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Greenhouse gas emissions from cocoa production systems in the Atlantic Forest, southern Bahia, Brazil

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Abstract This study aimed to characterize greenhouse gas (GHG) fluxes in different cocoa production systems and correlate them with soil quality attributes in the Atlantic Forest biome. The research was conducted in the experimental area of the Executive Commission of the Cocoa Farming Plan (CEPLAC) in Ilhéus, Bahia, Brazil. The land-use systems analyzed were full-sun cocoa with Fabaceae cover crops (CFs); full-sun cocoa with *Urochloa decumbens* cover crops (CBs); full-sun cocoa with spontaneous vegetation cover (CVE); an agroforestry cocoa system of the *cabruca* type (SAFCAB); an agroforestry cocoa system with rubber trees (SAFSE); and a natural forest (FOREST). GHG flux monitoring was carried out twice in 2022 using the static chamber method. The chambers were constructed from plastic buckets, and the internal volume of each chamber was previously measured to enable the calculation of gas fluxes. Soil samples were collected at 0–0.10 m depth for the analysis of ammonium (NH_4^+), nitrate (NO_3^-), soil bulk density, soil moisture, and water-filled pore space (WFPS). Gas samples were collected using a manual vacuum sampling pump, and the gas was transferred to storage vials and subsequently transported to the laboratory, where GHG concentrations were determined by gas chromatography. Negative CH_4 fluxes were recorded in the CF, CVE, and SAFCAB systems during the high-rainfall period, with mean values of -4.08, -0.98, and -5.98 mg m^{-2} h^{-1}, respectively. The forest showed a positive flux of 6.50 mg m^{-2} h^{-1}. Regarding CO_2, SAFCAB and the forest presented the highest mean fluxes, 1.13 and 0.70 g m^{-2} h^{-1}. CVE showed the lowest value, 0.49 g m^{-2} h^{-1}. All cultivated systems emitted N_2. O into the atmosphere, with no evidence of gas uptake. Among the agroforestry systems, SAFSE presented the lowest GHG fluxes, while SAFCAB showed unexpectedly elevated CO_2 emissions attributed to litter accumulation and microclimatic conditions favorable to organic matter decomposition. These findings provide new insights into how cocoa management systems influence soil GHG dynamics

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and highlight the contrasting environmental profiles of different agroforestry arrangements in tropical cocoa landscapes.

Keywords Agroforestry systems · Full-sun cocoa · Land use · Carbon dioxide · Methane · Nitrous oxide

Introduction

The substantial increase in atmospheric concentrations of greenhouse gases (GHGs), particularly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), is primarily attributed to anthropogenic activities. Brazil ranks among the five largest global emitters of GHGs, with emissions predominantly associated with the agriculture and land-use change sectors, which constitute the principal sources of national emissions (IPCC 2023).Tropical agriculture plays a prominent role both as a source and as a potential sink of CO_2, depending on the management practices adopted (Abreu et al. 2024). Therefore, the characterization of emissions from different land-use systems is essential for the formulation of mitigation and adaptation strategies to address climate change (Cabezas-Andrade et al. 2024).

In this context, cocoa (*Theobroma cacao* L.) cultivation represents a relevant example concerning GHG emissions, particularly in tropical countries where production is mainly concentrated in the Amazon and Atlantic Forest biomes (Hernandes et al. 2022). Cocoa production models range from agroforestry systems (AFSs), which integrate shade trees and native species (Vervuurt et al. 2022; Lander et al. 2025), to more intensive monoculture systems, which may be associated with higher GHG fluxes and increased pressure on natural resources. In the southern Bahia region of Brazil, a traditional and culturally distinctive AFS known as the "cabruca" system involves planting cocoa trees beneath the thinned canopy of native Atlantic Forest trees, maintaining much of the original forest structure while enabling cocoa production—a practice that has shaped the region's landscape for over a century (Monroe et al. 2016).

Agroforestry systems tend to conserve carbon stocks in both biomass and soil while providing greater resilience to climate variability (Crespo et al. 2023). Studies have shown that cocoa-based AFS has the potential to reduce GHG emissions, increase soil carbon sequestration, and sustain stable yields over the long term (Vervuurt et al. 2022; Cabezas-Andrade et al. 2024).

Recent evaluations of cacao agroecosystems have shown that biodiversity-based systems, such as shaded and agroforestry cacao systems that integrate multiple plant species, significantly reduce CO_2, N_2O, and total GWP when compared with conventional full-sun management (Sterling et al. 2025).

In humid tropical regions, cocoa-based agroforestry systems (AFSs) can exhibit annual soil N_2O fluxes comparable to those of adjacent forests (Iddris et al. 2020). In Brazil, high N_2O emissions are often recorded following fertilization and rainfall events, reinforcing the importance of measuring water-filled pore space (WFPS) and mineral N in the sampling design (Nogueira et al. 2015). At the area scale, the trend is consistent: moderate shading in AFS reduces the GHG footprint without compromising profitability, which is in line with a more stable soil microclimate that helps mitigate N_2O peaks (Hawkins et al. 2024).

These benefits are associated with practices such as maintaining shade trees, properly managing crop residues, and ensuring permanent soil cover, all of which play crucial roles in soil conservation (Hernandes et al. 2022). Conversely, full-sun cocoa cultivation, while potentially achieving higher short-term yields, is often linked to the removal of native vegetation, residue burning, and intensive use of agricultural inputs, which contribute to greater GHG fluxes and soil carbon losses (Vervuurt et al. 2022).

In the Southern Bahia, within the Atlantic Forest biome, region of Northeast Brazil, there is still a lack of in situ studies assessing GHG emissions in the main cocoa production systems, such as AFS and full-sun cultivation (Meurer et al. 2016). However, edaphic variables such as soil organic carbon content, moisture, temperature, and nitrogen forms—directly influence the dynamics of these gas fluxes (Abreu et al. 2024).

Given the increasing global demand for cocoa and the need for sustainable production systems that combine agricultural efficiency, food security, and environmental conservation, deepening the understanding of these relationships becomes not only timely but also essential.

Therefore, this study was grounded in the hypothesis that cocoa agroforestry systems emit GHGs at

levels comparable to native forests and lower than those observed in full-sun cocoa cultivation systems. The objective of this study was to quantify CO_2, CH_4, and N_2O fluxes in cocoa production systems (agroforestry and full-sun cocoa) and in native Atlantic Forest, and to relate these fluxes to soil physical and chemical attributes.

Material and methods

The cocoa production systems evaluated are located within the experimental area of the Executive Commission of the Cocoa Farming Plan (CEPLAC), in the municipality of Ilhéus, Bahia, Brazil, at coordinates 14° 47′ 20″ S and 39° 02′ 56″ W, at an altitude of approximately 60–70 m above sea level. The regional climate is classified as Af according to Köppen and Geiger (1928), characterized as a hot and humid tropical rainforest. The annual precipitation exceeds 1300 mm and is distributed throughout the year, with an average temperature of 23 °C and a relative air humidity of 80%, according to data from the CEPLAC/CEPEC/SERAM Meteorological Station.

The soil in the study area is classified as Eutrophic Haplic Nitisol (saprolitic), with a slope of less than 5% (Santos et al. 2025). At the beginning of the study, soil samples were collected from the 0–0.10 m layer to determine the physical and chemical attributes of the soil, following the methodology described by Teixeira et al. (2017) (Table 1).

Sampling was conducted in March and August 2022, representing the wet and dry seasons, respectively, which characterize the contrasting climatic conditions for the year 2022. Figure 1 illustrates the precipitation distribution throughout 2022. March was the second wettest month (252.1 mm), while August was the second driest (65.5 mm), making them adequate representatives of the seasonal extremes. In March, temperatures ranged from 20.4 °C to 29.5 °C, with an average of 24.1 °C. In August, temperatures varied between 17.6 °C and 27.3 °C, with an average of 21.9 °C (Fig. 1).

Six cocoa production systems and one fragment of Atlantic Forest were evaluated, as detailed in Table 2.

The experimental design was completely randomized, with four replicates for the CB, CF, CVE, SAFCAB, and SAFSE treatments. Each treatment was established in a single continuous area, within which four sampling subplots were distributed. One static chamber was installed per subplot, totaling 24 chambers across all cultivated systems. In the FOREST area, four chambers were randomly distributed across the accessible area of the fragment, following the same sampling protocol as the cultivated systems. The study was conducted within a single year, covering both the wet and dry seasons. The forest area (FOREST) was used as a natural reference.

Greenhouse gas (GHG) fluxes were measured via the static chamber method, which consists of a fixed base inserted into the soil (up to a depth of 0.10 m) and a movable lid, both made of polyvinyl chloride (PVC), measuring 0.30 m in diameter and 0.25 m in

Table 1 Chemical and physical attributes of the Eutrophic Haplic Nitisol in the studied cocoa production systems in the 0–0.10 m soil layer

	pH	P	K	S	Ca	Mg	OM	Clay	Sand	Silt	Bd
		mg dm^{-3}		cmolc dm^{-3}			g dm^{-3}	g kg^{-1}			g cm^{-3}
CF	6.0	53.3	64.3	15	7.7	2.4	3.6	300	631	69	1.07
CB	6.0	48.3	132.6	14	7.4	2.5	3.1	290	613	97	1.03
CVE	6.0	42.3	72.0	12	7.8	2.6	3.2	265	628	107	1.04
SAFCAB	5.9	44.6	43.6	13	7.7	2.2	3.7	295	635	70	1.23
SAFSE	5.4	70.0	84.0	14	9.6	2.8	2.3	255	675	70	1.39
FOREST	5.8	27.1	63.8	14	7.8	2.3	3.6	130	827	43	1.20

where CF—full-sun cocoa cultivation with Fabaceae cover crops; CB—full-sun cocoa cultivation with *Brachiaria* cover crops; CVE—full-sun cocoa cultivation with spontaneous vegetation cover; SAFCAB—*Cabruca*-type agroforestry cocoa system; SAFSE—agroforestry cocoa system with rubber trees; and FOREST—fragment of forest under regeneration. The abbreviations are as follows: P, phosphorus; K, potassium; S, sulfur; Ca, calcium; Mg, magnesium; pH, soil pH in water; OM, organic matter; and Bd, bulk density

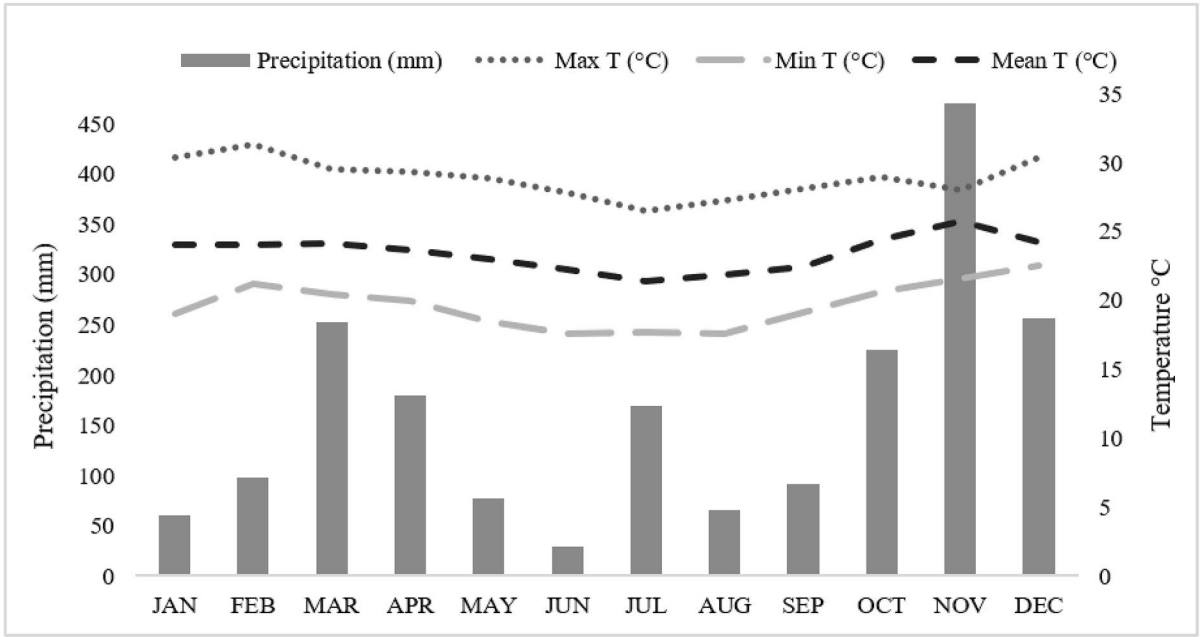

Fig. 1 Monthly precipitation and maximum, mean, and minimum temperatures for the year 2022. Source: CEPLAC/CEPEC/SERAM Meteorological Station. (14° 47′ 20″ S and 39° 02′ 56″ W altitude of approximately 60–70 m)

height, similar to that described by Hutchinson and Mosier (1981). Holes were made in the lids to allow gas sampling via syringes (Mascarenhas et al. 2020). In each system, one chamber was installed per replication, totaling 24 chambers, to monitor GHG fluxes.

Similar static-chamber configurations have been successfully applied in cacao agroecosystems in tropical islands and humid forests (Sterling et al. 2025).

The chamber bases were installed 24 h prior to the first sampling. Chambers remained in the same position throughout the gas collection period, following the procedures described by Nascimento et al. (2020). The chambers were installed along the cocoa tree rows, whereas they were placed randomly in the forest. Before each sampling, the internal volumes of the chambers were verified to ensure uniformity across all the chambers (Steudler et al. 1989; Alves et al. 2017).

Greenhouse gas (GHG) samples were collected in 2022 during two distinct periods: March 14–25 (high rainfall) and August 01–12 (low rainfall) (Nogueira et al. 2015). Gas collection was performed in the morning between 7:00 and 10:00 a.m. every three days, totaling fifteen sampling days per period. No nitrogen fertilizer was applied to any of the systems during the study period. The sampling times were 0, 30, and 60 min after chamber closure, according to Alves et al. (2017), and the chamber linearity was verified.

The concentrations of carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) in the collected samples were determined via gas chromatography (Shimadzu GC-2014) at the Laboratory of Agri-environmental Analyses of Embrapa Rice and Beans. A flame ionization detector (FID) was used for CO_2 and CH_4, and an electron capture detector (ECD) was used for N_2O.

Rainfall and mean air temperature data were obtained from the CEPLAC/CEPEC/SERAM Meteorological Station (14° 47′ 20″ S, 39° 02′ 56″ W), which is located less than one kilometer from the experimental area. In addition, the air temperature (inside and outside each chamber) and soil temperature at a depth of 0.05 m were measured at each of the three sampling times (0, 30, and 60 min) via a portable digital thermometer (Incoterm®).

Soil samples were collected from the 0–0.10 m soil layer to determine soil moisture, ammonium (NH_4^+) and nitrate (NO_3^-) concentrations, pH, bulk density, gravimetric and volumetric moisture, and water-filled

Table 2 Description of cocoa production systems and forest in the Atlantic Forest biome evaluated, Southern Bahia, Brazil

Production system (treatments)	Description and system history
Full-sun cocoa with Brachiaria (*U. decumbens*) cover crops (CB)	Cocoa trees (clone CEPEC 2002) established in 2020 under full sun (1.5 × 4 m spacing) and propagated by cuttings. The soil was prepared by subsoiling to a depth of 0.5 m and received phosphate fertilization at a rate of 144 kg ha^{-1} of P_2O_5. Ground cover with *U. decumbens* was established eight months after cocoa planting and managed by bimonthly mowing
Full-sun cocoa with Fabaceae cover crops (CF)	Cocoa trees (clone CEPEC 2002) grown under full sun in 2020 (1.5 × 4 m spacing), propagated by cuttings. Successive use of *Crotalaria breviflora*, *Cajanus cajan*, and *Arachis pintoi* (2022–present). The soil was prepared by subsoiling and received 144 kg ha^{-1} of P_2O_5 as phosphate fertilization. Ground cover was managed through periodic mowing
Full-sun cocoa with spontaneous vegetation cover (CVE)	Cocoa trees (clone CEPEC 2002) established in 2020 (1.5 × 4 m spacing), with native spontaneous ground cover. The soil was prepared by subsoiling and received 144 kg ha^{-1} of P_2O_5 as phosphate fertilization. Bimonthly mowing was carried out to maintain vegetation. Common species include *Panicum maximum*, *Bidens pilosa*, and *Commelina benghalensis*
Cabruca-type agroforestry cocoa system (SAFCAB)	Cocoa trees (clone CEPEC 2002) established under the Atlantic Forest canopy in 1985 (3 × 3 m spacing; 1111 plants ha^{-1}), with approximately 40 native trees per hectare. No management has been conducted over the past 10 years
Agroforestry cocoa system with rubber trees (SAFSE)	The system was established more than 30 years ago. Rubber trees are arranged in double rows spaced 3.0 × 2.5 m apart, with 15 m between double rows, resulting in a density of 400 trees per hectare. Cocoa trees are planted in quadruple rows between the double rows of rubber trees, with 3.0 × 3.0 m spacing (780 cocoa trees ha^{-1})
Forest (FOREST)	Fragment of Atlantic Forest under natural regeneration for more than 40 years, without anthropogenic intervention, and adjacent to the cultivated systems

pore space (WFPS). In each subplot, three soil samples were collected adjacent to the chamber base and pooled into a single composite sample per replicate for NH_4^+ and NO_3^- analyses. For bulk density and gravimetric moisture, one undisturbed core sample per replicate was collected using volumetric rings. Samples intended for NH_4^+ and NO_3^- analyses were stored at −20 °C and transported to the laboratory in insulated boxes with ice. Ammonium and nitrate were extracted using a 1 mol L^{-1} potassium chloride (KCl) solution, following the procedure described by Teixeira et al. (2017), and subsequently quantified by UV–Vis spectrophotometry coupled with a flow injection analysis system (FIALAB 2500) at the Agroenvironmental Analysis Laboratory of Embrapa Rice and Beans.

Soil bulk density and gravimetric moisture (105 °C) were determined via the volumetric ring method (Teixeira et al. 2017). The water-filled pore space (WFPS) was calculated from gravimetric moisture (θg) and bulk density (Bd) according to Eq. (1), described by Paul and Clark (1996):

$$WFPS\% = \frac{(Us * Bd)}{(1 - (Bd/Pd)} \quad (1)$$

where Us is the gravimetric soil moisture (%), Bd is the soil bulk density (g cm^{-3}), and Pd is the particle density of the soil 2,65 (g cm^{-3}).

Nitrous oxide (N_2O) fluxes were calculated via linear regression. When fluxes were underestimated by the linear model, the function proposed by Hutchinson and Mosier (1981) was applied as follows:

$$Fc = \frac{\left(C_1 - C_0\right)^2}{t_1\left(2C_1 - C_2 - C_0\right)} x \ln \frac{\left(C_1 - C_0\right)}{\left(C_2 - C_1\right)} \quad (2)$$

where Fc is the GHG flux (nL L^{-1} h^{-1} for N_2O and µL L^{-1} h^{-1} for CO_2 and CH_4); C_0, C_1, and C_2 are the concentrations of N_2O (ppbv) and CO_2 or CH_4 (ppmv) measured at 0, 30, and 60 min, respectively; and t_1 is the time interval between measurements.

The calculated fluxes were then converted into mass units via the universal gas law equation, and the mean value from all chambers was considered the daily measurement for comparison, expressed as ng m^{-2} s^{-1} of $N–N_2O$ or µg m^{-2} s^{-1} of $C–CO_2$ and $C–CH_4$. All the data were tested for normality (Shapiro–Wilk) and homogeneity of variance (Levene) before being subjected to analysis of variance (ANOVA). When statistical significance was detected, Tukey's test ($p \leq 0.05$) was applied for mean comparison. Pearson's correlation analysis was also performed, considering the associated significance level. The classification of correlation coefficients (r) followed the criteria proposed by Mukaka (2012): insignificant (0.00–0.30), low (0.31–0.50), moderate (0.51–0.70), high (0.71–0.90), and very high (0.91–1.00).

Results and discussion

Soil temperature and water-filled pore space (WFPS)

The soil temperature varied across the evaluated periods characterized by high and low rainfall, although the interaction effect between the studied systems and the two seasons was not significant. In all systems, soil temperature was higher during the high-rainfall period, as shown in Table 3. Favorable soil temperature contributes to proper root respiration and accelerates the decomposition of soil organic matter, increasing microbial activity and consequently increasing CO_2 diffusion (Carey et al. 2016; Voigt et al. 2017). According to Kellman et al. (2015), Lu et al. (2019), and Wang et al. (2019), temperature is the main factor influencing the production and fluxes of soil GHGs. These patterns agree with results from cacao systems in Central Africa, where CO_2 fluxes closely followed variations in rainfall, soil moisture, and temperature**,** increasing during wetter periods (Sterling et al. 2025).

The WFPS varied among the studied systems, ranging from 61% to 59.67% in the full-sun cultivation systems (CF, CB, and CVE), whereas the SAFSE system presented the lowest WFPS value (46.23%). The SAFCAB and FOREST systems did not differ significantly from each other (Table 3). The higher WFPS values in the full-sun systems indicate a greater proportion of soil pore space occupied by water, whereas the lower WFPS observed in SAFSE suggests a smaller fraction of water-filled pores (Fig. 2A) (Oertel et al. 2016).

Table 3 Soil temperature and moisture in cocoa cultivation systems in the 0–0.10 m soil layer

Soil management system	WFPS (%)		Soil temperature (°C)	
	High rainfall	Low rainfall	High rainfall	Low rainfall
CF	61.70 AB	57.63A	28.53 A	24.45 A
CB	63.37 A	58.97A	28.53 A	24.45 A
CVE	62.97A	58.87A	28.53 A	24.45 A
SAFSE	48.52 D	43.93C	27.30 AB	25.55 AB
SAFCAB	54.03C	53.46B	25.66 B	23.70 B
FOREST	54.17BC	52.32B	25.49 B	22.20 B
Mean soil temperature			27.34 a	24.13 b

where: CF—Full-sun cocoa cultivation with Fabaceae cover crops; CB—Full-sun cocoa cultivation with Brachiaria cover crops; CVE—Full-sun cocoa cultivation with spontaneous vegetation cover; SAFSE—Agroforestry cocoa system with rubber trees; SAFCAB—*Cabruca*–type agroforestry cocoa system; FOREST—Fragment of native forest. Means followed by the same uppercase letters in the same column do not differ significantly from each other. Means followed by different lowercase letters in the row indicate significant differences according to Tukey's test ($p \leq 0.05$)

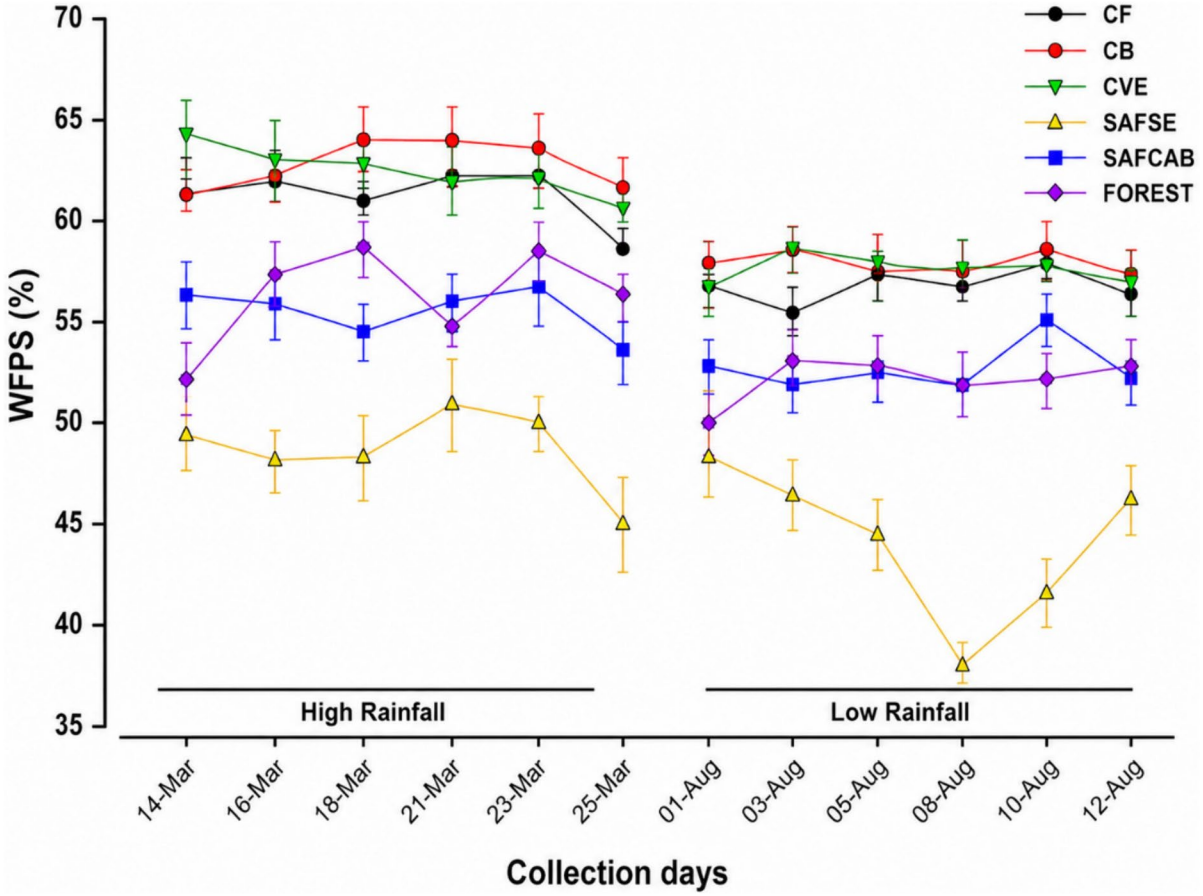

Fig. 2 Water-filled pore space (WFPS) in cocoa cultivation systems during the two GHG sampling periods in Ilhéus, Bahia, Brazil. where: CF—Full-sun cocoa cultivation with Fabaceae cover crops; CB—Full-sun cocoa cultivation with Brachiaria cover crops; CVE—Full-sun cocoa cultivation with spontaneous vegetation cover; SAFSE—Agroforestry cocoa system with rubber trees; SAFCAB—Cabruca-type agroforestry cocoa system; FOREST—Fragment of forest under regeneration

During the high-rainfall period, soil WFPS values were generally higher across all systems. In contrast, during the low-rainfall period, a declining trend in soil moisture was observed, with some variation depending on the cultivation system (Fig. 2). Compared with the SAFSE, SAFCAB, and FOREST systems, the CF, CB, and CVE systems presented WFPS values above 55%, indicating greater water retention in these environments, which is consistent with the mulching effect of cover crops in reducing evaporation (Iamaguti et al. 2015; Silva-Olaya et al. 2013). Regarding soil temperature, the lower values observed in SAFCAB, SAFSE, and FOREST systems in relation to full-sun systems (Table 3) reflect the role of canopy shading in intercepting solar radiation and moderating soil surface temperatures (Niether et al. 2017).

In full-sun cocoa systems with cover crops (CF, CB, and CVE), higher WFPS values were recorded in both evaluated periods, whereas the highest CO_2 emissions were observed in the SAFCAB system. Similar results have also been observed in shaded cocoa systems in other tropical regions (Sterling et al. 2025). In these environments, the greater input of leaf litter and the more humid microclimate create ideal conditions for microbial activity, which increases soil respiration. As a result, CO_2 fluxes can reach levels as high as –or even higher than– those recorded in full-sun systems (Sterling et al. 2025). It should be noted that litter biomass was not quantified in the present

study, which represents a limitation in the mechanistic interpretation of CO_2 dynamics; future studies should integrate litter mass and above-ground biomass measurements to improve understanding of substrate-driven respiration differences among systems (Morales-Belpaire et al. 2025).

This condition can be attributed to the presence of cover plants and mowing management, which promote straw accumulation and reduce water loss through evaporation (Iamaguti et al. 2015; Silva-Olaya et al. 2013). In contrast, in the agroforestry systems (SAFCAB and SAFSE) and in the forest, the higher density of mature trees—averaging 40 years old—implies greater water demand, which may explain the lower soil moisture observed, even under shaded conditions (Abdulai et al. 2018; Hawkins et al. 2024).

Greenhouse gas fluxes

CO_2 fluxes in the studied systems during both low- and high-rainfall periods averaged 0.38 g C–CO_2 m^{-2} h^{-1} in SAFSE and 1.13 g C–CO_2 m^{-2} h^{-1} in SAFCAB. The full-sun systems presented mean values of 0.49, 0.55, and 0.68 g C–CO_2 m^{-2} h^{-1} for CF, CB, and CVE, respectively (Figs. 3A and B).

When the two evaluated periods were compared, the mean CO_2 flux during the high-rainfall season was greater and significantly different from that observed during the low-rainfall season in the CVE and FOREST systems. This pattern is consistent with the combined role of temperature and soil moisture as primary regulators of soil respiration (Table 3) (Oertel et al. 2016; Carey et al. 2016; Wang et al. 2019).

During the high-rainfall period, the mean CO_2 flux in the SAFCAB system was greater and significantly different from those in the CF and SAFSE systems, which is consistent with the greater litter input and carbon stocks in shaded cocoa systems, increasing the availability of respirable substrates (Monroe et al. 2016; Gama-Rodrigues et al. 2011; Fonkeng et al. 2024).

A similar trend was observed during the low-rainfall period for the same systems (Fig. 3B), indicating that although temperature sensitivity is an important driver, water limitation modulates the overall response of CO_2 fluxes (Carey et al. 2016; Oertel et al. 2016).

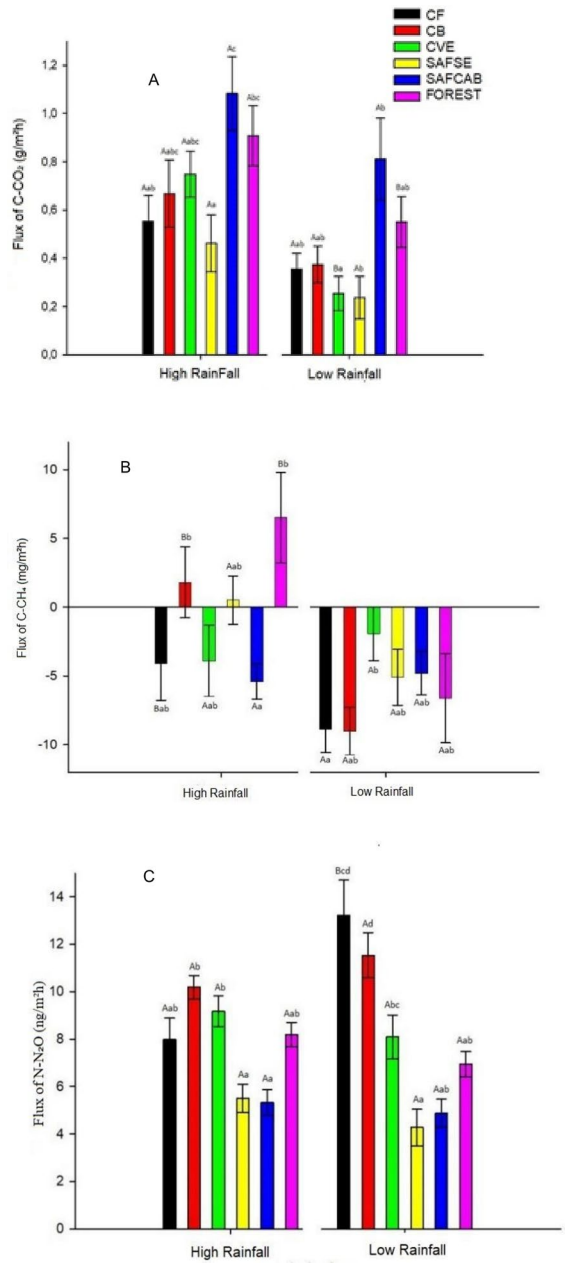

Fig. 3 Daily fluxes of C–CO_2 (g m^{-2} h^{-1}) (**A**) Mean CO_2 fluxes, (**B**) CH_4 fluxes, and (**C**) N_2O fluxes for the different land-use systems across both seasons. The seasonal means followed by the same uppercase letters did not differ significantly within the same land-use system according to Tukey's test ($p \leq 0.05$). The means of the land-use systems followed by the same lowercase letters did not differ significantly according to Tukey's test ($p \leq 0.05$)

The variations in CO_2 fluxes among the evaluated systems may be related to soil respiration and microbial activity, which are directly influenced by land-use characteristics, management practices, and climatic seasonality (Silva-Olaya et al. 2013; Oertel et al. 2016).

In addition to the observed results, other studies have shown that soil cover and agroforestry systems can influence GHG emissions. Schembergue et al. (2017) reported that agroforestry systems (AFSs) with greater tree structure and biomass accumulation present greater carbon storage potential and contribute to mitigating GHG emissions.

Agricultural systems with vegetation cover and crop rotation tend to emit less CO_2 and N_2O due to enhanced carbon cycling and soil carbon retention (Abreu et al. 2024). Furthermore, Siqueira-Neto et al. (2011) demonstrated that variations in soil moisture resulting from different types of land cover and use are strongly correlated with CO_2, CH_4, and N_2O fluxes in Cerrado ecosystems.

In both evaluated periods, the highest CO_2 emissions were observed in the SAFCAB system (Fig. 3A). In the Cabruca system, cocoa trees were planted beneath the forest canopy, creating an environment similar to that of forest systems. Low CO_2 emissions were expected in this system due to the presence of native vegetation, which can increase carbon sequestration.

However, the results indicated a more complex interaction between cultivation practices and CO_2 fluxes. In this system, the combination of high soil moisture, favorable temperatures, and accumulated plant residues may have intensified microbial activity and accelerated organic matter decomposition, thereby increasing CO_2 fluxes (Oertel et al. 2016; Carey et al. 2016).

In cocoa agroforestry systems, there is evidence of higher carbon stocks and fractions, as well as greater litter accumulation, which increases the amount of respirable substrate (Monroe et al. 2016; Gama-Rodrigues et al. 2011; Fonkeng et al. 2024). Moreover, studies on AFSs in Brazil indicate that GHG balance and CO_2 fluxes reflect the effects of management practices and the microclimate generated by the canopy, which can result in soil emissions of similar magnitude to those of full-sun systems when soil moisture and substrate availability are high (Torres et al. 2017; Crespo et al. 2023).

In full-sun systems with cover crops, temporary increases in CO_2 fluxes following wetting events and under elevated temperatures are common, with values ranging from tens to hundreds of mg $C–CO_2$ m^{-2} h^{-1} and approaching 1 g $C–CO_2$ m^{-2} h^{-1} under favorable conditions (Silva-Olaya et al. 2013; Iamaguti et al. 2015; Oertel et al. 2016).

The daily CH_4 fluxes ranged from −39.76 to 63.36 mg m^{-2} h^{-1} during the evaluation period. In the low-rainfall season, daily CH_4 fluxes ranged from −30.074 to −20.807 mg m^{-2} h^{-1}, whereas in the high-rainfall season, they ranged from −36.144 to 63.36 mg m^{-2} h^{-1} (Fig. 3B). It is well established that methanogenesis occurs under strictly anaerobic conditions; in environments with greater water accumulation and limited O_2 diffusion, anoxic microsites are formed, favoring CH_4 production (Le Mer and Roger 2001; Oertel et al. 2016). During the high-rainfall period, the CH_4 emissions observed in the CB, SAFSE, and FOREST systems are consistent with this mechanism and with the role of saturated or waterlogged soils in enhancing methanogenesis (Silva et al. 2011; Oertel et al. 2016).

In contrast, in the full-sun systems and the SAFCAB system, CH_4 influxes were observed, characterizing them as CH_4 sinks—typical behavior of well-aerated soils, where methanotrophic oxidation predominates (Le Mer and Roger 2001; Oertel et al. 2016; Zanatta et al. 2010). During the low-rainfall period, all systems exhibited CH_4 uptake, suggesting a strong reduction in methanogenesis and a predominance of CH_4 consumption under relatively low soil moisture (Siqueira-Neto et al. 2011; Nogueira et al. 2015; Oertel et al. 2016).

During the high-rainfall period, the SAFSE, CB, and FOREST systems emitted more methane than the other systems. For CB, the higher emission may be associated with its higher WFPS (61%) (Table 3), which indicates reduced oxygen availability, particularly within the soil aggregates. Soils with high moisture levels are more favorable to methanogenesis. The positive CH_4 flux recorded in FOREST during the high-rainfall period is noteworthy; although forest soils are generally expected to act as CH_4 sinks, the accumulation of decomposing litter and fine root activity under high moisture conditions can create localized anaerobic microsites that favor methanogenesis even in well-structured soils (Le Mer and Roger 2001; Silva et al. 2011). However, even in

predominantly aerated soils, localized methanogenesis may occur within anaerobic microsites, especially under certain agricultural management practices and in the presence of abundant organic residues (Le Mer and Roger 2001). This condition may explain the higher methane emissions observed in SAFSE, despite their lower WFPS values (48.52% during the high-precipitation period and 43.93% during the low-precipitation period). Small microsites with low redox potential can still sustain methanogenic activity (Le Mer and Roger 2001; Oertel et al. 2016; Paul and Clark 1996; Cardoso and Andreote 2016).

In terms of evidence, positive CH_4 emissions under flooded or saturated conditions are widely reported in tropical soils (Silva et al. 2011) and in poorly drained soils such as gleysols, where both emissions and uptake occur depending on moisture and management conditions (Zanatta et al. 2010). In contrast, well-drained soils of the Cerrado and Amazon regions typically exhibit negative CH_4 fluxes (uptake), particularly during low-rainfall periods (Siqueira-Neto et al. 2011; Nogueira et al. 2015), corroborating the interpretation that, during the dry season, all systems tended to act as methane sinks.

CH_4 influx is associated with the activity of methanotrophic bacterial communities, which use CH_4 as their sole source of carbon and energy (Cardoso and Andreote 2016). During this process, methane is partially oxidized, generating organic intermediates such as methanol or acetate, which may subsequently be involved in denitrification reactions that produce CO_2 and N_2O.

Specifically, CH_4 production was negatively correlated with WFPS (Table 4), since methanogenesis requires strictly anaerobic conditions and is generally promoted by high soil moisture and organic residue accumulation at the surface. However, even in oxygen-rich environments such as well-aerated soils, anaerobic microsites can occur that locally favor CH_4 production, as reported by Silva et al. (2011) in irrigated rice systems. Conversely, under predominantly aerobic conditions, soils tend to function as methane sinks due to CH_4 oxidation by methanotrophic bacteria—recognized as a key mitigation mechanism for CH_4 emissions (Le Mer and Roger 2001).

The daily N_2O fluxes ranged from 0.584 to 27.838 ng $N–N_2O$ m^{-2} h^{-1}, with an overall mean of 4.886 ± 10.856 ng m^{-2} h^{-1}, regardless of the cocoa cultivation system (Fig. 3C). The mean fluxes by system, in decreasing order, were CB = 10.856 > CF = 10.473 > CVE = 8.630 > FOREST = 7.562 > SAFCAB = 5.102 > SAFSE = 4.886 ng m^{-2} h^{-1}. During the low-rainfall period, the CF system showed the

Table 4 Pearson correlation between greenhouse gas (GHG) fluxes and soil attributes at the 0–0.10 m depth

	CH_4	CO_2	N_2O	Bd	Us	WFPS	Clay	Silt	Sand	NH_4^+	NO_3^-	NH_3
CO_2	0.01	1										
N_2O	−0.01	0.18*	1									
Bd	0.13*	−0.04	−0.09	1								
Us	−0.05	−0.02	0.23*	−0.38*	1							
WFPS	0.13*	0.04	0.09	−1.00*	0.38*	1						
Clay	−0.13	−0.01	0.28*	−0.25*	0.14*	0.250	1					
Silt	−0.06	−0.06	0.07*	−0.9*	0.47*	0.294	0.47*	1				
Sand	0.15*	0.08	−0.22*	0.17*	−0.20*	−0.72	−0.72*	−0.54*	1			
NH_4^+	0.01	0.07	0.15*	0.07	0.01	−0.075	0.069	0.01	−0.01	1		
NO_3^-	0.01	−0.02	−0.02	−0.09	0.01	0.094	−0.026	0.01	−0.06	0.10	1	
NH_3	0.05	0,18*	−0.03	−0.06	0.01	0.06	0,001	0.10	−0.06	0.12	0.11	1
TEMP	−0,01	0.06	0,07	−0,11	0,18*	0.10	0,25*	0,24*	−0,18*	0,14*	−0,20*	0,19*

where CH_4—methane; CO_2—carbon dioxide; N_2O—nitrous oxide; Bd—bulk density; Us—soil moisture; WFPS—water-filled pore space; Clay—clay content; Silt—silt content; Sand—sand content; NH_4^+—ammonium; NO_3^-—nitrate; NH_3—ammonia; and TEMP—temperature. *Significance level ($p \leq 0.05$). Note: the perfect negative correlation ($r = -1.00$) between Bd and WFPS results from the algebraic dependency between these variables, as WFPS is calculated directly from Bd (Eq. 1); this value should therefore be interpreted as a mathematical artifact rather than an independent empirical finding

Significance level ($p \leq 0.05$)

highest efflux. In contrast, the SAFSE and SAFCAB systems presented the lowest fluxes during the high-rainfall period compared with the CB and CVE systems. During the low-rainfall period, SAFSE presented lower fluxes than did the three full-sun systems and values similar to those of SAFCAB and FOREST (Fig. 3C). In both periods, positive N_2O fluxes predominated across all systems and in the forest, with no evidence of net N_2O uptake. Among all systems, only CF showed significantly higher N_2O emissions during the low-rainfall period compared to the high-rainfall period. This pattern likely reflects the combined effect of relatively elevated WFPS (Table 3) and the nitrogen inputs derived from Fabaceae residue decomposition, which together create favorable conditions for both nitrification and denitrification (Bateman and Baggs 2005; Oertel et al. 2016). The absence of seasonal differences in the other systems suggests that the Fabaceae nitrogen contribution in CF is a distinctive driver of N_2O dynamics that warrants further investigation.

Furthermore, the trend of lower N_2O fluxes in agroforestry systems than in monocultures (SAFSE/SAFCAB < full sun) observed in this study is consistent with reductions previously reported for agroforestry arrangements (Luo et al. 2022; Shao et al. 2023).

Soil N_2O emissions may occur through nitrification or denitrification, the latter being favored under moist, oxygen-limited conditions (Bateman and Baggs 2005). In agreement with our findings, conventional cacao systems in high-moisture environments exhibit higher N_2O peaks, particularly under elevated WFPS and available mineral N (Sterling et al. 2025).

In the agroforestry systems analyzed, the lower N_2O emissions are likely related to the greater input of carbon-rich plant material to the soil, leading to microbial nitrogen immobilization. The high deposition of organic residues with elevated C contents in cocoa agroforestry systems promotes continuous organic matter input, potentially inhibiting N_2O release (Gama-Rodrigues et al. 2011). Additionally, in the SAFSE system, rubber trees (*Hevea brasiliensis*) are deciduous, shedding all leaves during part of the year, thus contributing substantial amounts of C-rich litter to the soil. Monroe et al. (2016) reported that litter deposition in cocoa agroforestry systems results in the formation of a thick organic layer, increasing soil organic matter accumulation. Residues with a high C:N ratio may stimulate microbial N immobilization, reducing its availability for processes involved in N_2O production (Rosa et al. 2011), which could explain the lower N_2O emissions observed in the agroforestry systems evaluated.

N_2O emissions in full-sun cocoa systems with Fabaceae and Brachiaria cover crops (CF and CB) were the highest during the dry season. These treatments also presented the highest WFPS values, suggesting favorable conditions for the formation of microsites with reduced O_2 availability and increased denitrification, thereby increasing N_2O production (Bateman and Baggs 2005; Oertel et al. 2016). This interpretation is consistent with the significant positive correlation ($r = 0.23$) observed between N_2O flux and soil moisture in this study, since higher WFPS values tend to maximize N_2O emissions (Bateman and Baggs 2005; Oertel et al. 2016).

Moreover, the greater availability of surface residues may increase nitrification and denitrification rates and, consequently, N_2O fluxes (Paul and Clark 1996; Cardoso and Andreote 2016). Evidence from tropical environments indicates that soil moisture and management practices are key determinants of the spatiotemporal variability in N_2O emissions, which aligns with the patterns observed for the CF and CB systems (Iddris et al. 2020; Nascimento et al. 2020).

Correlation between soil attributes and greenhouse gas fluxes

Physical and chemical soil properties, such as bulk density (Bd), soil moisture (Us), texture, and nitrogen forms, influence GHG emissions. In this study, Pearson correlations indicated that bulk density was positively correlated with CH_4 ($r = 0.13$) and that soil moisture was positively correlated with N_2O ($r = 0.23$) (Table 4). These patterns suggest the coexistence of microaerobic and anaerobic microsites that favor different microbial pathways (nitrification and denitrification), which is consistent with previous findings (Wrage et al. 2001).

The clay content was positively correlated with N_2O ($r = 0.28$), which is consistent with its greater water retention capacity in micropores and, consequently, an increase in the fraction of water-filled pore space (WFPS), creating small anaerobic zones within the soil that favor denitrification (Oertel et al. 2016).

The NH_4^+ concentration was also positively correlated with N_2O ($r = 0.15$*), indicating that ammonium availability may contribute to the production of nitrogen oxides through nitrification, as also reported by Zanatta et al. (2010), who reported a strong relationship between ammonium levels and NH_4 emissions ($R^2 = 0.82$; $p < 0.001$), reinforcing the combined role of substrate availability and soil moisture in driving microbial activity.

These complex interactions between soil attributes and GHG dynamics reinforce that management practices influencing soil moisture, texture, and nitrogen cycling are central to understanding emission variability across cocoa production systems.

Conclusions

Cocoa agroforestry systems exhibited contrasting responses in terms of greenhouse gas (GHG) emissions, demonstrating that the presence of trees does not necessarily result in lower emissions. While the rubber-based agroforestry system (SAFSE) showed the lowest GHG fluxes over the evaluation period, the Cabruca system (SAFCAB) exhibited the highest CO_2 emissions, indicating that different agroforestry configurations can modulate soil GHG dynamics in distinct ways.

Although SAFSE exhibited the lowest GHG emissions, it also exhibited the lowest soil pH, the lowest organic matter content, and the highest bulk density among the evaluated systems, indicating that reduced GHG fluxes are not necessarily associated with improved soil quality. These findings underscore that sustainability assessments of cocoa production systems should concurrently consider GHG emissions, soil quality indicators, and productive potential, rather than relying on a single environmental attribute.

The positive association between GHG fluxes and soil moisture, clay content, and ammonium concentration underscores the central role of soil physical properties and nitrogen availability in regulating GHG emissions from cocoa production systems. Therefore, management practices aimed at optimizing these soil conditions represent a promising strategy for mitigating GHG emissions.

The hypothesis that agroforestry systems would exhibit GHG emissions comparable to those of forest systems and lower than those of full-sun cocoa cultivation was only partially supported. This finding indicates that the composition and management of agroforestry systems are more important drivers of GHG dynamics than the mere presence of tree cover.

Overall, this study demonstrates that the environmental performance of cocoa agroforestry systems is determined by the interaction among soil properties, microenvironmental conditions, and management practices, rather than by the presence of trees alone. These findings reinforce the need for integrated sustainability assessments that simultaneously consider GHG emissions, soil quality, and agricultural productivity. Furthermore, long-term studies encompassing different soil types, climatic conditions, and management histories are essential to improve our understanding of the mechanisms regulating GHG emissions and to support the development of more effective strategies for sustainable cocoa production and climate change mitigation.

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Author contribution DGO conceived the study, conducted the fieldwork, performed the laboratory analyses, organized the database, carried out the statistical analyses, and drafted the manuscript. JCM contributed to the study conception, provided scientific supervision, interpreted the results, and critically revised the manuscript. JDR contributed to data analysis and interpretation and revised the manuscript. SRM contributed to the discussion of the results and critically revised the scientific content. PCLM critically revised the scientific content. IPSS contributed to the fieldwork and site monitoring. MCAA assisted with fieldwork, laboratory analyses, and manuscript revision. BEM contributed to the methodology and laboratory analyses, the interpretation of the results, scientific discussion, and final revision of the manuscript. All authors read and approved the final manuscript.

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Data availability The data generated and analyzed in this study are part of the first author's doctoral thesis, developed within the Graduate Program at the Federal University of Southern Bahia (UFSB). The data are not currently deposited in a public repository but are available from the corresponding

author upon reasonable request for verification, reproducibility, and academic use, in accordance with the guidelines of the journal and the institution.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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