± 0.03 cA	0.38 ± 0.10 aB	0.32 ± 0.05 bB
MBC (mg C kg^{-1})	00–05	135 ± 3.41 cB	525 ± 1.30 aB	437 ± 1.50 bB
	05–10	126 ± 2.51 cB	498 ± 1.10 aB	407 ± 1.22 bB
	10–20	113 ± 2.60 cA	476 ± 1.41 aB	388 ± 1.40 bB
qMic (%)	00–05	1.58 ± 0.90 cA	2.45 ± 0.78 aA	2.12 ± 0.52 bB
	05–10	1.61 ± 0.79 cB	2.68 ± 0.41 aA	2.30 ± 0.83 bB
	10–20	1.59 ± 0.39 cB	3.03 ± 0.60 aA	2.51 ± 0.23 bB
qCO$_2$ (mg C-CO$_2$ g^{-1} C h^{-1})	00–05	1.55 ± 0.79 aB	0.99 ± 0.52 bB	0.96 ± 0.52 bB
	05–10	1.35 ± 0.80 aB	0.88 ± 0.47 bB	0.90 ± 0.47 bB
	10–20	1.24 ± 0.49 aB	0.79 ± 0.9 bB	0.82 ± 0.47 bB
		Rainy Season		
TOC (g C kg^{-1})	00–05	9.2 ± 2.78 bA	24.1 ± 3.40 aA	23.9 ± 3.19 aA
	05–10	8.9 ± 2.20 bA	20.4 ± 3.81 aA	19.8 ± 3.39 aA
	10–20	6.3 ± 1.62 bA	16.9 ± 2.61 aA	17.9 ± 2.70 aA
SBR (mg C-CO$_2$ kg^{-1} h^{-1})	00–05	0.29 ± 0.03 cA	0.67 ± 0.07 aA	0.61 ± 0.04 bA
	05–10	0.21 ± 0.03 cA	0.55 ± 0.09 aA	0.48 ± 0.04 bA
	10–20	0.16 ± 0.02 bA	0.46 ± 0.08 aA	0.45 ± 0.04 aA
MBC (mg C kg^{-1})	00–05	165 ± 2.33 cA	598 ± 3.12 aA	540 ± 2.92 bA
	05–10	145 ± 2.12 cA	547 ± 2.89 aA	512 ± 2.59 bA
	10–20	115 ± 1.80 cA	521 ± 2.72 aA	479 ± 1.91 bA
qMic (%)	00–05	1.58 ± 0.90 cA	1.79 ± 1.81 bB	2.48 ± 2.12 aA
	05–10	1.86 ± 1.62 bA	2.68 ± 2.22 aA	2.58 ± 0.90 aA
	10–20	1.83 ± 0.89 cA	3.08 ± 1.92 aA	2.67 ± 0.72 bA
qCO$_2$ (mg C-CO$_2$ g^{-1} C h^{-1})	00–05	1.76 ± 0.72 aA	1.12 ± 0.28 bA	1.13 ± 0.32 bA
	05–10	1.45 ± 0.69 aA	1.01 ± 0.34 bA	0.94 ± 0.26 bA
	10–20	1.40 ± 0.65 aA	0.88 ± 0.25 bA	0.94 ± 0.29 bA

Means (±standard deviation) followed by the same lowercase letter among areas and uppercase letter between seasons do not significantly differ using the Tukey test ($p < 0.05$).

TOC decreased with increasing soil depth, about one-third to one-quarter lower in the 10–20 cm layer than in the 0–5 cm layer. Similar patterns occurred with soil basal respiration (SBR) and microbial biomass carbon (MBC). However, the SBR was significantly higher in the agroforestry system (AS) compared with CA, and more than double that observed in the GR, in several soil layers. Furthermore, reductions in SBR with soil depth were generally more significant relative to total organic carbon (TOC) content (Table 4). MBC was consistently higher in AS than in CA and three to four times higher than in GR, while the decreases with increasing soil depth tended to be similar to those of TOC and, thus, proportionally lower than in SBR.

The microbial quotient (qMic) was also higher in AS and CA than in GR in most soil layers and seasons, although it averaged only about 50% higher values. The comparisons of AS and CA revealed differences related to the seasons (Table 4).

In the dry season, the quotient in AS was significantly higher than in CA in all soil layers, but the differences were not consistent in the rainy season. Also, contrary to the previously presented variables, qMic increased with increasing soil depth, with values up to 20% higher in the deeper than in the superficial layer.

The metabolic quotient (qCO_2) had the inverse pattern of the other variables regarding the land uses. It was higher in GR than in AS and CA, which did not significantly differ (Table 4). The quotient was also higher in the rainy than in the dry season and decreased slightly with increasing soil depth.

4. Discussion

4.1. Soil Respiration Response to Environmental Factors

Despite corresponding to winter and spring months, the dry season had higher soil surface temperature (T_{soil}) than the rainy season (Figure 3). This was probably due to the cloudless skies, the absence of the cooling effect of water loss from the dry soils, and slight differences in solar radiation throughout the year in this intertropical area. Similar results were reported by Marques et al. [49]. Lower temperatures in AS and CA, particularly during the rainy season, could be explained by their denser canopy, which decreases direct sunlight incidence. In contrast, the overgrazed grassland with many bare spots exposes the soil to direct sun radiation. Higher soil temperatures in grasslands compared with in the native Caatinga have been observed by several authors working in the Brazilian semiarid region [6,29,50,51].

The higher soil moisture (θv) in AS could be attributed to the sporadic watering to keep the system functional. The higher moisture in GR compared with in CA may be related to less evapotranspiration from grassland than from Caatinga. The canopy in CA could intercept more of the rain, which could evaporate before reaching the soil, but the larger vegetation structure could absorb and transpire more water than the sparse grassland. Lima et al. [29] also reported lower soil moisture in a Caatinga area than in a grassland, but Lopes et al. [52] found higher soil moisture content in an Atlantic Forest patch in Minas Gerais state than in a degraded grassland. The different patterns in Minas Gerais could be influenced by the higher rainfall, with a more uniform distribution throughout the year.

The R_{root}, R_{het}, and R_{root} were affected by changes in soil moisture (θv), soil surface temperature (T_{soil}), soil organic matter (OM), and land use changes. The high soil respiration rate detected in the AS and CA areas is related to the greater substrate availability (TOC), which is essential for soil microbial activity, in addition to a better physical structure, such as greater total porosity, lower density, and mechanical resistance to penetration, than GR. Total soil respiration in the AS remained above 2 μmol CO_2 m^{-2} s^{-1}, probably due to the influence of the sporadic watering during the longer dry spells to keep them productive. Although the soil under GR had slightly higher moisture throughout the experimental period than the CA, its respiration rate, SBR, and MBC were lower. This can be attributed to lower substrate availability than in the other systems. Das et al. [53] observed a positive relationship between soil respiration and organic carbon and microbial biomass carbon in forest ecosystems.

Notably, all evaluated areas had higher soil respiration during the rainy season. This shows how adequate soil water enhances microorganism activities, expressed by SBR and MBC. In the dry season, the lower respiration rates were conditioned by low soil moisture (θv), despite higher temperatures (T_{soil}) [29]. Studies have shown that the interaction between high temperature and low soil moisture reduces soil respiration, inhibiting microbial activity, restricting pore-water connectivity, and decreasing the solubility and mass transport of organic carbon, which constitutes a source of energy for heterotrophic microorganisms [6,20,54].

Root respiration (R_{root}) was higher in CA and AS (Figure 4), due to the greater diversity of plant species with higher canopy volumes and different root systems. R_{root} is directly related to the photosynthetic process and root growth [55,56]. In the rainy season, the highest value of R_{root} in the CA was 2.14 μmol CO_2 m^{-2} s^{-1}, and significantly decreased to 0.30 μmol CO_2 m^{-2} s^{-1} in the dry season, concomitant with the reduction in plant physiological activities and leaf fall to avoid water loss [29].

The contributions of the roots (RC) to the total respiration is a crucial variable and may comprise between 28 and 40% of the annual soil respiration in a forest [57]. The RC values found throughout the evaluation period for the CA and AS fell within this range (33.2% and 32.9%, respectively), but that of GR (22.7%) was lower. This low proportion may be due to the high soil compaction, expressed by its density and resistance to penetration, which hampers root growth. However, these RC values may be underestimated because some roots could grow below the 30 cm depth of the collar plate. Considering that the soils are shallow (about 40 cm deep) and most of the roots concentrate in the superficial layers, especially in GR, the underestimations may be relatively small. Feng et al. [58] reported that heterotrophic respiration in grassland ecosystems contributed to 72.8% of the annual respiration, resulting in a proportion of root respiration close to that found for GR. Jian et al. [25] concluded that the global contribution of root to total soil respiration represented 42%.

Soil respiration responded to the variation in θv in a quadratic manner (Figure 5), that is, R_{root}, R_{het}, and R_{root} increased with soil moisture up to an average of 0.275 cm^3 cm^{-3} in CA and 0.375 cm^3 cm^{-3} in GR, and then fell with the continuous increase in θv. This is due to low soil moisture impairing the photosynthetic process of plants and the soil microbiota activity, while high soil moisture reduces aerobic respiratory activity, which is responsible for most of the activity, and creates a physical impediment to the passage of CO_2 to the soil–atmosphere interface [20,54,59,60]. Efficient microbial activity and root respiration are maintained when soils are at their field capacity, i.e., when macropores are free of water and micropores are occupied with water [61,62]. Meena et al. [63] evaluated different land uses in a semiarid ecosystem in Delhi, India, and reported that soil moisture is the main controlling factor of soil respiration. In a semiarid environment and a grassland, Wei et al. [64] and Yang et al. [23] observed that soil respiration correlated positively with soil moisture, thus corroborating our results.

On the other hand, there was a negative correlation between T_{soil} and soil respiration in all systems (Figure 6; Table 2), i.e., increasing T_{soil} decreases the soil respiration rate. The increase in T_{soil}, due to high solar radiation during the dry season, attenuates the physiological processes of plants and inhibits microorganism activity, reducing their consumption of the available substrate and reducing soil respiration. Many studies conducted in semiarid environments [23,29,65,66] have described the negative correlation between soil temperature and respiration.

In all systems, the Q_{10} values were below one (1) (Table 3), probably due to the narrow annual temperature range in the region. Several works have shown that Q_{10} values are higher in temperate environments, with Q_{10} greater than 1, due to their wide temperature variations that often pass from negative to positive values [18,67]. Wang et al. [68] had already pointed out that Q_{10} tends to be higher in temperate than semiarid or arid environments, and Feng et al. [58] detected a decrease in Q_{10} due to an increase in soil temperature, corroborating the idea that Q_{10} tends to be higher in colder regions.

Except for AS, the greater Q_{10} values for R_{root} reflect the greater sensitivity of specific root respiration to soil temperature and the seasonal variation in root biomass, which is generally high with elevated temperature. Similar results, in which root respiration responded more strongly to increased temperature, have been reported by other studies [57,69].

Notably, the highest Q_{10} values were observed in AS, indicating that these systems are more sensitive to changes in soil temperature, which is confirmed by the high rate of R_{root} (1.68 μmol CO_2 m^{-2} s^{-1}) compared with the other systems (1.10 μmol CO_2 m^{-2} s^{-1} in CA and 0.4 μmol CO_2 m^{-2} s^{-1} in GR). Zhou et al. [57] pointed out that ecosystems with greater root respiration should be more sensitive to warming.

In the analysis of an isolated day of the dry period, it is noted that T_{soil} had little influence on R_{total}, R_{het}, and R_{root} throughout the day (Figure 7A–C) due to the reduction in microorganisms and the physiological activities of plants, some of which had entered dormancy. Researchers warn that the interaction of low humidity and high soil temperature can considerably reduce soil respiration. Several studies point to moisture as one of the main factors controlling soil respiration, especially in semiarid environments, where water is a limiting factor [29,30,65].

In the rainy season, the diurnal patterns of soil respiration were generally associated with the variation in T_{soil} in all three systems (Figure 7D–F). Under ideal humidity conditions, higher temperatures favor soil microorganism activity that feeds on organic compounds (SOM), thus increasing CO_2 efflux. Tang et al. [70] suggested that soil temperature catalyzes enzymatic activities to decompose organic compounds by the soil microbial community. Likewise, temperature can also impact plant biomass production, root activities, and litter and organic matter decomposition, leading to changes in substrate C availability for plant roots and soil microbes [11,71,72].

4.2. TOC and Microbiological Attributes

The higher TOC in AS, followed by CA (Table 4), may be associated with the higher vegetation biomass in these systems than in the grassland, thus leading to higher aboveground and root litter production, accumulation, and decomposition into soil organic matter, mainly during the rainy season. Removal of the grazed vegetation in the overstocked grassland further decreases litter accumulation [73]. Part of the plant production in AS is also removed for human and animal consumption, but the biomass accumulation may be compensated for by sporadic watering, the diversity of plant species, and the intense management in the system. Implementing agroforestry systems offers ecosystem services by capturing atmospheric carbon, being that C has a positive impact on soil structure and water retention, thus contributing to soil recovery [31,74].

The higher TOC in the rainy season compared with in the dry season (Table 4), in all areas, was probably the result of increased soil microbiota activity with the increased soil water content, decomposing part of the litter accumulated in the dry season with defoliation and root senescence after the rains of the previous rainy season stopped. Higher TOC in the superficial soil layers is a well-known occurrence, since the aboveground litter is deposited on the soil surface and most of that originating from the roots is concentrated in these first layers [75–77].

The higher MBC and MBC/TOC ratios (qMic) in the CA and AS systems compared with in GR reflect their higher TOC and nutrient supply [31,78] and probably the increased diversity of plant residues, which may favor the establishment of different microbe communities [79,80]. MBC values higher in the native vegetation than in grassland and in other human-altered environments have been found [81,82]. The qMic values, from 1.58 to 2.68%, agree with the range reported by Jenkinson and Ladd [83] and Lepcha [84]. Absence of difference from AS and native forests is a result similar to that found by Pezarico et al. [85], evaluating different land use systems.

They stated that the stability of these systems favors the availability of organic matter in quantity and quality, benefiting the development of the soil microbial community.

The higher soil basal respiration values (SBRs) observed in the AS system and native vegetation (CA) may be related to the greater substrate availability (OM and TOC) present in these areas, as well as more significant diversities and densities of microorganisms that act in the decomposition of these substrates.

The microbial quotient (qMic) has been considered a good indicator of alterations in soil processes. High qMic values in the AS and CA areas come from metabolic energy established by the diversity of microorganisms in these systems. In other words, it means better soil quality and greater efficiency of microbial communities in using soil organic matter [86,87]. Low values of qMic in the GR are related to a reduction in the capacity of microbial biomass to convert organic C into microbial tissues when under stress [88,89].

The high value of qCO_2 in the grassland may be related to inadequate system management and indicates that the area may be under stress or disturbance. It is believed that, in the grassland, there are more significant fluctuations in temperature due to the lack of trees and soil cover, which, in the rainy season, favor a rapid decomposition of organic matter by soil microorganisms. Overgrazing can also contribute to raising the metabolic quotient in the soil, since the high hoof pressure can destroy soil aggregates and expose organic matter, causing rapid mineralization and subsequent release of CO_2. The results found in this work indicate that the Caatinga (CA) and the agroforestry system (AS) are more stable environments for the soil microbial community than the grassland (GR).

5. Conclusions

The conversion of the Caatinga forest to various land uses significantly impacts soil and root respiration, and microbial activities in the semiarid region of Brazil. Our findings indicate that higher soil respiration rates occurred in the agroforestry system (AS) than in the grassland (GR), being similar to those of native dry forest (CA), particularly during the rainy season. Root contributions to total soil respiration were approximately one-third in AS and CA, but only one-fifth in GR. Soil respiration was positively correlated with volumetric soil moisture and negatively correlated with soil temperature. During the dry season, temperature had minimal influence on daily soil respiration patterns; however, in the rainy season, both temperature and soil moisture interacted to affect respiration rates. The Q_{10} values indicated that root respiration was more responsive to temperature increases, with AS showing greater sensitivity, and qCO_2 suggesting that GR was experiencing disturbance. Soil carbon storage was lower in GR than in native CA and AS, leading to reduced microbial activity, indicated by lower soil basal respiration and microbial biomass carbon. Thus, confirming our hypotheses, AS had a higher C dynamic than GR but the higher C loss by respiration was more than compensated for by the higher input of organic matter, resulting in higher soil C stocks. Therefore, substitution of the native dry forest by agroforests systems is a more sustainable option than substitution by grasslands. Where grasslands are maintained, better management techniques must be sought in order to increase organic matter inputs to the soil and to reduce soil C stock losses.

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