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# Carbon emissions in hydromorphic soils from an estuarine floodplain forest in the Amazon River

## Emissão de carbono de solos hidromórficos em floresta de várzea estuarina do rio Amazonas

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## ABSTRACT

Carbon dioxide ($CO_2$) is produced only in biological activities. Understanding how soil tillage practices affect the dynamics of $CO_2$ production is important, as these processes are influenced by the temperature and humidity conditions of the place. This paper aimed at quantifying $CO_2$ flux in hydromorphic floodplain soils under different açai palm tree grove management strategies, correlating it with litter deposition, soil environment, and season of the year. Conducted in the city of Mazagão-AP, four areas of açai palm tree groves were selected with different types of management. During the evaluation period (October, November, and December 2012, and February, March, and April 2013), $CO_2$ flux, soil moisture, and temperature were measured, and litter samples were collected. In addition, rainfall data for the region were also obtained. The $CO_2$ fluxes obtained ranged from 0.37 to 28.55 µmol $CO_2$ $m^{-2}$ $s^{-1}$, with a total average of 6.20 µmol $CO_2$ $m^{-2}$ $s^{-1}$. In broad analysis, soil variables did not show significant correlations with $CO_2$ emissions. A positive relationship between flux and litter and soil temperature, as well as a negative relationship with its moisture, were observed only in a few months and specific systems.

**Keywords:** soil respiration; wetlands; Amazon estuary; *Euterpe oleracea* management.

## RESUMO

A produção de dióxido de carbono ($CO_2$) do solo de várzea está relacionada às atividades biológicas, interagindo com sua dinâmica de inundação e manejo. Compreender a forma pela qual práticas de manejo de açaizais afetam as dinâmicas da produção de $CO_2$ é importante, pois elas podem aumentar a emissão em relação à floresta. O objetivo do trabalho foi quantificar o fluxo de $CO_2$ do solo hidromórfico de várzea sob diferentes manejos de açaizais, analisando suas relações com a deposição de serapilheira, ambiente do solo e o período do ano. Realizado no município de Mazagão-AP, foram selecionadas quatros áreas de açaizais com diferentes tipos de manejos. Durante o período avaliado (out/2012, nov/2012, dez/2012, fev/2013, mar/2013 e abr/2013), abrangendo períodos sem inundação (verão amazônico) e com inundação (inverno), foram medidos o fluxo de $CO_2$, umidade e temperatura do solo, e deposição de serapilheira. Além disso, também foram obtidos dados de precipitação da região. O fluxo de $CO_2$ variou de 0,37 a 28,55 µmol $CO_2$ $m^{-2}$ $s^{-1}$, com média de 6,20 µmol $CO_2$ $m^{-2}$ $s^{-1}$. No geral, as variáveis do solo não apresentaram correlações significativas com a emissão de $CO_2$. Apenas em alguns meses e em sistemas específicos, observou-se relação positiva do fluxo com a serapilheira e temperatura do solo e relação negativa com sua umidade.

**Palavras-chave:** respiração do solo; áreas úmidas; estuário amazônico; manejo de *Euterpe oleracea*.

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## Introduction

Global observations recorded by the World Meteorological Organization (WMM) until 2018 show that carbon dioxide concentration ($CO_2$) in the atmosphere is now 147% higher than in the pre-industrial era. This occurs, mainly, due to emissions from the burning of fossil fuels, deforestation, and other changes in soil management. Radiative forcing of long-lasting greenhouse gases (GHGs) has increased 43%, with 81% of that percentage related to $CO_2$ (WMO, 2019). It is common sense that greenhouse gases, notably $CO_2$ and methane ($CH_4$), are more and more associated with the rising of the Earth's surface temperature and other climate imbalances.

In Brazil, near 74% of GHG emissions occur due to soil management, being 36% in the Amazon (Seeg, 2018), which can release carbon stocks from trees and the land. Forests and forest lands are the primary land sinks for atmospheric carbon (C), that is the reason why vegetation cover may change C stocks, both from arboreal biomass and lands (Gomes, 2014). In the case of floodplains, it is modulated by floods, because in anaerobic environments such as saturated soils exposed to anoxia conditions, $CH_4$ is also formed, and it is another important GHG occurring during the process of organic matter decomposition (Bartlett et al., 1990).

In the Amazon region, floodable areas are covered with floodplain forests, meadows, *igapós*, and mangroves (Prance, 1980). Floodplains are seasonally inundated by the waters of whitewater rivers with a high load of sedimentary material of Andean and pre-Andean origin (Wittmann et al., 2010). In the Amazon estuarian region, these forests are subjected to a daily cycle of floods and ebbs, due to the effect of oceanic tides (Almeida et al., 2004). In addition to daily variation, tidal cycles also vary depending on the moon and the seasonality of precipitation.

In the first half of the year, when there is greater precipitation (Amazonian winter), the level of the Amazon River rises, increasing the flooding capacity of the forest by its waters dammed by ocean tides. In the second semester (Amazonian summer), precipitation is lower, with the least rainy months being September, October, and November (Souza and Cunha, 2010). During this period, most of the estuarine floodplain area is not flooded, and flooding may occur for a shorter period, only in low floodplains and in large spring tides (Nunes Filho, 2016).

Due to flooding, floodplain environments are considered wet areas that have several peculiar characteristics, such as their floristic diversity. Many species are endemic to this environment and play an important role in balancing the ecosystem and maintaining biodiversity (Lima et al., 2014).

In estuarine floodplain forests, families usually extract natural resources as a livelihood opportunity because several forest species of high economic value are found in these areas. Among these, the açai palm tree (*Euterpe oleraceae* Mart.) stands out. This palm tree provides the heart of palm and açai berries (Almeida and Jardim, 2012; Farias, 2012). In the last three decades, açai palm trees have been standing out for their positive impact on the economy, with the extractive exploitation of palm hearts and, since the 1980s, with the increase in the consumption of açai drink (Azevedo, 2010), named locally as "açai wine". Due to the countless alternative uses of açai, strategies were proposed to maintain the production and sustainability of açai palm tree groves, among them: the establishment of a local production organization and implementation of public policies to aid in the conservation of traditional management practices, among other suggestions (Almeida and Jardim, 2012).

As a result, this drink, which has been consumed as part of the meals of Amazonian populations for centuries, has gained national and international notoriety in recent decades. Thus, riverside populations have been increasingly dedicating themselves to the management of açai palm tree groves, increasing the areas and production, to meet the demand of local, regional, national, and international markets (Oliveira et al., 2017; Tagore, 2017). The production of açai berries in 2018 turned around approximately 600 million Brazilian *reais*, nearly half of the value of all Brazilian extractive production (IBGE, 2019).

The empirical management of açai trees native to the Amazon estuary includes selective thinning of trees and other palm trees, in addition to enriching the area with açai trees to increase the penetration of sunlight and fruit production. The intensity of these interferences depends on the profile of the producers, which can be classified into different categories, from light management, carried out more frequently during the harvest period, to more intensive management, when there is excessive thinning of the forest (Araújo and Navegantes-Alves, 2015).

However, even in the case of light management, these interferences can affect aspects of ecosystem functioning. The thinning and pruning of trees, for example, by introducing organic material into the soil in addition to the natural fall, can influence their biological activity, especially biogeochemical cycling and decomposition of organic matter by edaphic organisms. Thus, depending on the type of management, there may be a greater or lesser $CO_2$ flux inside the soil, due to root respiration and the activity of organisms that make up the soil (Primavesi, 2002), including, hydromorphic soils.

As the flux of $CO_2$ from the soil is the result of the interaction of various chemical, physical and biological processes that favor the production and transportation of this gas within the soil, both biotic and abiotic factors can be related to $CO_2$ flux (Silva et al., 2016), among them, temperature and humidity (Panosso et al., 2008). Regarding humidity, there is an optimal level, which favors the escape of gases. When this limit is exceeded, the water forms a protective layer in the soil, inhibiting the emission of $CO_2$ into the atmosphere, when the area floods (Sotta et al., 2004).

The exchanges of $CO_2$ between vegetation and the atmosphere create a balanced system that consists of the difference between the gains and losses of C from biological processes, which are fundamental in the absorption and release of greenhouse gases, such as $CO_2$ (Heimann and Reichstein, 2008). C balance may be more important than simply quantifying registers, as it is usually done in most works. The recognized lack of studies on carbon dynamics is even more accentuated in floodplain environments in the Amazon estuarine floodplain, especially in areas where açai palm tree groves are managed. Thus, this work aimed to quantify $CO_2$ flux from lowland soils under managed and unmanaged açai palm tree groves, establishing its relationship with litter deposition, soil environment, and season of the year, due to periods with different flooding capacities of the area by the tide.

## Materials and Methods

This study was conducted in açai palm tree groves in an estuarine floodplain forest, in the city of Mazagão, south of the State of Amapá, Brazil, with an area of approximately 1,318,900 ha (00º06'58.62" S and 51º17'20" O). According to Koppen's classification, the climate of the region is classified as Ami, equatorial super-humid (Brasil, 1974; Kottek et al., 2006), with an average annual temperature of 28.3°C and annual rainfall of 2,927 mm per year$^{-1}$. Rainfall is concentrated from January to June, and the typical dry season is from September to November (Inmet, 2019).

The vegetation is classified as Alluvial Dense Rainforest (IBGE, 2012), with a large number of arboreal individuals belonging to few species and families, with low diversity and high floristic similarity (Carim et al., 2008). The relief is relatively flat, with recessed areas and a shallow water table (IEPA, 2002). The soil is classified as melanic typic eutrophic gleysol Ta with texture, predominantly silty, and with high fertility (Pinto, 2014).

Floodplain forests are energetically open ecosystems, associated with the tidal regime of the whitewater river, in addition to presenting topographical differences as it is distanced from the main riverbank (Freitas, 2019). The interior of the forest is flooded daily, ranging from a high tide (high tide — maximum level reached by river waters) to a low tide (low tide — minimum level reached by river waters), because the waters of the Amazon River and its tributaries are dammed by the waters of the Atlantic Ocean (Nunes Filho, 2016). The phases of the moon (new and full moon) and the rainfall also increase the volume of the Amazon River, causing the water level in its channels to raise, overflowing the main river and flooding the entire forest (Pinto, 2014; Nunes Filho, 2016).

To quantify carbon dioxide flux from the soil, four areas of açai palm tree groves were selected:

- SYSTEM 1: native açai palm tree grove, without any type of management;
- SYSTEM 2: açai palm tree grove with traditional management, as performed by agricultural extractivists;
- SYSTEM 3: açai palm tree monoculture at Embrapa Amapá;
- SYSTEM 4: native açai palm tree grove, located close to the monoculture.

Systems 1 and 2 were located in the district of Mazagão Velho, and systems 3 and 4 were located near the city of Mazagão Novo. In each location, one managed and one reference açai palm tree grove located in an unmanaged forest were assessed.

The four açai palm tree grove systems were selected based on the following criteria:

- the açai palm tree grove had to be flooded during high tide;
- the number of clumps of açai trees had to be greater than the average of the forest;
- it had to be close to the managed areas for better comparison.

For each açai palm tree grove, an area of 50 m × 50 m was segregated and subdivided into four quadrants of 25 m × 25 m. In each quadrant, four sampling points were allocated, equidistant 12.5 m from each other, making up 16 collection points per area (Figure 1).

$CO_2$ flux measurements were performed monthly, from October to December 2012, and from February to April 2013, except for January, when no evaluation was performed for being the transition period between the two evaluating periods:

- the period with lower precipitation and flooding of the areas (late Amazonian summer);
- the three months of greatest rainfall (peak of the Amazonian winter).

An EGM-4 infrared gas analyzer (PP Systems, Environment Gas) coupled to a closed-circuit chamber was used. A small part of the cutting ring of the air retention chamber was inserted 1 cm into the ground, without removing the litter to cause minimal impact on the soil and rhizosphere, so that there would be no gas exchange between the sampled volume inside the chamber and the surrounding atmosphere. The chamber was left for 5 minutes at each point, according to the methodology used by Sotta et al. (2006). Measurements were taken between 9 a.m. and 3 p.m.

At each point, in addition to $CO_2$ flux, the following measurements were also taken: soil temperature, recorded in degrees Celsius at 5 cm depth, obtained with the aid of the STP-1 (Soil Temperature Probe)

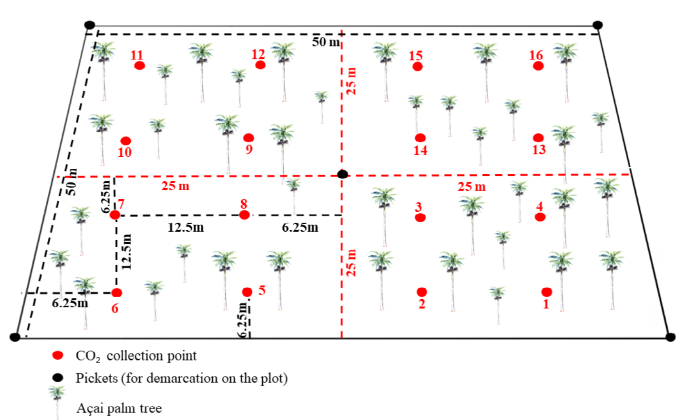


**Figure 1 – Schematic drawing of the sampling design of the açai area, divided into four quadrants and their respective collection points.**

sensor coupled to EGM-4; and soil moisture, obtained through a portable HH2 sensor — Moisture Meter, using Delta-T soil moisture sensors.

Rainfall data were obtained from the conventional meteorological station of Macapá (AP), located approximately 41 km from the city of Mazagão (AP).

To verify if there was any variation in the soil due to the types of açai palm tree grove management, soil and litter samples were collected. The litter was collected monthly, at the same evaluation points, after measuring the $CO_2$ flux. To collect the litter, a cylindrical iron collector with a cutting edge and an area of 0.13 $m^2$ was used. Subsequently, the samples were sent to Embrapa Amapá's laboratory, where they were placed in a forced circulation oven, at 65°C, until they showed constant weight. Monitoring was carried out with two daily weighing sessions, removing the samples from the oven and weighing each sample at once. After stabilization and three weighing sessions with no weight reduction, data from the last evaluation were entered in a spreadsheet as dry biomass until constant weight.

Soil samples were collected in October 2012 and April 2013, the first and last months of evaluation, which represent the Amazonian summer and winter, respectively. To assess physical soil properties, 16 soil samples (undisturbed) were collected per plot, using a 98 $cm^3$ metallic ring attached to an auger. To assess the chemical properties and texture of the soil, five simple soil subsamples (deformed) were collected per quadrant, with the aid of a Dutch auger at a depth of 0.10 cm. The samples were homogenized, forming one composed sample per quadrant, totaling 4 composed samples per plot. All analyses were carried out in the Soil Laboratory of Embrapa AP, according to Embrapa's methodology (2011).

In the different management systems, typical hydromorphic soil characteristics are predominant in the Amazon estuary, with silty loam texture, a high number of exchangeable bases, and medium to high levels of organic matter. They are eutrophic soils, with base saturation above 50%, and high fertility (Table 1).

Data were analyzed using descriptive statistics, homoscedasticity tests, and normality of residuals. The relationships between the $CO_2$ flux and the litter deposited in each type of açai palm tree grove, as well as soil moisture and temperature, were analyzed using Spearman's correlation. To assess whether $CO_2$ flux is altered by the management of native açai palm trees and whether the response depends on the variation over the months, a multiple analysis of variance (Shapiro-Wilk test) was performed with repeated measurements over time. A posteriori statistical analysis, to isolate the effects between the levels of the factors, was performed by comparing the confidence intervals generated with 95% certainty. All statistical analyses were performed using Statistica 7.0 trial version software (Statsoft, 2011).

## Results and Discussion

The emission of $CO_2$ in the hydromorphic soils of floodplain forests, in the studied açai palm tree groves, ranged from 0.37 to 28.55 μmol $CO_2$ $m^{-2}$ $s^{-1}$, with an average of 6.20 μmol $CO_2$ $m^{-2}$ $s^{-1}$. The temperature of these soils also varied, with a minimum of 25.2°C, a maximum of 30.5 °C, and an average of 27.2°C. The average soil moisture was 39.8% and the average amount of the litter pool was 49.52 g $m^2$ (Table 2).

In general, the average $CO_2$ flux found in this study was higher than the average found in studies on tropical forests in the Amazon, in dryland environments (Pinto-Júnior et al., 2009; Silva Júnior et al., 2013), being the same as the average found by Teles (2018) in the Central Amazon only. For the floodplain environment, studies on $CO_2$ emission are incipient, but other authors have concluded that hydromorphic soils have greater microbial activity than drained soils (Acosta et al., 2019). This was also verified in a laboratory experiment when soils that were irrigated up to field capacity (100%) and those that were flooded and kept under flooding, with a water depth of 2 cm above the ground, were observed to be the ones with the highest accumulation of $CO_2$ emission in 64 days (Denardin et al.,

**Table 1 – Average of soil properties, at 10 cm depth, in the four açai palm tree grove management systems (S), in a lowland estuarine forest in the city of Mazagão (AP).**

| Soil Properties | S1 | S2 | S3 | S4 |
|---|---|---|---|---|
| pH | 5.8 | 5.8 | 5.6 | 5.8 |
| MO (g $kg^{-1}$) | 51.6 | 42.4 | 44 | 35.7 |
| P (mg $dm^{-3}$) | 19.1 | 14.7 | 6.1 | 18.4 |
| K ($cmol_c$ $dm^{-3}$) | 0.2 | 0.2 | 0.2 | 0.4 |
| Ca+Mg ($cmol_c$ $dm^{-3}$) | 13.4 | 13.6 | 12.2 | 11.2 |
| Ca ($cmol_c$ $dm^{-3}$) | 10.6 | 10.3 | 9.15 | 8.15 |
| Al ($cmol_c$ $dm^{-3}$) | 0.1 | 0.1 | 0.3 | 0.1 |
| H+Al ($cmol_c$ $dm^{-3}$) | 4.6 | 4.7 | 6.8 | 5.5 |
| SB ($cmol_c$ $dm^{-3}$) | 13.6 | 13.8 | 12.4 | 11.6 |
| CTC ($cmol_c$ $dm^{-3}$) | 18.3 | 18.5 | 19.1 | 17.2 |
| V (%) | 74.9 | 74.7 | 64.9 | 68 |
| M (%) | 1 | 1 | 2.3 | 1.5 |
| Clay (g $kg^{-1}$) | 210.4 | 232.1 | 208.5 | 192.5 |
| Total Sand (g $kg^{-1}$) | 69.5 | 62.6 | 116.2 | 79.4 |
| Silt (g $kg^{-1}$) | 720.1 | 705.2 | 675.2 | 738.1 |
| DA (g $cm^{-3}$) | 0.8 | 0.8 | 0.8 | 0.8 |
| DP (g $cm^{-3}$) | 2.3 | 2.4 | 2.5 | 2.5 |
| Porosity (%) | 60.7 | 64.7 | 66 | 68.5 |
| Moisture (%) | 61.6 | 62.3 | 55.2 | 66 |

pH: hydrogen potential; MO: organic matter; P: phosphorus; K: potassium; Ca+Mg: calcium and magnesium; Ca: calcium; Al: aluminum; H+Al: exchangeable acidity; SB: base sum; CTC: cation exchange capacity; V: base saturation; M: aluminum saturation; DA: apparent density; DP: particle density. S1 and S4 Systems (açai palm tree groves in the forest, no management), S2 (traditional management), S3 (monoculture).

**Table 2 – General descriptive statistics (n = 384) of carbon flux and soil variables in an estuarine floodplain forest with açai palm tree groves in the city of Mazagão (AP), after monthly measurements from October 2012 to April 2013.**

| Parameters | $CO_2$ Flux ($\mu$mol m$^{-2}$ s$^{-1}$) | Temperature (°C) | Moisture (%) | Litter (g m$^{-2}$) |
|---|---|---|---|---|
| Minimum | 0.37 | 25.2 | 8.8 | 5.23 |
| Maximum | 28.55 | 30.5 | 85.3 | 304.80 |
| Average | 6.20 | 27.2 | 39.8 | 49.52 |
| Median | 5.30 | 27.2 | 42.0 | 35.01 |
| Variance | 13. 22 | 1.36 | 260.6 | 1,813.36 |
| Asymmetry | 2.24 | 0.23 | -0.03 | 2.37 |

2020). Therefore, a possible explanation is the increased respiration of microorganisms associated with high moisture levels and flooding of the soil in the floodplain environment.

Additionally, the higher fertility and lower acidity of the soils in the studied açai palm tree groves (Table 1), compared to dryland soils in the Amazon, usually with lower pH values (Worbes, 1997), may also help explain the higher $CO_2$ flux averages in the floodplain. It has been proven that high active acidity conditions and low pH contribute to reduced microorganism activity (Silva et al., 2014; Alves and Martins, 2015).

Another factor that must also be considered to explain a high flux of $CO_2$ in the floodplain is its phytosociology, with a greater abundance of palm trees (Almeida et al., 2004; Jardim et al., 2007; Carim et al., 2008; Souza and Jardim, 2015) compared to dryland forests. Palm trees, like grasses, have a fasciculate root system, with greater production of fine roots that are metabolically more active, which can lead to higher $CO_2$ emissions (Hanson et al., 2000; Konda et al., 2010).

In general, when analyzing all data from the systems collectively, there were no significant correlations between the $CO_2$ flux and the environmental variables analyzed. In the case of soil temperature, the low variability between areas over time may explain the absence of correlations. In the case of soil moisture and the amount of litter, factors for which a greater association would be expected, the lack of a general correlation indicates that this may depend on the period in which the areas are flooded and on the specific interactions of the factors with each system. Thus, it is likely that the variables that determine $CO_2$ emissions from the soil in these açai palm tree groves are associated with the different characteristics of the local vegetation and the internal spatial variability of each system. It has already been demonstrated that $CO_2$ emissions in native forests are complex phenomena, and it is not possible to identify a single attribute of the soil or the environment that would explain, in isolation, its variation in space (D'Andrea et al., 2010).

The multiple analysis of variance of the responses ($CO_2$, litter, humidity, and temperature), evaluated between the levels of management systems of the açai palm tree groves with repeated measurement over time, showed a significant response (Wilks = 0.002; F = 13.9; $p < 0.001$). This indicates significant differences between the management systems, of the means of at least one of the evaluated responses. When analyzing only the main response of interest in this paper, which is the emission of $CO_2$, it appears that the interaction between types of management and the temporal variation over the months of data collection was also significant (F = 4.430, $p < 0.001$). However, the comparison between management systems, considering the average of total $CO_2$ flux over all the monitoring months, was not significant (F = 1.241, p = 0.303). So, this variable will be analyzed later, considering the interactions with each management system.

On the other hand, the variation in $CO_2$ flux over the months of data collection, the average of all areas for each evaluation, was significant (F = 3.054, p = 0.010). This can be seen in Figure 2, mainly between November (5.12 $\mu$mol $CO_2$ m$^{-2}$ s$^{-1}$) and December (7.18 $\mu$mol $CO_2$ m$^{-2}$ s$^{-1}$). It appears that, even with a high variation between the averages, there are excluding confidence intervals that do not capture other averages, which ensures significant differences in $CO_2$ emissions between months.

The lower $CO_2$ emission in November may be related to the lower precipitation in this month and the previous one, with precipitation below 20 mm, resulting in lower soil moisture in November and lower river levels. However, in October, soil moisture was higher, even with less rainfall than in November (Table 3), which may be a result of accumulated rainfall in September and/or flooding of the areas by a tide before measurement. During this period, the areas are only flooded in the high tides.

Even though it is a typical Amazonian summer month, also with little rainfall, October had a greater emission of $CO_2$ from the soil than November. This was probably due to rainfall that occurred at the beginning of the second fortnight, a period close to the fortnight period of measurement. Although rainfall was low [9.6 mm] (Inmet, 2012), it was enough to generate greater soil moisture compared to November, when rainfall was concentrated in the last two days of the month, after the evaluations were carried out.

December had the maximum value of $CO_2$ flux, both in terms of average values (7.18 $\mu$mol $CO_2$ m$^{-2}$ s$^{-1}$) and absolute values, which can be explained by constant rainfall in the beginning, with an increase of 329 mm per month, providing an immediate stimulus to soil decomposing microorganisms as a response to increased water availability. After a dry period, the first rainfall and the accumulation of a greater amount of organic matter in the soil favor an increase in $CO_2$ flux (Nunes, 2003), in addition to filling the soil pores with water, expelling $CO_2$ (Zanchi et al., 2003). This variation in $CO_2$ flux according to seasonality is mainly due to rainfall patterns and water potential between the soil and the atmosphere (Salimon, 2003). The highest $CO_2$ fluxes in the rainy season, regardless of the system, corroborate other studies carried out in the Amazon (Dias, 2006; Silva Júnior, 2008; Zanchi et al., 2012; Oliveira, 2014; Lessa, 2016).

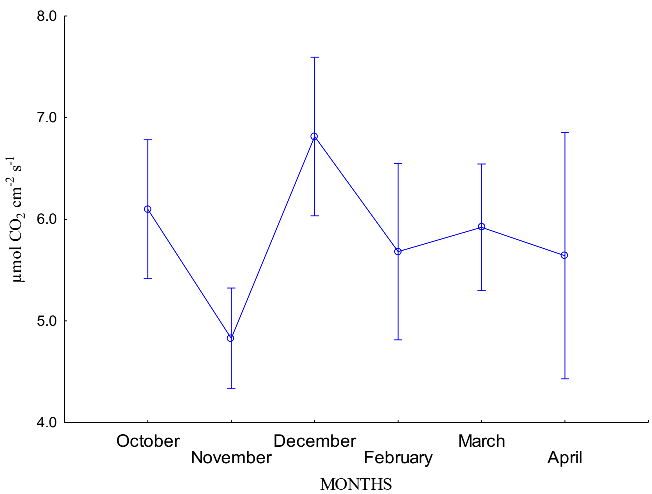


**Figure 2 – The average flux of $CO_2$ from the soil (with a 95% confidence interval — CI), considering all the different management systems of açai palm tree groves, depending on the months of evaluation (Oct/2012, Nov/2012, Dec/2012, Feb/2013, Mar/2013, and Apr/2013), in an estuarine floodplain forest in the city of Mazagão (AP).**

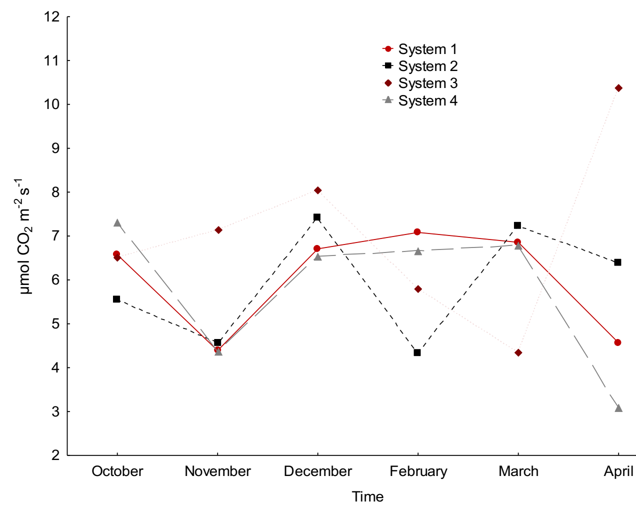


**Figure 3 – Average monthly flux of $CO_2$ from the soil, from October 2012 to April 2013, as a result of the type of açai palm tree grove management in an estuarine floodplain forest in Mazagão (AP). Systems 1 and 4 (açai palm tree groves in the forest, no management), 2 (traditional management), 3 (monoculture).**

**Table 3 – Total monthly precipitation values and average soil moisture and temperature values over the months of study conduction on $CO_2$ emission in an estuarine floodplain forest in the city of Mazagão (AP).**

| Months | Precipitation (mm) | Soil moisture (%) | Soil temperature (°C) |
|---|---|---|---|
| October | 9.6 | 26.7 | 26.7 |
| November | 16.4 | 17.9 | 28.1 |
| December | 111.2 | 38.6 | 28.5 |
| January | 328.8 | --- | --- |
| February | 427.4 | 46.9 | 25.8 |
| March | 387.7 | 53.3 | 27.8 |
| April | 516.5 | 55.3 | 27.0 |

Source: Inmet (2012) and elaborated by the authors.

The significant interaction between types of management and temporal variation shows that differences in average $CO_2$ emissions between the systems depend on the period analyzed and vice versa. Thus, it is important to analyze the behavior of each of the systems throughout the entire collection period, as shown in Figure 3. It is verified that the two reference açai palm tree groves, System 1 and System 4, located in an unmanaged forest, had a unique pattern of variation over time despite being located in different spots. There were lower emissions in November and April, and December to March had values of approximately 7 µmol $CO_2$ $m^{-2}$ $s^{-1}$. This is consistent with the seasonal variation expected for natural systems in estuarine floodplains due to extreme periods of lower (November) and higher (April) flooding capacity of the forests by river waters dammed by ocean tides (Nunes Filho, 2016).

Although soil moisture and periodic flooding favor microbial activity and, consequently, $CO_2$ emission (Denardin et al., 2020), in longer periods of flooding, such as in April and May, this relationship can become negative due to a long anoxia time without soil aeration. Sotta et al. (2004) state that the formation of a water layer on the ground for a long period prevents the emission of $CO_2$ into the atmosphere when the area is flooded.

On the other hand, the managed systems showed different and divergent behaviors over time, justifying the significance of the interaction between the factors. Considering the interactions and differences between the management systems in each month and the differences between the months within each management system, $CO_2$ emissions in the area traditionally managed by riverside communities were observed, in general, to replicate the trends of unmanaged forests. A divergence was only found in February, when there was a greater reduction in this system.

The monoculture of açai trees was the system that showed the greatest divergence and variation. In November, when all the other systems presented similar and low values, the highest $CO_2$ emissions were observed in the monoculture, and in March it was the opposite (Figures 4A and 4B).

In April, when there was a reduction in the other systems, the açai palm tree monoculture area showed a marked increase, reaching the maximum mean value observed during the entire monitoring period, above 10 µmol $CO_2$ $m^{-2}$ $s^{-1}$ (Figure 3). This high average is the result of five measurements (out of the 16 measurements performed in this system in April) above that value, with some measurements close to 20 µmol $CO_2$ $m^{-2}$ $s^{-1}$.

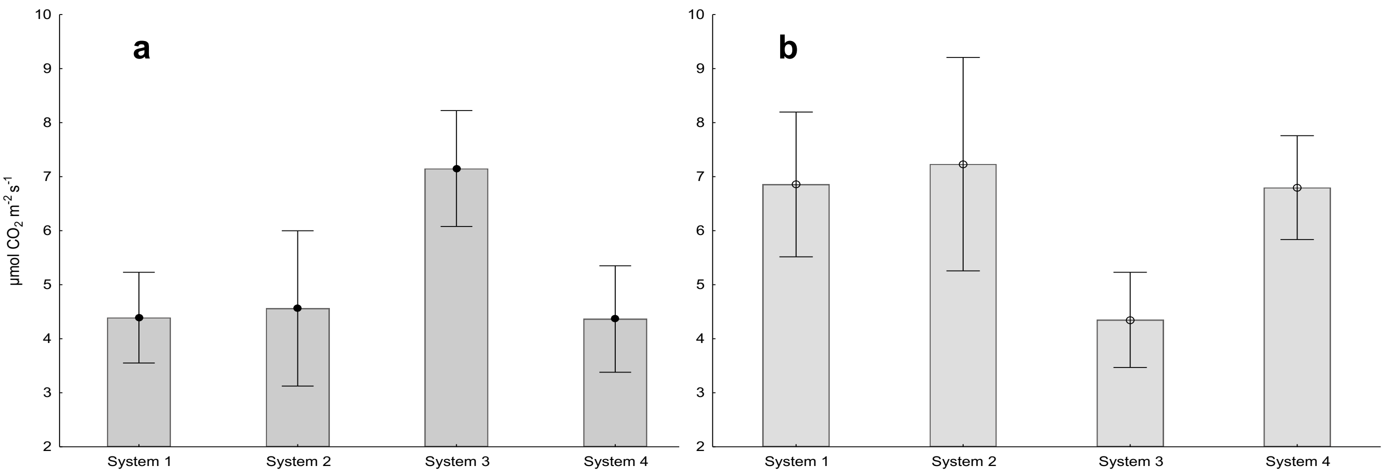


**Figure 4 – Average soil $CO_2$ flux (confidence interval - 95% CI) as a function of the açai palm tree grove management system, in the months of (A) November and (B) March, in an estuarine floodplain forest in the city of Mazagão (AP). Systems 1 and 4 (açai palm tree groves in the forest, no management), 2 (traditional management), 3 (monoculture).**

The greatest significant difference ($p = 0.005$) observed between the systems occurred in April, with greater emissions in System 3 when compared to System 4. This maximum $CO_2$ value, found in the açai palm tree grove of System 3, must be related to the tidal flood (Table 4), which started at the time of flux measurement, causing the $CO_2$ present in the soil to be released into the atmosphere (diffusion process) by the entry of water into the soil.

Sotta et al. (2004) state that water in the soil is an important controller of $CO_2$ flux. Zanchi et al. (2003) claim that after a rainfall event, water fills the pores, forcing the emission of $CO_2$. Vincent et al. (2006) elucidate that if the soil has a moisture content above 40%, there is $CO_2$ emission due to excess water and lack of oxygen in the soil. But this increase in $CO_2$ emission occurs as soon as the pores are filled with water. Over time, it is expected that the flux will decrease considerably since most of the microorganisms that are most efficient in decomposing the organic matter found in the soil are aerobic. With the flooding of the area and the formation of an environment with anoxia, without oxygen availability, the aerobic microbial activity decreases, as already verified by Pinto-Júnior et al. (2009), who found a reduction in the average $CO_2$ flux in the rainy season due to the effect of pore saturation with water and reduced aerobic activity.

The absence of forest and understory in this monoculture system, which is always kept clean with frequent weeding and cleaning, facilitates the inflow and outflow of water from the area when tidal flooding occurs, also facilitating the loss of moisture through evaporation. This probably also contributes to less accumulation of litter and sediment, which are carried away by the tides that invade the area, in addition to determining the existence of a lower abundance of fine roots. The homogeneity and low contribution of litter in the soil, due to the presence in the area of açai trees only, also reduce the contribution of biogeochemical nutrient recycling. In general, monocultures and poorly diversified systems can reduce environmental quality (Silva et al., 2016).

All of these factors affect root respiration and the role of microorganisms in the process of soil decomposition and mineralization, and, consequently, may be associated with a variation in the emission of $CO_2$ into the atmosphere, as well as the saturation of water in the soil during periods of flooding. Therefore, simplifying systems in monocultures of açai palm trees can contribute to their greater susceptibility to environmental variations and, consequently, variability in $CO_2$ measurements over time.

Forest systems have a denser and more heterogeneous litter on the soil surface due to the high presence of arboreal species, in addition to açai trees and other palms, such as *murumuru* (*Astrocaryum murumuru*), in its floristic composition. This also favors the greater contribution of roots, activity, and diversity of microorganisms found in the soil. Systems that have species diversity in space and time enhance the physical structure and chemical composition of the soil, improving energy and the amount of matter retained in the form of organic compounds and edaphic biota, enabling the soil to exercise its functions in nature (Vezzani and Mielniczuk, 2009).

Analyzing the relationships between the variables for each month, there is a negative relationship between $CO_2$ emission and soil moisture in October ($r = - 0.83$; $p < 0.05$) and November ($r = - 0.59$; $p < 0.05$), these months have lower soil moisture and low precipitation when areas are only flooded sporadically. Lowland silty soil is rich in 2:1 clay minerals, such as smectite and illite, favoring contraction movements during the wetting and drying cycles (Pinto, 2014). All these dynamics can cause cracks and the physical release of $CO_2$ through the diffusion process (Guedes, 2007).

Analyzing each system separately, it was possible to verify that in the unmanaged forest, there was a positive correlation between tem-

Table 4 – Time of measurements for Systems 3 (monoculture) and 4 (açai palm tree grove in an unmanaged forest) concerning the tidal dynamics in April, on 04.05.2012, based on the tide table at Port of Santana, Amapá.

| Tidal range (m) | Tide times | $CO_2$ efflux measurement points | System 3 | | Sistema 4 | |
|---|---|---|---|---|---|---|
| | | | Measurement time | Efflux $CO_2$ ($\mu$mol $CO_2$ $m^{-2}$ $s^{-1}$) | Measurement time | Efflux $CO_2$ ($\mu$mol $CO_2$ $m^{-2}$ $s^{-1}$) |
| 0.4 | 07:04 | 1 | 10:36 | 5.10 | 08:21 | 3.09 |
| 2.9 | 12:04 | 2 | 10:42 | 2.95 | 08:26 | 3.10 |
| 0.5 | 19:36 | 3 | 10:48 | 2.52 | 08:32 | 5.71 |
| | | 4 | 10:53 | 3.68 | 08:38 | 5.19 |
| | | 5 | 11:00 | 3.90 | 08:44 | 2.51 |
| | | 6 | 11:06 | 20.99 | 08:50 | 4.37 |
| | | 7 | 11:12 | 7.02 | 08:55 | 4.29 |
| | | 8 | 11:17 | 4.98 | 09:02 | 1.49 |
| | | 9 | 11:22 | 4.43 | 09:09 | 1.69 |
| | | 10 | 11:26 | 4.50 | 09:15 | 1.85 |
| | | 11 | 11:33 | 2.56 | 09:22 | 2.09 |
| | | 12 | 11:39 | 28.55 | 09:27 | 2.14 |
| | | 13 | 11:44 | 26.60 | 09:35 | 3.80 |
| | | 14 | 11:51 | 18.30 | 09:40 | 3.13 |
| | | 15 | 11:57 | 10.46 | 09:47 | 3.51 |
| | | 16 | 12:07 | 19.77 | 09:53 | 1.50 |

perature and $CO_2$ flux in December, both for System 1 ($r = 0.71$; $p < 0.05$) and for System 4 ($r = 0.91$; $p < 0.05$). This may be an indication that increased rainfall in December (Table 3) activated the microbial community and the decomposition of organic matter in these systems, contributing to higher $CO_2$ emissions, since microbial activity in the soil releases heat and can contribute to an increase in its temperature (Xavier et al., 2006; Karhu et al., 2014).

## Conclusions

In general, the hydromorphic soils of estuarine floodplains with the presence of açai palm trees indicate high levels of $CO_2$ emissions. Those under monoculture show a high variation in the emission rate when compared to systems where other forest species are found.

There is a variation in $CO_2$ flux over the evaluation period, with increased emissions at the beginning of the rainy season and a rise in the water table during floods. There is no correlation between $CO_2$ emission and litter, but in specific situations, there are positive relationships with soil temperature and negative relationships with soil moisture, in the period of less rainfall during the Amazonian summer.

Further studies aiming at analyzing variations in GHG fluxes in estuarine floodplains are recommended, which should focus on physical processes (gas diffusion), as these may be more relevant than chemical or biological soil processes.

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## Contribution of authors:

Lira-Guedes, A.C.: Conceptualization, Investigation, Methodology, Project administration, Supervision, Validation, Visualization, Writing — original draft, Writing — review & editing; Leal, G.A.: Data curation, Formal analysis, Investigation, Software, Validation, Visualization, Writing — original draft, Writing — review & editing; Fischer, G.R.: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing — original draft, Writing — review & editing; Aguiar, L.J.G.: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing — original draft, Writing — review & editing; Melém Júnior, N.J.: Conceptualization, Investigation, Project administration, Supervision, Validation, Visualization, Writing — original draft, Writing — review & editing; Baia, A.L.P.: Investigation, Software, Validation, Visualization, Writing — original draft, Writing — review & editing; Guedes, M.C.: Conceptualization, Funding, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing — original draft, Writing — review & editing.

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