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Article

Dynamics of Greenhouse Gas Fluxes in Açaí Cultivation: Comparing Amazonian Upland and Floodplain Soils

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Abstract: Global warming is driven by the increasing atmospheric emissions of greenhouse gases. Soils are highly sensitive to climate change and can shift from carbon reservoirs to carbon sources under warmer and wetter conditions. This study is the first to simultaneously measure trace gas fluxes in *Euterpe oleracea* (açaí) plantations in upland areas, contrasting them with floodplain areas managed for açaí production in the eastern Amazon. Flux measurements were conducted during both the rainy and dry seasons using the closed dynamic chamber technique. In upland areas, CO₂ fluxes exhibited spatial (plateau vs. lowland) and temporal (hourly, daily, and seasonal) variations. During both the rainy and dry months, CH₄ uptake in upland soils was higher in lowland areas compared to the plateau. When comparing the two ecosystems, upland area emitted more CO₂ during the rainy season, while floodplain areas released more CH₄ into the atmosphere. Unexpectedly, during the dry season, floodplain soils produced more CO₂ and captured more CH₄ from the atmosphere compared to upland soils. In upland areas, CO₂-equivalent production reached 59.1 Mg CO₂-eq ha⁻¹ yr⁻¹, while in floodplain areas, it reached 49.3 Mg CO₂-eq ha⁻¹ yr⁻¹. Soil organic matter plays a vital role in preserving water and microorganisms, enhancing ecosystem productivity in uniform açaí plantations and intensifying the transfer of CH₄ from the atmosphere to the soil. However, excessive soil moisture can create anoxic conditions, block gas diffusion, reduce soil respiration, and potentially turn the soil from a sink into a source of CH₄.

Keywords: soil carbon flux; forest management; soil microorganism; Amazon

1. Introduction

Global warming is caused by the increase in atmospheric emissions of greenhouse gas (GHG), resulting from the burning of fossil fuels and land-use changes [1]. This rise in atmospheric temperature is already significantly impacting the behavior of terrestrial ecosystems, such as the reduction in soil moisture (IPCC, 2018), which is an important regulator of GHG [2], especially in estuarine regions. In natural systems, soil respiration significantly contributes to the flux of CO₂ into the atmosphere [3]. It is estimated that soil can store 23.8 Gt of CO₂-eq annually on a global scale [4]. Recent studies indicate that tropical soils are susceptible to climate change and may shift from being a carbon reservoir to a carbon producer under warmer and wetter conditions [5]. This is due to the influence of soil temperature and moisture [6] on substrate quality, managed area, and the diversity of soil organisms [2], factors that affect GHG fluxes.

The Brazilian Amazon is primarily divided into terra firme (upland) and várzea (floodplain), representing 87% and 13%, respectively, of its total area of 5.5 million km² [7]. Soil saturation, whether in upland or floodplain, alters organic matter decomposition processes due to changes in redox conditions [8,9]. Soil GHG emissions are closely linked to biological activities, which interact with

flooding patterns and land management practices [10]. In the Amazon estuarine region, floodplain areas experience daily cycles of flooding and dry, driven by oceanic tides [11]. These tidal patterns are indirectly influenced by lunar phases and seasonal rainfall variations [12].

The *upland* region also experiences zones of anoxia during rainy periods, leading to the CH₄ production [9]. This gas can also be released due to increased termite activity resulting from higher litter accumulation [13]. However, there is limited understanding of CO₂ and CH₄ fluxes following the transformation of degraded areas into productive lands or secondary forests. Agricultural soils are a primary source of GHG emissions, with approximately 70% of CH₄ production originating from anthropogenic sources and 30% from natural processes [14]. The pressure to convert tropical forests into productive regions is alarming [15]; yet, vast areas of already degraded land hold significant potential for restoration and productivity.

Açaí (*Euterpe oleracea*) is a hyperdominant species native to the Amazon, thriving naturally in floodplain regions with hydromorphic soils that drain water twice daily along river margins [11]. The increasing demand for açaí fruit is transforming floodplain forests into monocultures, significantly altering ecosystem structures and services [16,17]. The economic demand for açaí has driven its cultivation to upland irrigated areas [18], transitioning from an extractive production of 4.2 Mg fruits ha⁻¹ to irrigated upland plantations producing 15.0 Mg fruits ha⁻¹ [19]. Typically, açaí cultivation in uplands (ATF) is carried out in abandoned or already degraded areas [20]. This expansion in açaí production, both in floodplains and uplands, may obscure environmental risks [21]. This research aims to evaluate the contribution of CO₂ and CH₄ fluxes in intensively managed areas for açaí production in floodplain and irrigated upland regions of the eastern Amazon, to enhance global GHG models.

2. Material and Methods

The floodplain area of the estuary (AV) studied (Figure 1C) is located in the municipality of Belém (1°30'02.0" S and 48°27'31.6" W). The climate type is classified as Af according to the Köppen classification [22], with an annual average temperature of 27 °C and annual precipitation of 3,286 mm [23]. The soils are classified as Haplic Gleysol, characterized by a high proportion of silt and clay, and a low proportion of sand [24]. The floristic composition was previously more diverse [11] but is now predominantly composed of *Euterpe oleracea* Mart. [17] with 960 clumps per hectare, averaging three stems per clump.

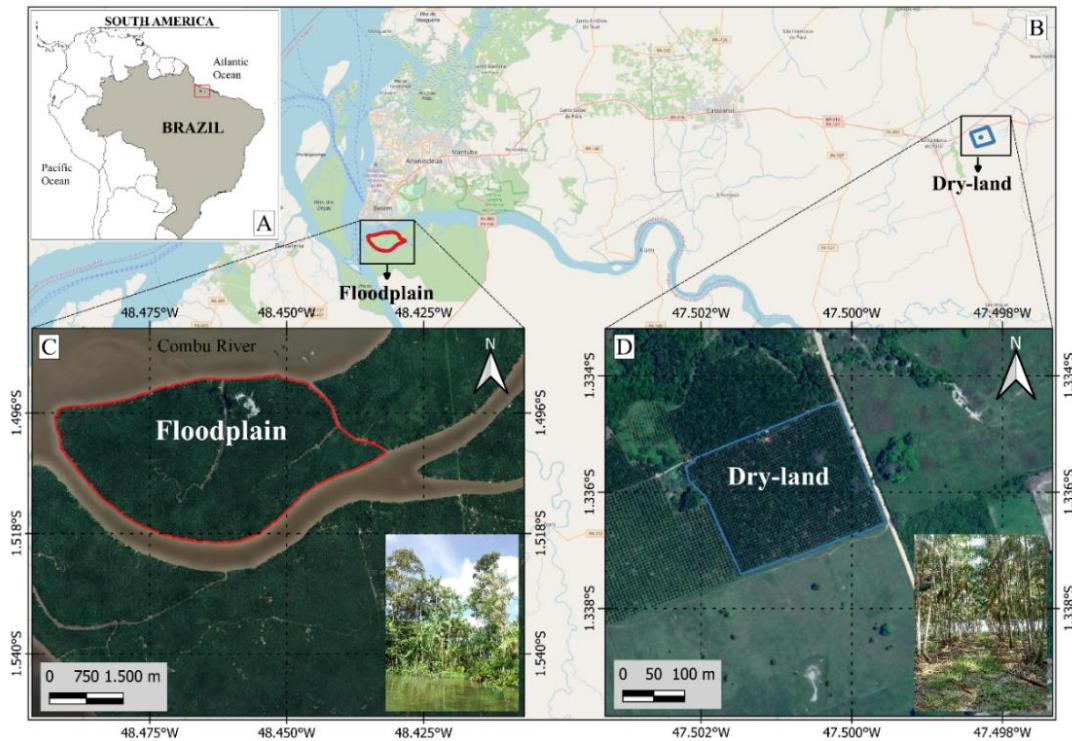


Figure 1. Location of the study areas: estuarine floodplain area (AV), in the municipality of Belém (B and C), and upland area (ATF), in the municipality of Santa Maria do Pará (B and D).

The upland area (ATF) studied (Figure 1D) is located in the municipality of Santa Maria do Pará ($1^{\circ}20'10.0''$ S and $47^{\circ}30'04.0''$ W). The climate is classified as Af according to the Köppen classification [22], with an average annual air temperature of 27°C and annual precipitation of 2,250 mm [23]. The soils are classified as Yellow Latosol with a medium sandy texture [24]. In this already degraded area, açaí was planted in 2011 with a spacing of $5\text{ m} \times 5\text{ m}$, resulting in a density of 400 clumps per hectare. Each clump can contain up to three stems and is organically fertilized, without the application of soluble chemical fertilizers.

2.1. Experimental Design

2.1.1. Experiment on Upland

The measurements to detail spatial variation in ATF were conducted in September 2020 (dry season), simultaneously in high topography (plateau, Top1) and low topography (lowland, Top2). In each topography four rings were fixed in the planting line (L) and four in street (R) where the machines operate, in a homogeneous açaí plantation area (Figure 2A) located in the municipality of Santa Maria do Pará (Figure 1B and D). Simultaneous measurements were taken hourly, from 09:00 to 17:00 (local time), from September 21 to 25, 2020. For the same time interval, measurements in AV was conducted one week earlier, over two consecutive days, in high and low floodplain areas, respectively, using eight flux chambers at a single time point each day (Figure 2b).

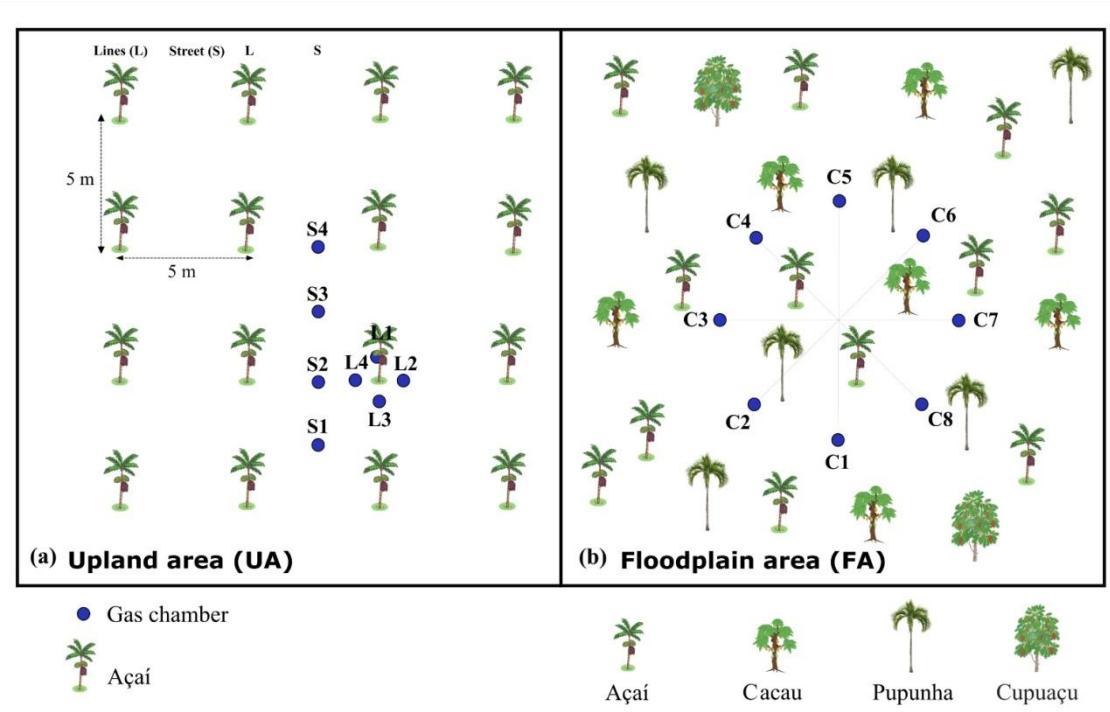


Figure 2. Experimental design for flow analysis in the area: (a) açaí plantation on upland (ATF), with flow chambers (blue dots) in the planting lines (L) around the clumps, and on the street (R) where the machinery passes, in Santa Maria do Pará, and (b) in the floodplain area (AV), in the estuary in Belém, with the flow chambers randomly distributed in a circle.

2.1.2. Comparison Between Dry Land and Floodplain

During the rainy season (April 3 to 7, 2021), only the high topography was evaluated in ATF and AV. The measurements were conducted simultaneously from 08:00 to 17:00. In all GHG flux analyses in ATF, due to the uniformity of the planting, four sequential measurements were taken every hour in L and four in R (Figure 2A) over five consecutive days. In AV, the measurement points were randomly allocated in a 700 cm diameter circle (Figure 2B). The measurements took place on the same days and times as the measurements conducted in ATF.

2.2. Trace Gas Flux Measurements

The closed dynamic chamber methodology [9] was utilized to measure soil CO_2 (FCO_2) and CH_4 (FCH_4) fluxes. The flux chambers were constructed with polyvinyl chloride (PVC) rings measuring 12.0 cm in height and 20.0 cm in diameter, inserted approximately 4.0 cm deep into the soil (Figure 2). During each measurement period, the rings were sequentially closed with a lid for three minutes, forming the flux chamber. This chamber was connected to a Los Gatos portable gas analyzer (Ultra-portable Greenhouse Gas Analyzer, U.S.A.), which recorded the gas concentrations (ppm) inside the chamber at two second intervals [25]. After the measurements, the height of each ring was measured at four equidistant points using a ruler. The FCO_2 and FCH_4 values were calculated based on the increase/decrease in GHG concentrations [6,26]. The flux was considered zero when the linear regression achieved an $R^2 < 0.30$ [27].

2.3. Soil Sampling and Analysis and Environmental Characterization

After each measurement period (ATF and AV), six soil samples were collected using an auger at a depth of 0-10 cm. In the ATF, three samples were collected in the L and three in the R at each flux measurement point (Figure 2). The samples were appropriately conditioned and sent to the Chemical Analysis Laboratory of the Emílio Goeldi Museum, located in Belém (PA).

The concentration of C and N in microbial biomass was investigated using the soil microwave irradiation method [28], conducted only during the dry period due to a lack of chemicals in the laboratory. The determination of microbial biomass carbon (Cm) was performed through Dichromate oxidation [29,30]. The quantification of nitrogen in microbial biomass (Nm) followed the method by Brookes et al., (1985), substituting fumigation with irradiation. For this, we used the equation proposed by Jenkinson (1988), which calculates the difference between the amount of N in irradiated and non-irradiated soil divided by the constant k ($k = 0.45$). Samples of fine (diameter ≤ 0.2 mm; RF) and coarse (diameter > 0.2 mm; RG) root biomass were collected during both dry and rainy seasons, at a depth of 10 cm, in the previously described ATF and AV locations. After separation from the soil, the roots were oven-dried at 65 °C for 72 hours and weighed using an analytical balance [26]. Soil pH was measured using a potentiometer in deionized water, calibrated with standard solutions of pH 4.0 and pH 7.0 [33].

2.4. Environmental Characterization

Precipitation data for the AV were provided by the National Institute of Meteorology [23], with the automatic data collection station located in Belém (1°26'09.00" S and 48°26'14.00" W). For the ATF, precipitation data were supplied by the National Water and Basic Sanitation Agency [34], with the meteorological station located in Santa Maria do Pará (1°21'24.5" S; 47°34'27.5" W). Soil moisture determination (Us; %) was conducted using the Gravimetric Method [33]. During the trace gas flux measurements, soil temperature (Ts, °C) was quantified using a portable digital thermometer (TP101). Additionally, air temperature (Ta, °C) and relative humidity (HR, %) were recorded every 5 minutes using a Hobo pro V2 data logger.

2.5. Statistical Analysis

The topographical variation in ATF was compared to that of the estuary's AV. In the ATF, hourly and daily analyses were conducted using subdivided plots, with two treatments (high and low topography) divided into line (L) and street (R). The Shapiro-Wilks method was used to assess the normality of the FCH₄ and FCO₂ data and the soil physicochemical parameters. When normality was not achieved, logarithmic transformations were applied. Student's t-test was used to determine if there were differences in the means between the times and days of data collection at the same site and between the studied sites. Significant differences ($p < 0.05$) in flux between the different locations were evaluated using ANOVA and Tukey's LSD test. Pearson correlation coefficients were calculated to establish the connections between environmental variables and gas fluxes in the months (dry and rainy seasons) when soil chemical characteristics were analyzed simultaneously with gas flux measurements. The free statistical software Infostat 2015® was used to perform the statistical analyses.

3. Results

3.1. Carbon Dioxide and Methane Flux

3.1.1. Spatial Analysis of Homogeneous Açaí Planting in the Dry Season

The analysis of gas flux across different topographies (Top1 and Top2) was conducted simultaneously along the line (L) and street (R) in a homogeneous açaí plantation on upland soil during the dry season. The results are presented as mean \pm standard error. The FCO₂ was significantly higher ($p < 0.01$) in Top2 (19.561 ± 0.522 g CO₂ m⁻² d⁻¹) compared to Top1 (7.416 ± 0.292 g CO₂ m⁻² d⁻¹). In Top1, there was significant variation ($p < 0.01$) between the analyzed days. The highest fluxes were observed on the fifth day of sampling (15.997 ± 0.229 g CO₂ m⁻² d⁻¹), compared to the second day (9.827 ± 0.688 g CO₂ m⁻² d⁻¹), with both being significantly higher ($p < 0.01$) than the first (6.900 ± 0.229 g CO₂ m⁻² d⁻¹) and third days (5.057 ± 0.187 g CO₂ m⁻² d⁻¹). The third day did not differ statistically ($p > 0.05$) from the fourth day of analysis (4.772 ± 0.215 g CO₂ m⁻² d⁻¹). In Top2, there was no significant variation ($p > 0.05$) in FCO₂ over the five days of analysis.

Only in the plateau topography (Top1) did FCO_2 vary significantly between the analyzed time periods, being higher ($p < 0.05$) between 09:00 and 12:00 compared to other times (Figure 3A). In Top1, FCO_2 levels were higher in the early morning (09:00 to 12:00) compared to other times (Figure 3C), with significantly higher values ($p < 0.01$) in L ($8.187 \pm 0.449 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$) compared to R ($6.582 \pm 0.362 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$). However, in Top2, the fluxes did not vary between time periods, but were significantly higher ($p < 0.001$) in L ($25.834 \pm 0.734 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$) compared to R ($13.017 \pm 0.253 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$) across all time periods (Figure 3E).

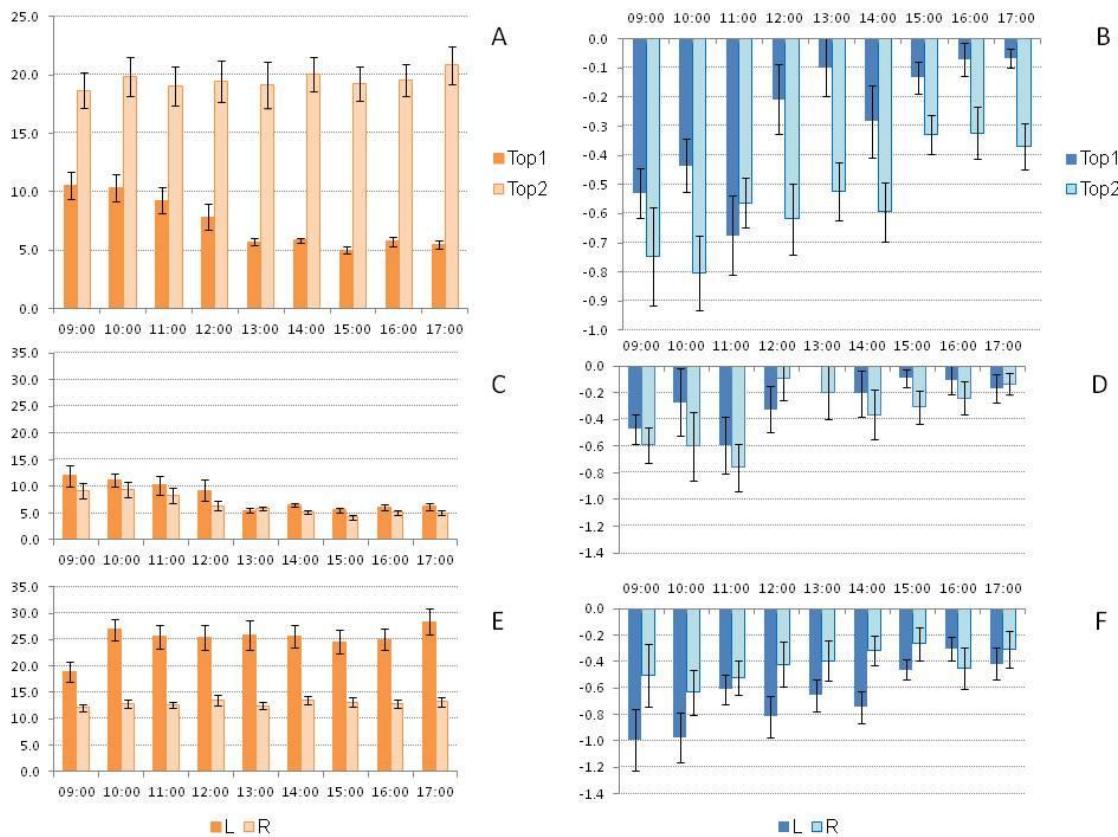


Figure 3. A) CO_2 flux (FCO_2 ; $\text{g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$) in high topography (Top1) and low topography (Top2) in the dry period; B) CH_4 flux (FCH_4 ; $\text{mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$) in Top1 and Top2 in the dry period; C) FCO_2 in Top1 comparing lines (L) with streets (R) in the dry period; D) FCH_4 in Top1 comparing L with R in the dry period; E) FCO_2 in Top2 comparing L with R; F) FCH_4 in Top2 comparing L with R in the dry period, in an area of homogeneous açaí plantation on dry land, in the municipality of Santa Maria do Pará (Brazil).

On all analyzed days, there was a consumption of CH_4 from the atmosphere by soil bacteria (Figure 3). On average, the CH_4 influx was significantly higher ($p < 0.001$) in Top2 ($-0.540 \pm 0.037 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$) compared to Top1 ($-0.291 \pm 0.038 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$). In Top1, the CH_4 influx was significantly higher on the fifth day of sampling ($-0.835 \pm 0.155 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$), while no significant differences were observed between the other days ($-0.236 \pm 0.038 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$). In Top2, no significant variation ($p > 0.05$) in CH_4 influx was observed across the analyzed days. The CH_4 influx was higher during the morning (until 12:00) compared to the afternoon in Top1 (Figure 3D), with no significant difference ($p = 0.221$) in fluxes between L ($-0.259 \pm 0.054 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$) and R ($-0.383 \pm 0.057 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$). In Top2, the influx was also higher in the morning compared to the afternoon (Figure 3F), with a significant variation ($p < 0.01$) in FCH_4 between L ($-0.683 \pm 0.054 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$) and R ($-0.440 \pm 0.052 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$).

3.1.2. Simultaneous Flow Measurements in Upland and Floodplains

Simultaneous flux measurements were conducted during the rainy season in March 2021, exclusively in Top1 (higher topography), covering both upland (ATF) and floodplain (AV) areas. When comparing simultaneous measurements in ATF and AV, the distribution of GHG fluxes did not follow a normal distribution ($p < 0.001$) in either location, even after logarithmic transformation. Consequently, a non-parametric test was selected for comparing the means. The average FCO_2 in ATF ($20.691 \pm 0.563 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$) was significantly higher ($H = 101.532; p < 0.001$) than that observed in AV ($12.869 \pm 0.475 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$). During the rainy season, FCO_2 in ATF did not show significant variation ($H = 6.906, p = 0.647$) across the sampled times. However, in AV, FCO_2 levels were significantly lower ($H = 45.171, p < 0.001$) in the late afternoon, starting from 15:00 (Figure 4A).

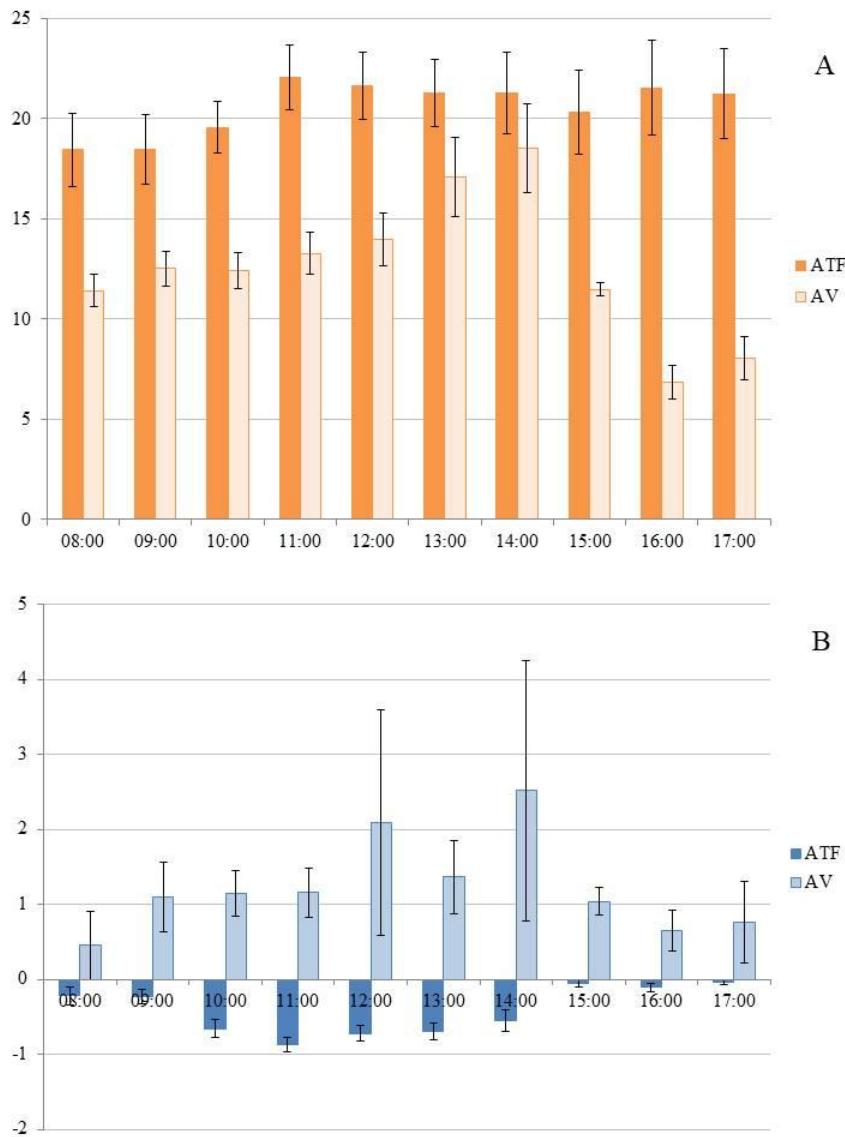


Figure 4. A) CO₂ flux (FCO₂; g CO₂ m⁻² d⁻¹) in homogeneous açaí plantation in upland (ATF) and in managed floodplain forest (VA) in the rainy season; B) CH₄ flux (FCH₄; mg CH₄ m⁻² d⁻¹) in homogeneous açaí plantation in upland (ATF) and in managed floodplain (VA) area, in the rainy season.

During the rainy season, there was an influx of CH₄ in ATF ($-0.464 \pm 0.038 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$), which was significantly lower ($H = 137.451, p < 0.001$) than the efflux observed in AV ($1.278 \pm 0.255 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$). In ATF, the CH₄ influx was significantly higher ($H = 62.835, p < 0.001$) between 10:00 and 13:00 compared to the other analyzed time periods (Figure 4B). However, during the same rainy

season, in AV, the fluxes did not vary significantly ($H = 4.755$, $p = 0.804$) across the analyzed time periods (Figure 4B).

3.2. Seasonal Flux of Greenhouse Gases

When comparing GHG fluxes along the L and R in ATF during the two months of the rainy season on the plateau (Top1-Rainy) and the dry season on both the plateau (Top1-Dry) and lowland (Top2-Dry), a significant difference was observed between the sampled locations (Figure 5A). During both seasons, in Top1 and Top2 (only during the dry season), FCO₂ was significantly higher ($p < 0.001$) in L compared to R (Figure 5). However, regarding FCH₄, only in Top2 during the dry season was the CH₄ influx significantly higher in L compared to R (Figure 5B), while no significant differences ($p > 0.05$) were observed in the other measurements.

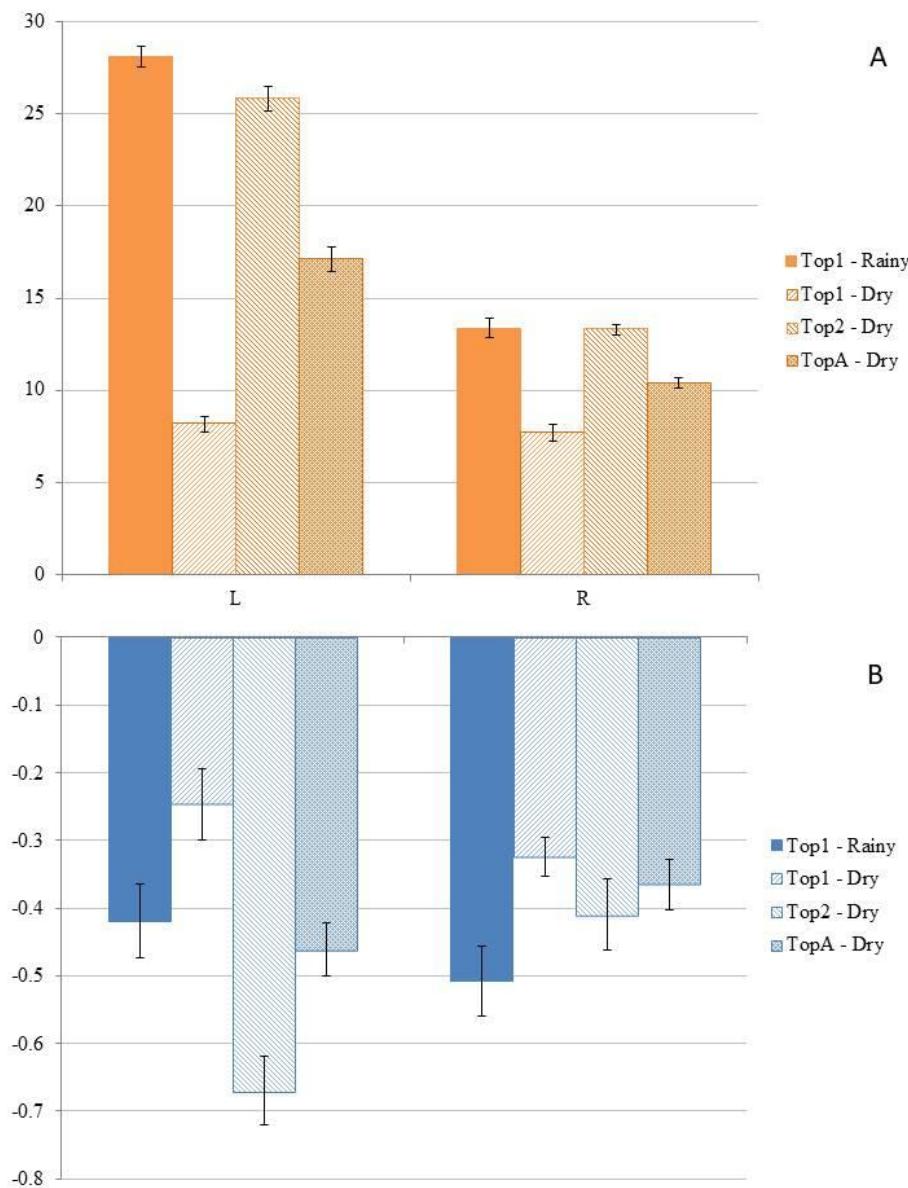


Figure 5. A) CO₂ efflux (FCO₂) in the upland area (ATF) in the plateau (Top1), shoal (Top2), and average (TopA) topography during the months sampled in the wet and dry season. B) CH₄ influx (FCH₄) in the upland area (ATF) in the plateau (Top1), shoal (Top2), and average (TopA) topography, during the months sampled in the wet and dry season. The bars represent the standard error of the mean.

In March (rainy season), when fluxes were measured simultaneously, FCO_2 was significantly higher ($H = 101.532$, $p < 0.001$) in ATF ($20.691 \pm 0.563 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$) compared to AV ($12.869 \pm 0.475 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$) (Figure 6A). However, in September (dry season), FCO_2 was significantly lower ($H = 290.921$, $p < 0.001$) in ATF at Top1 ($7.416 \pm 0.292 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$) than at Top2 ($19.561 \pm 0.522 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$), where the efflux did not differ significantly from FCO_2 in AV ($20.647 \pm 1.741 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$) (Figure 6C). When considering both topographies in ATF as a single high topography (Top1), the fluxes in AV were significantly higher ($H = 15.664$, $p < 0.001$) than in ATF ($13.590 \pm 0.400 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$). In ATF, the FCO_2 measured during the rainy season was significantly higher ($H = 102.696$, $p < 0.001$) than the efflux during the dry season. Conversely, in AV, the CO_2 efflux during the dry season was significantly higher ($H = 23.636$, $p < 0.001$) than during the rainy season.

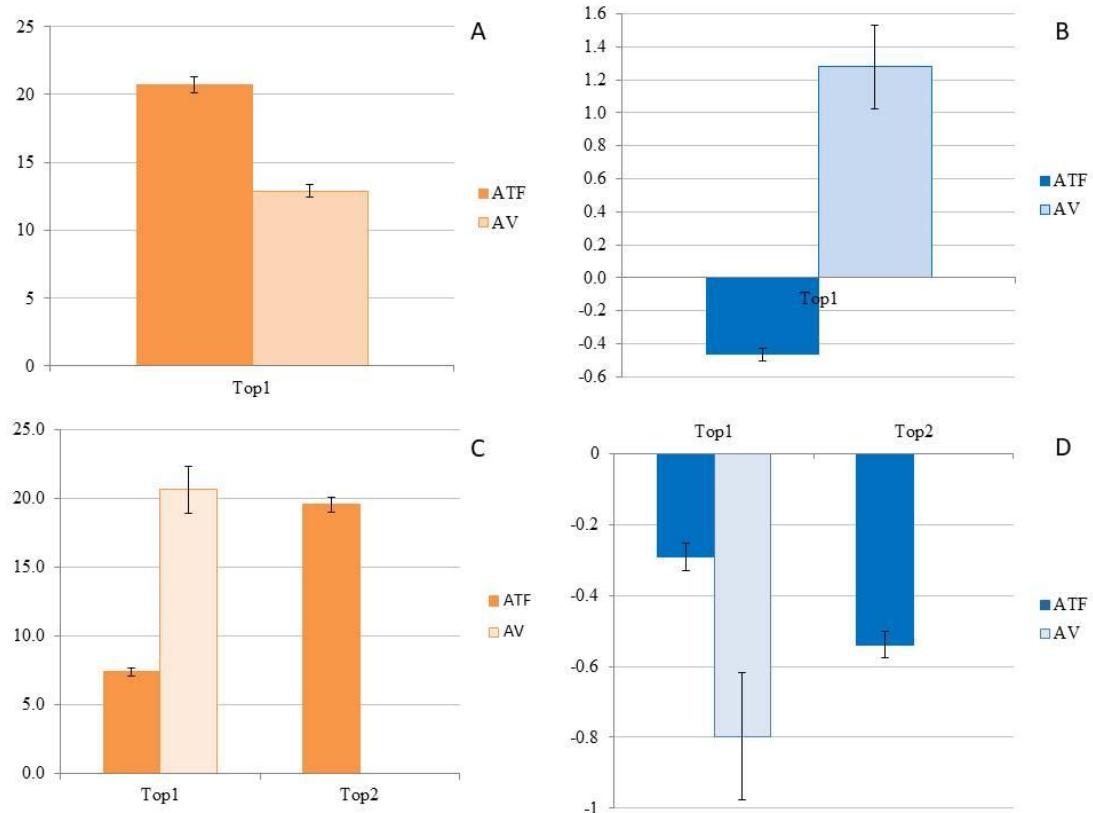


Figure 6. A) CO_2 flux (FCO_2 ; $\text{g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$) in the rainy season (March) in homogeneous açaí plantation in upland (ATF) and in managed floodplain (AV), in high topography (Top1); B) CH_4 flux (FCH_4 ; $\text{mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$) in the rainy season (March) in homogeneous açaí plantation in Terra Firme (ATF) and in managed Várzea forest (AV, in high topography (Top1); C) CO_2 flux (FCO_2 ; $\text{g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$) in the dry season (September) in homogeneous açaí plantation in upland (ATF) in high topography (Plateau; Top1) and low topography (Lowlands; Top2), and in managed floodplain (VA), in high topography (Top1); D) CH_4 flux (FCH_4 ; $\text{mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$) in the dry season (September) in homogeneous açaí plantation in upland (ATF) in high topography (Top1) and low topography (Top2), and in managed floodplain (AV) in high topography (Top1).

In March (rainy season), when the flows were measured simultaneously in the two places, the FCH_4 was higher ($H = 137.451$, $p < 0.001$) in AV ($1.278 \pm 0.255 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$) compared to the influx in ATF ($-0.464 \pm 0.0375 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$) (Figure 6B). However, in September (dry season), the CH_4 influx in the high topography (Top1) of AV ($-0.798 \pm 0.179 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$) did not differ from the CH_4 influx in the lowland (Top2) of ATF ($-0.539 \pm 0.037 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$), both of which were higher ($H = 52.422$, $p < 0.001$) than the CH_4 influx on the Top1 ($-0.292 \pm 0.039 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$) (Figure 6D). Considering the average flux rates of the two topographies in the ATF, the CH_4 influx in AV was higher ($H = 10.302$, $p < 0.001$) than the CH_4 influx in ATF ($-0.418 \pm 0.0273 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$). In ATF, the CH_4 influx measured during the rainy season did not differ ($p > 0.05$) from that during the dry season.

However, in AV, the CH_4 efflux during the rainy season was higher ($H = 33.407$, $p < 0.001$) than the influx during the dry season.

3.3. Environmental Variables

The total annual precipitation (from August 2020 to July 2021) was 2,634.0 mm in the Santa Maria do Pará region (ATF) and 3,915.3 mm in the Belém region (AV) (Figure 7A). For both ATF and AV, the wettest months span from December to May, with climatological totals of 1,588.0 mm and 1,760.0 mm, accounting for 81.5% and 83.6% of the total annual precipitation, respectively (Figure 7B). Precipitation was consistently lower in ATF compared to AV, except during the months of May, July, and August (Figure 7A). During the study period, rainfall exceeded the climatological averages by 538 mm and 1,596 mm in ATF and AV, respectively, coinciding with a La Niña event (Figure 7B). In both locations, precipitation was above the climatological average (values above zero) for most of the months studied, particularly during the dry season (Figure 7B).

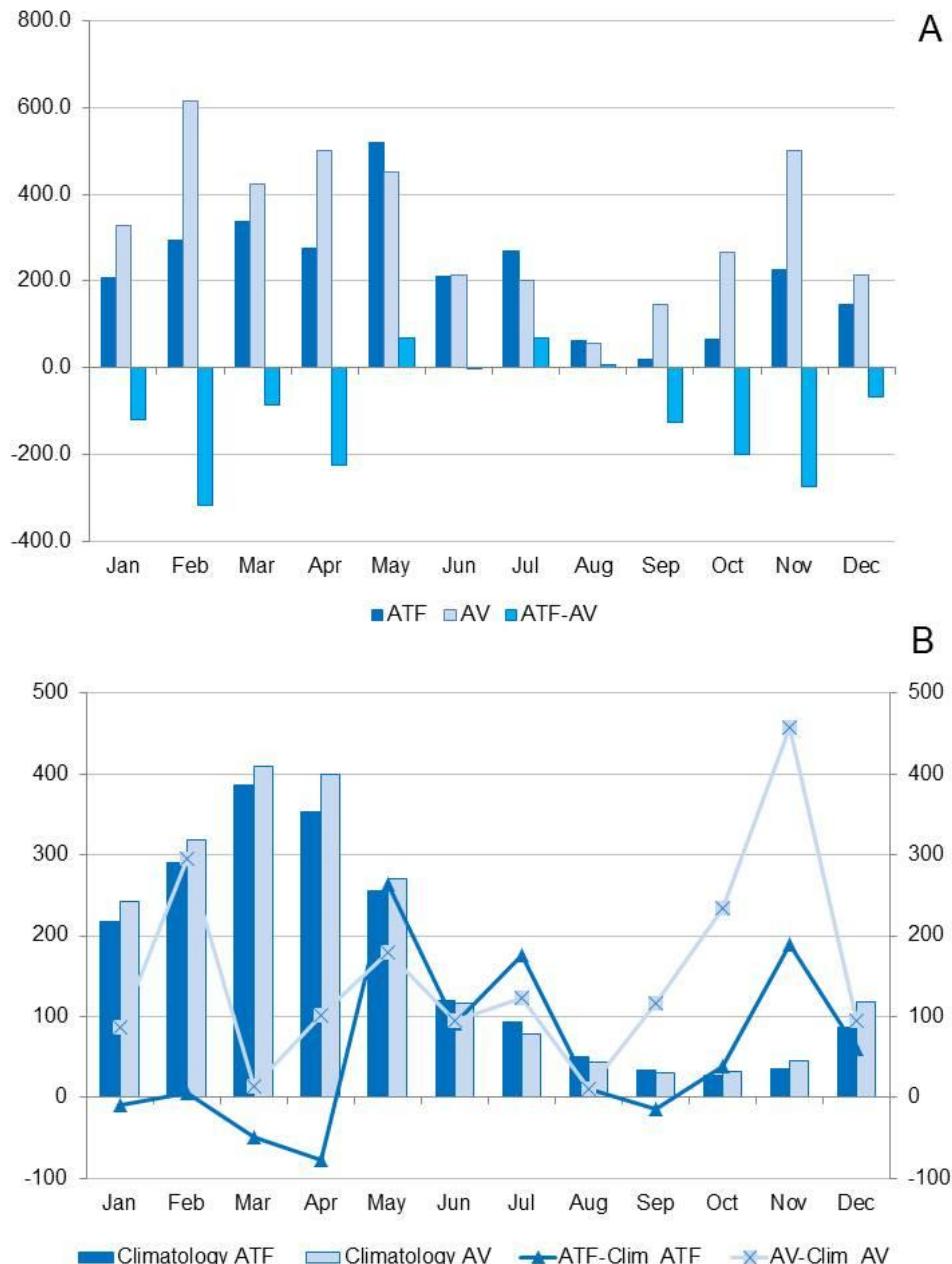


Figure 7. A) Precipitation (mm) in the dry land area (ATF) in Santa Maria do Pará, compared to the floodplain area (AV) in Belém, and the difference in precipitation between the two locations (ATF-

AV), from 2020 to 2021; B) Climatology (mm) in the dry land area (Climatology ATF) in Santa Maria do Pará in the floodplain area (Climatology AV) in Belém, and the difference between precipitation (mm) during the study period and the Climatology in ATF (ATF - Clim_ATF) and the Climatology in AV (AV - Clim_AV).

Air temperature and relative humidity (UR) did not follow a normal distribution, necessitating the use of non-parametric tests to compare the means. Temperatures were highest between 12:00 and 14:00 (Figure 8) in both ATF ($H = 264.327$, $p < 0.001$) and AV ($H = 128.898$, $p < 0.001$). Additionally, temperatures were higher during the dry season compared to the rainy season in both ATF ($H = 215.845$, $p < 0.001$) and AV ($H = 97.727$, $p < 0.001$). The highest temperatures ($H = 405.651$, $p < 0.001$) were recorded in AV during the dry season (30.98 ± 0.10 °C), followed by ATF during the dry season (29.05 ± 0.12 °C). These values were significantly higher than those recorded in ATF (27.92 ± 0.14 °C) and AV (27.38 ± 0.10 °C) during the rainy season, respectively.

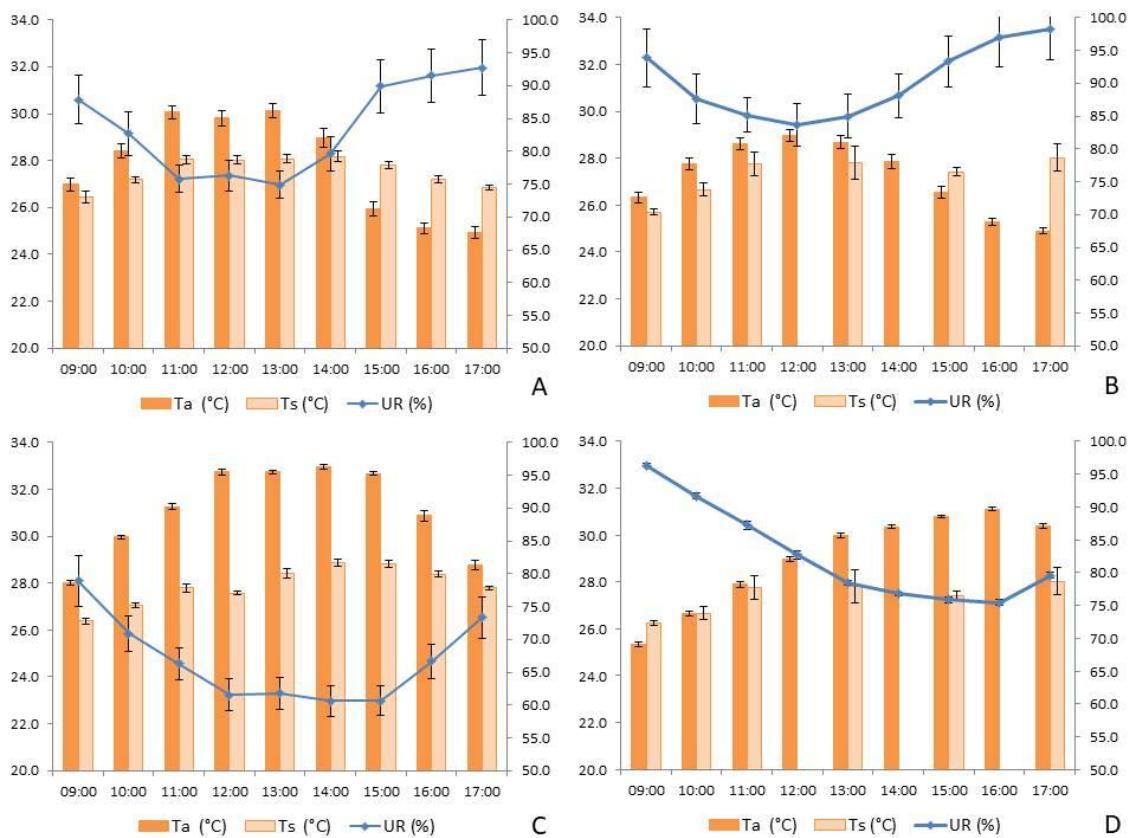


Figure 8. Behavior of Temperature (Ta, °C) and Relative Humidity (RH, %) of the air, and Soil Temperature (Ts, °C) in: A) dry land area (ATF) in the rainy season; B) floodplain area (AV) in the rainy season; C) ATF in the dry season; D) AV in the dry season. Times that have no value were due to the impossibility of collecting the data.

Relative humidity (UR) was higher at 09:00 and 17:00 in both ATF ($H = 175.494$, $p < 0.001$) and AV ($H = 157.412$, $p < 0.001$). As expected, UR was higher during the rainy season compared to the dry season in both ATF ($H = 368.694$, $p < 0.001$) and AV ($H = 124.181$, $p < 0.001$). There was a significant variation when comparing the locations and seasons. During the rainy season, UR was higher in AV ($89.59 \pm 0.37\%$) compared to ATF ($83.13 \pm 0.47\%$), which did not differ significantly from AV during the dry season ($82.65 \pm 0.45\%$). Both of these values were higher than those recorded in ATF during the dry season ($67.27 \pm 0.38\%$).

In ATF, soil temperature (Ts) was higher than in AV during both the rainy season ($H = 30.10$, $p < 0.001$) and the dry season ($H = 16.78$, $p < 0.001$). At both study sites, there was significant variation in Ts across the different sampling times during both the rainy and dry seasons. In ATF, the warmest

Ts values were recorded between 11:00 and 15:00 (Figures 8A and 8C), whereas AV did not show significant variation in Ts throughout the day (Figures 8B and 8D).

Soil moisture (Us) was higher during the rainy season (Table 1) in both ATF ($H = 14.29$, $p < 0.001$) and AV ($H = 7.50$, $p < 0.01$). Additionally, Us was consistently higher in the floodplain area (AV) compared to ATF during both the rainy ($H = 9.38$, $p < 0.001$) and dry seasons ($H = 10.59$, $p < 0.001$). Soil pH did not show statistically significant differences ($p > 0.05$) between the seasons in either of the sampled areas (Table 1). However, pH was higher in ATF during both the rainy ($H = 7.38$, $p < 0.01$) and dry seasons ($H = 4.27$, $p < 0.05$) when compared to AV. Fine root biomass did not differ significantly ($p > 0.05$) either seasonally within each site or between the sites within the same season (Table 1).

In ATF, root biomass (RG) was higher during the rainy season ($H = 8.20$, $p < 0.01$), whereas in AV, it was higher during the dry season ($H = 4.34$, $p < 0.05$). However, when comparing the two sites, RG differed only during the rainy season (Table 1), being higher in ATF ($H = 13.95$, $p < 0.001$) compared to AV (Table 1). Microbial carbon (Cmic) and microbial nitrogen (Nmic) were analyzed only during the dry season, with both Cmic and Nmic being higher in AV ($HC_{mic} = 8.00$, $p < 0.01$; $HN_{mic} = 8.00$, $p < 0.01$) compared to ATF (Table 1).

Table 1. Seasonality of some environmental data in upland (ATV) and floodplain (AV) treatments in the eastern Amazon region. Numbers report the mean \pm standard error, with lowercase letters comparing the seasonality in each treatment, and uppercase letters comparing treatments in the same seasonality. ND means that there was no analysis.

| | Upland | | Floodplain | |
|--------------------------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| | Dry | Rainy | Dry | Rainy |
| Soil moisture (Us, %) | 8.64 ± 0.51^{bb} | 23.12 ± 0.77^{ab} | 26.44 ± 0.70^{ba} | 53.27 ± 1.12^{aa} |
| pH | 4.83 ± 0.21^{aA} | 5.16 ± 0.05^{aA} | 4.15 ± 0.01^{ab} | 4.15 ± 0.04^{ab} |
| Fine roots ($Mg\ ha^{-1}$) | 2.61 ± 0.28^{aA} | 2.96 ± 0.36^{aA} | 4.64 ± 0.88^{aA} | 2.25 ± 0.42^{aA} |
| Thick roots ($Mg\ ha^{-1}$) | 11.38 ± 1.17^{aA} | 8.87 ± 0.77^{ba} | 5.91 ± 0.91^{aA} | 3.39 ± 0.60^{bb} |
| Total Roots ($Mg\ ha^{-1}$) | 13.59 ± 1.38^{aA} | 11.84 ± 1.04^{aA} | 6.57 ± 0.40^{ab} | 5.64 ± 0.89^{ab} |
| Microbial carbon ($g\ kg^{-1}$) | 0.42 ± 0.03^b | ND | 1.56 ± 0.10^a | ND |
| Microbial nitrogen ($mg\ kg^{-1}$) | 6.12 ± 0.74^b | ND | 46.28 ± 2.12^a | ND |

3.4. Correlations Between Flow and Environmental Variable

In ATF during the rainy season, FCO_2 showed positive correlations with Us, RG, TR, and Ta, while exhibiting negative correlations with RF, UR, Pa, and pH (Table 2). Conversely, FCH_4 was positively correlated with Us, UR, and Pa, and negatively correlated with Ts and Ta (Table 2). During the dry season, FCO_2 was positively correlated with Us, RF, Cm, and pH, but negatively correlated with FCH_4 , Ts, and RG (Table 2). Meanwhile, FCH_4 was positively correlated with Ts, RG, and Nm, and negatively correlated with Us, RF, Pa, Cm, and pH (Table 2).

In AV during the rainy season, FCO_2 was positively correlated with FCH_4 , Ts, RF, RG, TR, and Ta, while showing negative correlations with Us, UR, Pa, and pH (Table 2). In the same season, FCH_4 did not show significant correlations with any of the analyzed variables, except for a positive correlation with FCO_2 . During the dry season, only FCO_2 exhibited positive correlations with Ta and UR (Table 2).

Table 2. Correlation coefficient between CO_2 (FCO_2) and CH_4 (FCH_4) fluxes with soil temperature (Ts), soil moisture (Us), fine root biomass (RF), coarse root biomass (RG), total root biomass (TR), air temperature (Ta), relative humidity (UR), atmospheric pressure (Pa), microbial carbon (Cm),

microbial nitrogen (Nm), pH in açaí monoculture grown on dry land (ATF) and açaí agroforestry in the estuary floodplain area (AV), in the rainy and dry seasons.

| Rainy Season | | | | | | | | | | | | | | |
|------------------|------------------|---------|----------|---------|---------|---------|---------|---------|----------|---------|--------|--------|--------|--------|
| ATF | FCH ₄ | Ts | Us | RF | RG | TR | Ta | UR | Pa | Cm | Nm | pH | | |
| FCO ₂ | -0,111 | 0,250** | 0,287** | 0,174** | - | 0,293** | 0,156** | 0,259** | -0,245** | - | ND | ND | 0,743* | * |
| | 1,000 | - | 0,137 | - | 0,08 | 0,02 | - | 0,009 | -0,493** | 0,500** | 0,142* | ND | ND | -0,067 |
| AV | | | | | | | | | | | | | | |
| FCO ₂ | 0,163** | 0,448** | -0,135* | 0,209** | 0,295** | - | 0,297** | 0,553** | -0,562** | -0,153* | ND | ND | 0,173* | * |
| | 1,00 | - | 0,04 | - | 0,07 | 0,02 | - | 0,01 | 0,079 | - | 0,017 | ND | ND | 0,00 |
| FCH ₄ | 0 | 3 | 0,081 | 8 | 5 | 9 | - | - | 0,099 | - | - | - | - | 7 |
| Dry Season | | | | | | | | | | | | | | |
| ATF | FCH ₄ | Ts | Us | RF | RG | TR | Ta | UR | Pa | Cm | Nm | pH | | |
| FCO ₂ | - | 0,316** | 0,151** | 0,626** | 0,570** | - | -0,009 | -0,053 | 0,062 | 0,05 | 0,441* | 0,001 | 0,419* | * |
| | 1,000 | 0,173** | -0,173** | 0,100** | - | 0,207** | 0,158** | 0,057 | -0,078 | - | - | 0,116* | 0,116* | 0,166* |
| AV | | | | | | | | | | | | | | |
| FCO ₂ | - | 0,05 | 0,19 | 0,209 | 0,20 | 0,25 | 0,24 | 0,406 | - | -0,370 | 0,112 | - | 0,24 | 8 |
| | 3 | 7 | 7 | 7 | 7 | 7 | 5 | * | * | * | 0,073 | - | 0,073 | 5 |
| FCH ₄ | 1,00 | - | 0,30 | - | 0,11 | 0,20 | 0,16 | 0,121 | - | -0,148 | -0,019 | - | 0,17 | - |
| | 0 | 7 | 7 | 0,209 | 9 | 0 | 9 | 0,241 | - | 0,019 | 0,019 | - | 0,019 | 5 |

* Significant p < 0.05; ** significant p < 0.01; ND not determined.

4. Discussion

4.1. Soil Carbon Flux in Açaí Plantation on Dry Land

During the dry season, in a La Niña year when rainfall significantly exceeded the climatological average (Figure 7B), the soil FCO₂ on the plateau (Top1) in ATF was considerably lower than the efflux in the lowland (Top2) area (Figure 6B). These results differ markedly from those observed in a mangrove forest in the Amazon estuary, where simultaneous CO₂ effluxes were higher in elevated topography compared to low-lying areas [26]. On the other hand, in a pristine tropical forest in the Guianas, no variation in CO₂ fluxes was found across different topographies, including plateaus and lowlands [35]. An important consideration is that, in our study, as well as in [26], the fluxes were measured simultaneously in both topographies using laboratory-calibrated equipment, with no statistical variation between the instruments.

To explain the difference in CO₂ efflux, fine root (RF) biomass was significantly higher (LSD = 0.814; $p < 0.01$) in Top2 (3.762 ± 0.222 Mg ha⁻¹) compared to Top1 (2.212 ± 0.309 Mg ha⁻¹). Similarly, soil moisture (Us) was significantly higher (LSD = 2.425; $p < 0.05$) in Top2 ($11.085 \pm 1.036\%$) than in Top1 ($8.641 \pm 0.508\%$). Additionally, microbial biomass was significantly greater (LSD = 0.106; $p < 0.001$) in Top2 (0.537 ± 0.047 kg Cmic kg⁻¹ soil) compared to Top1 (0.293 ± 0.021 kg Cmic kg⁻¹ soil). In this context, the higher moisture levels in the lowland area directly influence nutrient and organic matter dynamics, leading to increased fine root biomass [35] and microbial biomass [36], which in turn result in significantly higher CO₂ efflux. This may explain the greater soil respiration observed in the lowland area of an organic açaí plantation on upland terrain. Thus, soil organic matter plays a crucial role in maintaining water and microbial activity, enhancing ecosystem productivity in homogeneous açaí plantations.

When comparing the lines (L) and streets (R), the FCO₂ during the dry season in Top1 was 8.154 ± 0.450 g CO₂ m⁻² d⁻¹ in L, which was significantly lower ($H = 172.510$; $p < 0.001$) than the 25.825 ± 0.667 g CO₂ m⁻² d⁻¹ in L in Top2. In R, the FCO₂ in ATV in Top1 was 6.672 ± 0.361 g CO₂ m⁻² d⁻¹, which was also significantly lower ($H = 117.794$; $p < 0.001$) than the 13.297 ± 0.263 g CO₂ m⁻² d⁻¹ in Top2. When comparing the rainy season to the dry season, only in Top1 were both FCO₂ in L and R significantly higher ($p < 0.001$) during the rainy season compared to the dry season (Figure 3A). The results reveal that, in both L and R, the lowland topography (Top2) emits more CO₂ into the atmosphere compared to the plateau (Top1), a finding that contrasts with observations in an *Acacia mangium* plantation in Indonesia [37] and in a primary upland forest in the Amazon [38]. On the other hand, studies conducted in a closed-canopy upland forest in the central Amazon [39] and in a floodplain forest in the estuary (Aroni et al., n.d.) identified significant topographic variation, although, unlike the results presented here, the fluxes were higher in elevated topography compared to lowland areas. In an analysis of the annual average FCO₂, the efflux in L (21.025 ± 0.543 g CO₂ m⁻² d⁻¹) was significantly higher ($H = 166.519$; $p < 0.001$) than in R (11.251 ± 0.275 g CO₂ m⁻² d⁻¹), which could not be explained by root biomass (fine, coarse, or total), as no statistical variation ($p > 0.05$) was observed between L and R. However, the data show that soil moisture (Us) was significantly higher ($H = 5.859$; $p < 0.05$) in L ($28.458 \pm 3.434\%$) compared to R ($18.423 \pm 3.262\%$). During the dry season, irrigation is applied only to the açaí planting rows (L), which may enhance soil biological activity in upland areas of the Amazon region.

In the upland açaí plantation, the FCO₂ in the plateau (Top1) topography was significantly higher ($H = 253.615$, $p < 0.001$) during the rainy season (20.691 ± 0.563 g CO₂ m⁻² d⁻¹) compared to the dry season (7.388 ± 0.292 g CO₂ m⁻² d⁻¹). Despite daily irrigation during the dry season and the occurrence of a La Niña year, the fluxes were considerably higher during the rainy season, both when comparing the L and the R. Root biomass did not differ ($p > 0.05$) between the seasons; however, soil moisture (Us) mirrored the differences in FCO₂, being significantly higher ($H = 19.355$, $p < 0.001$) during the rainy season ($23.118 \pm 0.765\%$) compared to the dry season ($8.641 \pm 0.508\%$). On the other hand, soil temperature (Ts), although showing only a slight difference, was significantly higher ($H = 30.171$, $p < 0.001$) during the dry season (27.989 ± 0.071 °C) compared to the rainy season (27.371 ± 0.075 °C). Several studies in tropical forests have revealed pronounced seasonal fluctuations in CO₂ gas fluxes, with higher emissions during the rainy season compared to the dry season [37,40–42], a pattern also observed in an agroforestry system in Panama [43]. The data suggest that, despite irrigation during the dry season, it may not be sufficient to maintain soil productivity in upland açaí plantations.

During the dry season, the influx of CH₄ from the atmosphere into the soil of the açaí plantation was significantly higher ($H = 42.392$, $p < 0.001$) in Top2 (-0.539 ± 0.034 mg CH₄ m⁻² d⁻¹) compared to Top1 (-0.332 ± 0.024 mg CH₄ m⁻² d⁻¹). Only in Top2 was the CH₄ influx significantly higher ($H = 8.134$, $p < 0.01$) in the lines (L) (-0.670 ± 0.051 mg CH₄ m⁻² d⁻¹) compared to the streets (R) (-0.409 ± 0.052 mg CH₄ m⁻² d⁻¹) during the dry season. These results differ from those observed in an *A. mangium* plantation in Indonesia [37], where the CH₄ influx from the atmosphere was higher in the plateau compared to the lowland. As previously mentioned, both soil moisture (Us) and microbial biomass were higher in Top2, explaining the greater microbial activity and, consequently, the higher CH₄

influx from the planetary atmosphere. We understand that the higher Us in the lowland ($11.085 \pm 1.036\%$) was not sufficient to negatively influence the permeability of CH_4 and atmospheric O_2 into the soil [9,44], allowing the influx of CH_4 from the atmosphere to be consumed in the soil.

Only in Top2 was the influx of atmospheric CH_4 significantly higher ($H = 8.134$, $p < 0.01$) in the L ($-0.670 \pm 0.051 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$) compared to the R ($-0.409 \pm 0.052 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$). As previously shown, in this same topography, soil moisture (Us) was higher in L compared to R, meaning that the activity of methanotrophs was not hindered at Us levels close to 29%. In fact, the higher Us in the planting lines enhanced the activity of these organisms compared to the streets, and the diffusion of CH_4 and atmospheric O_2 into the soil was not impaired. When comparing only Top1, seasonality did not influence the influx of atmospheric CH_4 ($p > 0.05$), with values of $-0.360 \pm 0.031 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$ during the rainy season and $-0.291 \pm 0.038 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$ during the dry season.

Methane (CH_4) has a global warming potential 32 times greater than that of CO_2 over a 100-year period [45]. In this context, the removal of 1 Mg (Mega gram) of CH_4 has a significant impact on global warming [46]. Additionally, with an average tropospheric lifetime of about 10 years [47], land-use practices that reduce CH_4 emissions or contribute to the capture of atmospheric CH_4 can play a major role in global climate change mitigation. In this regard, organic açaí plantations in upland areas are estimated to absorb an average of $1.6 \pm 0.080 \text{ kg CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$, slightly lower than the values predicted in previous studies for different ecosystems, particularly when compared to the $2.7 \text{ kg CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$ for tropical soils [48] and significantly lower than the $2.5 - 4.0 \text{ kg CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$ removed by a secondary forest enriched with leguminous trees [41]. However, the atmospheric methane uptake is quite close to the $1.0 \text{ kg CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$ reported for a secondary forest in the eastern Amazon [9] and similar to the $1.6 \pm 0.9 \text{ kg CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$ removed by the soil in the Tapajós National Forest [49]. Most importantly, land use with organic and homogeneous açaí plantations in upland areas does not produce methane, even with the use of irrigation.

4.2. Soil Carbon Flux During the Rainy Season in Upland Planting Compared to Estuary Floodplain

It is important to note that during the rainy season, measurements in ATF and AV were conducted simultaneously using two laboratory-calibrated devices with no statistical variation between them. The FCO_2 in ATF ($16.176 \pm 0.347 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$) was significantly higher ($H = 19.286$, $p < 0.001$) than the flux in AV ($12.813 \pm 0.477 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$). On the sampling days and at all sampled times, the FCO_2 was higher in ATF compared to the efflux in AV (Figure 4A). Studies comparing CO_2 efflux between upland and floodplain ecosystems are scarce in the literature, especially those that measure simultaneously in both locations. Therefore, our comparison can only be made across distinct sites, though efforts were made to maintain similar ecosystem variations. Two-year measurements conducted in the Caxiuanã National Forest showed that the flux on the plateau (sandy soil) was 21.0% higher than in the lowland (clay soil) [38]. A study conducted in a region with significant topographic variation (25 m between plateau and lowland) in China, found that the plateau area produced 11.9% more CO_2 [50]. Similarly, in a topographic variation study in Guyana, the FCO_2 was 11.7% higher on the plateau compared to the lowland [35]. Consistent with these studies, our results during the rainy season show a 20.8% higher CO_2 production in the upland area (sandy soil - plateau) compared to the floodplain area of the Amazon estuary (clay soil - lowland).

Some studies suggest that the difference in soil FCO_2 between plateau and lowland is related to higher root biomass in sandy soils compared to clay soils [51]. In the present study, the higher CO_2 efflux in ATF during the rainy season can be explained by root biomass, as the total live root biomass in ATF ($11.839 \pm 1.041 \text{ Mg ha}^{-1}$) was twice as high ($p < 0.001$) compared to AV ($5.643 \pm 0.891 \text{ Mg ha}^{-1}$). However, FCO_2 during the rainy season was negatively correlated with fine root (RF) and positively correlated with coarse root (RG) and total root (TR) (Table 2). Unfortunately, we were unable to measure microbial carbon and nitrogen during this period, which would have allowed for a more detailed discussion of these results. Nevertheless, the entry of water into the soil, whether through rainfall, irrigation, or tidal movement, is associated with the immediate replacement of air-filled pores with water. This influx of water can initially expel air from the soil pores and subsequently form an insulating layer, hindering the diffusion of CO_2 from the soil to the atmosphere

[52], thereby reducing soil respiration [53]. Supporting this, during the rainy season in ATF, FCO_2 was positively correlated with soil moisture (Us) and soil temperature (Ts), while negatively correlated with relative humidity (UR) and atmospheric pressure (Pa) (Table 2). Other studies have also indicated correlations between FCO_2 and temperature [54,55] as well as soil moisture [56].

During the same rainy season, the CH_4 efflux in AV ($1.033 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$) was significantly higher ($H = 122.733$; $p < 0.001$) than the CH_4 influx in ATF ($-0.360 \text{ mg CH}_4 \text{ m}^{-2} \text{ d}^{-1}$). On all analyzed days, a high production of CH_4 was observed in AV, while an influx of CH_4 was recorded in ATF (Figure 4B). The production/influx of CH_4 are microbiological processes predominantly controlled by the absence/presence of oxygen, respectively, and the availability of easily degradable biomass [57]. Consequently, the higher soil moisture (Us) in AV (Table 1) facilitates the proliferation of methanogenic processes (microbial production of CH_4). In contrast, aerobic soils in ATF promote methanotrophy (microbial consumption of CH_4). This explains the negative correlation with soil temperature (Ts) and the positive correlation with soil moisture (Us) (Table 2), as Ts negatively affects the physiology and proliferation of microorganisms, while Us positively influences root growth, respiration, and microbial activity. In upland areas (ATF) with homogeneous organic açaí plantations, 34.9% of the CH_4 produced in managed floodplain areas for açaí production in the estuary is removed daily.

Soils in tropical upland areas are generally considered sinks for atmospheric CH_4 , and changes in land use, such as the homogeneous planting of açaí in this case, can reduce the intensity of this sink [58]. The influx of atmospheric CH_4 in the organic açaí plantation in upland areas during the rainy season was $1.7 \pm 0.1 \text{ kg CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$, while the production of CH_4 in the estuarine floodplain during the same period was $4.6 \pm 0.9 \text{ kg CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$. Concurrent measurements during the rainy season revealed that CH_4 production in AV was 2.7 times higher compared to the uptake in ATF (Figure 5B). Studies in the state of Rondônia (Brazil) showed that during the rainy season, pasture soils produced $6.1 \text{ kg CH}_4\text{-C m}^{-2} \text{ yr}^{-1}$, whereas soils in primary forest areas consumed $1.1 \text{ kg CH}_4\text{-C m}^{-2} \text{ yr}^{-1}$ [59]. It is understood that in the Amazon, soils with less than 35–40% of pore space filled with water act as CH_4 sinks, while those above these values act as sources [60]. In ATF, the soil had an average water content of 23.1%, while in AV it was 53.3%, which appears to align with this premise. The results presented here fall within the range of consumption reported for fine-textured soils in the Amazon rainforest, which was $1.5 - 2.0 \text{ kg CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$ [9]. Considering that CH_4 has a global warming potential 32 times greater than CO_2 over a 100-year period [45], the production of CO_2 -equivalents ($\text{CO}_2\text{-eq}$) in ATF was $59.1 \text{ Mg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$, while in AV it was $49.3 \text{ Mg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$.

4.3. Annual Soil Carbon Flux in Upland Planting Compared to Estuary Floodplain

FCO_2 was positively correlated with FCH_4 in AV during the rainy season and negatively correlated in ATF during the dry season (Table 2). In ATF, the sandy soil facilitates air exchange with the atmosphere, enhancing soil respiration and methane oxidation by methanotrophic organisms [61]. This process is hindered in AV due to the highly clayey soil and elevated moisture levels [9,60], as well as the anoxia caused by tidal water movement, which creates conditions favorable for the proliferation of methanogenic bacteria [62].

The increase in CO_2 efflux between the rainy and dry seasons (Figure 5A) is likely due to an increase in labile carbon available to microorganisms, greater soil oxygenation, resulting in intense microbial activity, and subsequent degradation of soil organic matter [63,64], which intensifies soil respiration. The onset of the rainy season leads to lower CO_2 efflux, which may be necessary to increase soil carbon and recover the carbon lost through decomposition during the dry season [65], when the soil is more aerated.

The efflux/influx of CH_4 in ATF during the rainy season (Figure 5B) was positively correlated with soil moisture (Us), relative humidity (UR), and atmospheric pressure (Pa), while negatively correlated with soil temperature (Ts) (Table 2). In contrast, during the dry season in ATF, FCH_4 was positively correlated with Ts, coarse roots (RG), total roots (TR), and microbial nitrogen (Nm), and negatively correlated with Us, fine roots (RF), Pa, microbial carbon (Cm), and pH (Table 2). In AV,

no significant correlations were found between FCH_4 and the studied variables during either season (Table 2). Our study revealed that an increase in soil moisture driven by precipitation during the wet season leads to higher CH_4 production. In contrast, during the dry season, elevated soil moisture resulting from irrigation reduces CH_4 production. Other studies have similarly demonstrated a correlation between CH_4 flux and soil moisture [66,67], highlighting that soil moisture regulates CH_4 uptake by controlling the diffusion of methane and oxygen within the soil atmosphere. Thus, we can confirm that waterlogged conditions promote the activity of methanogenic bacteria due to anoxia. However, as soil moisture decreases, reduced moisture levels favor the proliferation of methanotrophic bacteria, enhancing the diffusion and consumption of atmospheric CH_4 [68]. This shift in soil moisture may explain the high rates of CH_4 consumption observed in AV (Figure 6D). These results demonstrate that high floodplain areas are not always sources of CH_4 emissions to the atmosphere; under certain conditions, they can also function as significant sinks for this gas.

A significant positive correlation between variations in soil respiration and soil moisture indicates that, within a certain range, soil moisture is directly proportional to soil respiration. However, excessive increases in soil moisture can create anoxic conditions, hinder gas exchange, reduce respiration, and shift soil from CH_4 inflow to efflux. In this sense, the main environmental factors controlling CH_4 exchange between soil and the atmosphere are the proportion of pore space occupied by water, the availability and quality of carbon, and soil temperature [44,69,70]. Additionally, root exudates can increase CH_4 production in the soil due to the heightened demand for O_2 by decomposer organisms, thereby reducing methanotrophy from soil-derived carbon and stimulating intense, short-term changes in soil organic matter recycling (priming effect) [71]. This may explain the strong positive correlation between coarse roots (RG) and total roots (TR) with CH_4 flux during the dry season.

We agree that a limited number of observations of CH_4 fluxes, and the numerous environmental variables associated with its exchange between soil and atmosphere, constrain the parameterization of process based biogeochemical models [72]. This limitation is particularly significant given the complex interplay of factors influencing methane production, oxidation, and transport, such as soil moisture, temperature, organic matter availability, and microbial community dynamics. As a result, models often rely on simplified representations of these processes, which can lead to uncertainties in predicting CH_4 emissions under varying environmental conditions.

To improve model accuracy, there is a pressing need for more comprehensive and high-resolution datasets that capture the spatial and temporal variability of CH_4 fluxes across different ecosystems. Additionally, integrating multi-disciplinary approaches, such as combining remote sensing, eddy covariance measurements, and laboratory experiments, could enhance our understanding of the underlying mechanisms driving methane dynamics. Advances in machine learning and data assimilation techniques also offer promising avenues for refining model parameterizations and reducing uncertainties. Ultimately, a more robust representation of CH_4 fluxes in biogeochemical models is crucial for accurately projecting future methane emissions and informing climate change mitigation strategies.

5. Conclusion

The upland area produced a total of $59.1 \text{ Mg CO}_2\text{-eq ha}^{-1} \text{ year}^{-1}$, while the floodplain area produced $49.3 \text{ Mg CO}_2\text{-eq ha}^{-1} \text{ year}^{-1}$. During the dry season, spatial heterogeneity in the greenhouse gases flux was identified, with soil CO_2 flux and CH_4 consumption being higher in the lowland compared to the plateau, across all hours and days analyzed. In the rainy season, simultaneous measurements revealed that the CO_2 flux is higher in the upland, while CH_4 flux was greater in the floodplain, with atmospheric CH_4 consumption on upland. In the floodplain, CH_4 production was observed in the rainy month and consumption in the dry month. In the upland açaí plantation area, CO_2 fluxes were higher in the planting row compared to the streets, in both seasons of the year, with no variation in the atmospheric CH_4 consumption. Soil moisture and temperature appear to control gas fluxes only in the upland, but in contrasting ways during the two seasons analyzed. Soil organic matter plays a vital role in preserving water and microorganisms, enhancing ecosystem productivity

in uniform açaí plantations and intensifying the transfer of CH₄ from the atmosphere to the soil. However, excessive soil moisture can create anoxic conditions, block gas diffusion, reduce soil respiration, and potentially turn the soil from a sink into a source of CH₄. More detailed studies are needed to understand how greenhouse gas fluxes vary across different topographies in upland areas of the Amazon under agricultural production systems.

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