ABSTRACT

Carbon dioxide (CO₂) is produced only in biological activities. Understanding how soil tillage practices affect the dynamics of CO₂ production is important, as these processes are influenced by the temperature and humidity conditions of the place. This paper aimed at quantifying CO₂ 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), CO₂ flux, soil moisture, and temperature were measured, and litter samples were collected. In addition, rainfall data for the region were also obtained. The CO₂ fluxes obtained ranged from 0.37 to 28.55 μmol CO₂ m⁻² s⁻¹, with a total average of 6.20 μmol CO₂ m⁻² s⁻¹. In broad analysis, soil variables did not show significant correlations with CO₂ 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 (CO₂) 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 açaiais afetam as dinâmicas da produção de CO₂ é importante, pois elas podem aumentar a emissão em relação à floresta. O objetivo do trabalho foi quantificar o fluxo de CO₂ do solo hidromórfico de várzea sob diferentes manejos de açaiais, analisando suas relações com a deposição de serapilheira, ambiente do solo e o período do ano. Realizado no município de Mazagão-AP, foram selecionadas quatro áreas de açaiais com diferentes tipos de manejo. Durante o período avaliado (out/2012, nov/2012, dez/2012, fev/2013, mar/2013 e abr/2013), foram medidos o fluxo de CO₂, umidade e temperatura do solo, e deposição de serapilheira. Além disso, também foram obtidos dados de precipitação da região. O fluxo de CO₂ variou de 0,37 a 28,55 μmol CO₂ m⁻² s⁻¹, com média de 6,20 μmol CO₂ m⁻² s⁻¹. No geral, as variáveis do solo não apresentaram correlações significativas com a emissão de CO₂. 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.
Introduction

Global observations recorded by the World Meteorological Organization (WMO) until 2018 show that carbon dioxide concentration (CO₂) 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 CO₂ (WMO, 2019). It is common sense that greenhouse gases, notably CO₂ and methane (CH₄), 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, CH₄ 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 oleracea 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 exploita-
nized 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 CO₂ 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).

CO₂ 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 CO₂ 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)
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 CO₂ flux. To collect the litter, a cylindrical iron collector with a cutting edge and an area of 0.13 m² 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 cm³ 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 CO₂ 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 CO₂ 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 CO₂ in the hydromorphic soils of floodplain forests, in the studied açai palm tree groves, ranged from 0.37 to 28.55 μmol CO₂ m⁻² s⁻¹, with an average of 6.20 μmol CO₂ 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 CO₂ 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 CO₂ 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 CO₂ emission in 64 days (Denardin et al., 2019).

### 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 dm⁻³)   | 0.2           | 0.2           | 0.2           | 0.4           |
| Ca+Mg (cmol dm⁻³)| 13.4         | 13.6          | 12.2          | 11.2          |
| Ca (cmol dm⁻³)  | 10.6          | 10.3          | 9.15          | 8.15          |
| Al (cmol dm⁻³)  | 0.1           | 0.1           | 0.3           | 0.1           |
| H+Al (cmol dm⁻³)| 4.6           | 4.7           | 6.8           | 5.5           |
| SB (cmol dm⁻³)  | 13.6          | 13.8          | 12.4          | 11.6          |
| CTC (cmol 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).
April 2013.

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 | CO2 Flux (μmol 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\(_2\) flux, 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 μmol CO\(_2\) m\(^{-2}\) s\(^{-1}\)) and December (7.18 μmol 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 between 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 μmol 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).
The significant interaction between types of management and temporal variation shows that differences in average CO₂ 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 CO₂ 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, CO₂ 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 CO₂ 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, CO₂ 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 CO₂ 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 CO₂ 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 CO₂ m⁻² s⁻¹.
Carbon emissions in hydromorphic soils from an estuarine floodplain forest in the Amazon River

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 CO2 value, found in the açaí 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 CO2 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 CO2 flux. Zanchi et al. (2003) claim that after a rainfall event, water fills the pores, forcing the emission of CO2. Vincent et al. (2006) elucidate that if the soil has a moisture content above 40%, there is CO2 emission due to excess water and lack of oxygen in the soil. But this increase in CO2 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 CO2 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 açaí 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 CO2 into the atmosphere, as well as the saturation of water in the soil during periods of flooding. Therefore, simplifying systems in monocultures of açaí palm trees can contribute to their greater susceptibility to environmental variations and, consequently, variability in CO2 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 açaí 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 Mielińczuk, 2009).

Analyzing the relationships between the variables for each month, there is a negative relationship between CO2 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 CO2 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 (açaí 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 | CO₂ eflux measurement points | System 3 | System 4 |
|-----------------|------------|-----------------------------|----------|----------|
|                 |            | Measurement time | Efflux CO₂ (μmol CO₂ m⁻² s⁻¹) | Measurement time | Efflux CO₂ (μmol CO₂ 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 CO₂ 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 CO₂ 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 açaí palm trees indicate high levels of CO₂ 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 CO₂ 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 CO₂ 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.

Acknowledgments

To Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for granting a scholarship to Géssica de Almeida Leal. Embrapa Amapá, through FLORESTAM (02.09.01.012.00.00) and BEM DIVERSO (24.16.03.001.07.02) projects, provided the financing and logistics for carrying out the activities.
Carbon emissions in hydromorphic soils from an estuarine floodplain forest in the Amazon River

References
Acosta, A.; Casali, C.; Pocojeski, E.; Peppe, I.; Vicelli, J., 2019. Atributos microbiológicos de solos hidromórficos originados de basalto no Paraná. In: Barbosa, E.; Fonseca, A.; Giarola, N.; Barbosa, F.; Galvão, C.; Canalli, L.; Santos, J. (Eds.), Anais Reunião Paranaense de Ciência do Solo – RPCS. UEPG/PROEX, Ponta Grossa, pp. 581-584.

Almeida, A.; Jardim, M., 2012. A Utilização das espécies arbóreas da floresta de várzea da Ilha de Soroaora, Ananindeua, Pará, Brasil por moradores locais. Brazilian Journal of Environmental Sciences, (23), 48-54 (Accessed February 3, 2020) at: http://rbciambr.com.br/index.php/Publicacoes_RBCIAMBR/article/view/331.

Almeida, S.; Amaral, D.; Silva, A., 2004. Análise florística e estrutura de florestas de várzea no estuário amazônico. Acta Amazonica, v. 34, (4), 513-524. https://doi.org/10.1590/S0103-8478-2004-04-00205.

Alves, M.; Martins, J., 2015. Uso de gesso e silicatos no carbono orgânico do solo em sistema de semeadura direta. Journal of Agronomic Sciences, v. 4, (Especial), 201-231 (Accessed February 5, 2020) at: http://www.pag.uem.br/antecores/v4ne.

Araújo, C.; Navegantes-Alves, L., 2015. Do extrativismo ao cultivo do açaizeiro (Euterpe oleracea Mart.) no estuário amazônico: sistemas de manejo e suas implicações sobre a diversidade de espécies arbóreas. Revista Brasileira de Agroecologia, v. 10, (1), 12-23.

Azevedo, J., 2010. Sistema de manejo de açaízais nativos praticados por ribeirinhos. EDUFMA, São Luiz, 98 pp.

Bartlett, K.; Grill, P.; Bonassi, J.; Richey, J.; Harriss, R., 1990. methane flux from the Amazon river floodplain’ emissions during rising water. Journal of Geophysical Research, v. 95, (D10), 16773-16788. https://doi.org/10.1029/JD095iD10p16773.

Brasil. Departamento Nacional da Produção Mineral. 1974. Folha NA/BN.22 Macapá, geologia, geomorfologia, solos vegetação e uso potencial da terra. Levantamento de Recursos Naturais, v.6. Projeto Radam Brasil, Rio de Janeiro, 467 pp.

Carim, M.; Jardim, M.; Medeiros, T., 2008. Composição florística e estrutura da floresta de várzea no município de Mazagão, Amapá, Brasil. Scientia Florestalstia, v. 36, (79), 191-201.

D’Andrea, A.; Silva, M.; Freitas, D.; Curi, N.; Silva, C., 2010. Variações de curto prazo no fluxo e variabilidade espacial do CO2 do solo em floresta nativa. Pesquisa Florestal Brasileira, v. 30, (62), 85-92.

Denardin, L.; Alves, L.; Ortigara, C.; Winck, B.; Coblinisk, J.; Schmidt, M.; Carlos, F.; Toni, C.; Camargo, F.; Anghinoni, I.; Clay, D., 2020. How different soil moisture levels affect the microbial activity. Ciência Rural, v. 50, (6), 1-10. https://doi.org/10.1590/0103-8478cr20190831.

Dias, J., 2006. Fluxo de CO2, proveniente da respeiração do solo em áreas de floresta nativa da Amazônia. Dissertação de Mestrado, Escola Superior de Agricultura Luiz Queiroz, Universidade de São Paulo, Piracicaba. doi:10.11606/D.91.2006.tde-04102006-163445. Retrieved 2020-16-03, from www.teses.usp.br

Empresa Brasileira de Pesquisa Agropecuária (Embrapa). Centro Nacional de Pesquisas de Solos. 2011. Manual de métodos de análises de solos. 2. ed. Embrapa Solos, Rio de Janeiro, 230 pp.

Farias, J., 2012. Manejo de açaízais, riqueza florística e uso tradicional de espécies de várzeas do Estuário Amazônico. Dissertação de Mestrado, Programa de Pós-Graduação em Biodiversidade Tropical, Universidade Federal do Amapá, Macapá. Retrieved 2020-17-03, from https://www2.unifap.br/ppgbio/files/2010/05/DISSERTA%C3%87%C3%83O-JULIANA-EVELINE_28.06.2013.pdf.

Freitas, M., 2019. O extrativismo de açaí (Euterpe oleracea Mart.) e a natureza das assembleias de árvores em várzea amazônica. Tese de Doutorado, Programa de Pós-Graduação em Biologia Vegetal, Centro de Biociências, Universidade Federal de Pernambuco, Recife. Retrieved 2020-17-05, from https://repositorio.ufpe.br/handle/123456789/33472.

Gomes, M., 2014. Estoque de carbono e emissão de gases do efeito estufa em camissbloso sob plantações de Pinus taeda. Dissertação de Mestrado, Programa de Pós-Graduação em Ciências do Solo, Setor de Ciências Agrárias, Universidade Federal do Paraná, Curitiba. Retrieved 2020-20-03, from http://hdl.handle.net/1884/35531.

Guedes, V., 2007. Estudo do fluxo de gases através do solo de cobertura de areia de resíduos. Dissertação de Mestrado, Universidade Federal do Rio de Janeiro, Rio de Janeiro. Retrieved 2019-10-07, from http://www.ccc.ufrj.br/pt/dissertaes-de-mestrado/107-msc-pt-2007/2141-vinicius-paiva-guedes.

Hanson, P.; Edwards, N.; Garten, C.; Andrews, J., 2000. Separating root and soil microbial contributions to soil respiration: a review of methods and observations. Biogeochemistry, v. 48, (1), 115-146. https://doi.org/10.1023/A:1006244819642.

Heimann, M.; Reichstein, M., 2008. Terrestrial ecosystem carbon dynamics and climate feedbacks. Nature, v. 451, (17), 289-292. https://doi.org/10.1038/nature06591.

Instituto Brasileiro de Geografia e Estatística (IBGE). 2012. Manual técnico da vegetação brasileira. 2. ed. IBGE, Rio de Janeiro, 271 pp.

Instituto Brasileiro de Geografia e Estatística (IBGE). 2019. Produção da extração vegetal e da silvicultura (Accessed December 2, 2019) at: https://biblioteca.ibge.gov.br/index.php/biblioteca-catalogo?view=detalhes&id=774.

Instituto de Pesquisas Científicas e Tecnológicas do Estado do Amapá (IEPA), 2002. Macrodiagnóstico do Estado do Amapá: primeira aproximação do ZEE. IEPA, Macapá, 140 pp.

Instituto Nacional de Meteorologia (Inmet). 2012. Banco de Dados Meteorológicos para Ensino e Pesquisa (Accessed February 2, 2020) at: https://bdmep.inmet.gov.br/.

Instituto Nacional de Meteorologia (Inmet). 2019. Banco de Dados Meteorológicos para Ensino e Pesquisa (Accessed February 2, 2020) at: https://bdmep.inmet.gov.br/.

Jardim, M.; Santos, G.; Medeiros, T., Francez, D., 2007. Diversidade e estrutura de palmeiras em floresta de várzea do estuário amazônico. Amazônia: Ciência e Desenvolvimento, v. 2, (4), 67-84.

Karlo, K.; Aufrêt, M.; Dungait, J.; Hopkins, D.; Prosser, J.; Singh, B.; Subke, J.; Wookey, P.; Ågren, G.; Sebastiani, M.; Gouriveau, F.; Bergkvist, G.; Meir, P.; Nottingham, A.; Salinas, N.; Hartley, L., 2014. Temperature sensitivity of soil respiration rates enhanced by microbial community response. Nature, v. 513, 81-84. https://doi.org/10.1038/nature13604.

Konda, R.; Ohta, S.; Ishizuka, S.; Heriyanto, J.; Wicaksono, A., 2010. Seasonal changes in the spatial structures of N2O, CO2, and CH4 fluxes from Acacia mangium plantation soils in Indonesia. Soil Biology and Biochemistry, v. 42, (9), 1512-1522. https://doi.org/10.1016/j.soilbio.2010.05.022.

Kottke, M.; Grieser, J.; Beck, C.; Rudolf, B.; Rubel, F., 2006. World map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift, v. 15, (3), 259-263. https://doi.org/10.1127/0991-2948/2006/0130.

Lessa, A., 2016. Emissão de gases de efeito estufa em áreas pré-existentes à formação de reservatórios hidrelétricos na Amazônia: o caso da usina hidrelétrica de Belo Monte. Tese de Doutorado, Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia, Universidade Federal
do Rio de Janeiro, Rio de Janeiro. Retrieved 2020-20-03, from http://www.ppe.ufrj.br/index.php/pt/publicacoes/teses-e-dissertacoes/2016

Lima, R.; Aparício, P.; Ferreira, R.; Silva, W.; Guedes, M.; Oliveira, C.; Silva, D.; Batista, A., 2014. Volumetria e classificação da capacidade produtiva para *Mora paraenensis* (Ducke) no estuário amapaense. *Ciência Forestal*, v. 42, (101), 141-154.

Nunes Filho, J., 2016. Modelagem da inundação de florestas de várzea do estuário amazônico. Dissertação de Mestrado, Programa de Pós-Graduação em Biodiversidade Tropical, Universidade Federal do Amapá, Macapá. Retrieved 2020-20-03, from http://repositorio.ufap.br/handle/123456789/524.

Nunes, P.C., 2003. Influência de CO₂ no solo na produção de forragem numa pastagem extensiva e num sistema agrosilvopastoril, MT. Dissertação de Mestrado, Faculdade de Agronomia e Medicina Veterinária, Universidade Federal de Mato Grosso, Cuiabá.

Oliveira, A., 2014. Estudo de respiração do solo na Floresta Nacional de Caxiuanã, projeto Esecaflor/LBA. Dissertação de Mestrado, Programa de Pós-Graduação em Recursos Naturais da Amazônia, Universidade Federal do Oeste do Pará, Santarém. Retrieved 2019-20-11, from https://repositorio.ufop. edu.br/jspui/handle/123456789/217.

Oliveira, M.; Farias-Neto, J.; Mattiello, R.; Moehuitt, S.; Carvalho, A., 2017. Açai: Euterpe oleracea. ICA/PROCURIS, Buenos Aires, 31 pp (Accessed March 10, 2020) at: https://www.infofca.cntpi.embrapa.br/infofca/handle/doc/1096244.

Panosso, A.; Pereira, G.; Marques Júnior, J.; Scala Júnior, N., 2008. Variabilidade espacial da emissão de CO₂ em latossolos sob cultivo de cana-de-açúcar em diferentes sistemas de manejo. *Engenharia Agrícola*, v. 28, (2), 227-223. https://doi.org/10.1590/S0100-69162008000200003.

Pinto, E., 2014. Solos, hidrologia e estrutura populacional de praciueiras em florestas de várzea do estuário amazônico. Dissertação de Mestrado, Programa de Pós-Graduação em Biodiversidade Tropical, Universidade Federal do Amapá, Macapá. Retrieved 2014-20-11, from https://www2.ufap.br/ppgbio/dissertacoes/.

Pinto-Júnior, O.; Sanches, L.; Dalmolin, A.; Nogueira, J., 2009. Efluxo de CO₂ do solo em floresta de transição Amazônia Cerrado e em área de pastagem. *Acta Amazonica*, v. 39, (4), p. 813-822. https://doi.org/10.1590/S0044-59672009000400009.

Prance, G., 1980. A terminologia dos tipos de florestas amazônicas sujeitas a inundação. *Acta Amazonica*. v. 10, (3), 495-504. https://doi.org/10.1590/1809-43921980103499.

Primavel, A., 2002. Manejo ecológico do solo: a agricultura em regiões tropicais. Nobel, São Paulo, 549 pp.

Salimón, C., 2003. Respiração do solo sob florestas e pastagens na Amazônia Sul-Occidental, Acre. Tese de Doutorado, Centro de Energia Nuclear na Agricultura, Universidade de São Paulo, Piracicaba. doi:10.11606/TEd4.2003.tede/02062003-092035. Retrieved 2014-20-11, from www.teses.usp.br.

SEEG, Observatório do Clima. 2018. Emissões de GEE no Brasil e suas implicações para políticas públicas e a contribuição brasileira para o acordo de Paris. Documento de Análise. Retrieved 2020-20-03, from https://seegweb.com.br/wp-content/uploads/2018/11/Relatorios-SEEG-2018-Sintese-FINAL-v1.pdf

Silva, C.; Vasconcelos, S.; Mourão Júnior, M.; Bispo, C.; Kato, O.; Silva Junior, A.; Castellani, D., 2016. Variação temporal do efluxo de CO₂ do solo em sistemas agroflorestais com palma de óleo na Amazônia Oriental. *Acta Amazonica*, v. 46, (1), 1-12. http://dx.doi.org/10.1590/1809-4392201500193.

Silva, E.; Moitinho, M.; Teixeira, D.; Pereira, G.; Scala Júnior, N., 2014. Emissões de CO₂ do solo associada à calagem em área de conversão de laranja para cana-de-açúcar. *Engenharia Agrícola*, v. 34, (5), 885-898. http://dx.doi.org/10.1590/S0100-69162014000500008.

Silva Júnior, J., 2008. Efeitos da exclusão da chuvra no fluxo de CO₂ do solo na floresta nacional de Caxiuanã, Pará. Dissertação de Mestrado, Centro de Tecnologia e Recursos Naturais, Universidade de Campina Grande, Campina Grande. Retrieved 2014-20-11, from http://dspace.sti.ufcg.edu.br:8080/jspui/handle/riufgc/4847

Silva Júnior, J.; Costa, A.; Azevedo, P.; Costa, R.; Metcalfe, D.; Gonçalves, P.; Braga, A.; Malhi, Y.; Aragão, L.; Meir, P., 2013. Fluxos de CO₂ do solo na floresta nacional de Caxiuanã, Pará, durante o experimento ESECAFLOR/LBA. *Revista Brasileira de Meteorologia*, v. 28, (1), 85-94. https://doi.org/10.1590/S0102-77862013001000009.

Sota, E.; Meir, P.; Malhi, Y.; Donato Nobre, A.; Hodnett, M.; Grace, J., 2004. Soil CO₂ efflux in a tropical forest in the central Amazon. *Global Change Biology*, v. 10, (5), 601-617. doi:10.1111/j.1529-8817.2003.00761.x.

Souza, E.; Veldkamp, E.; Guimarães, R.; Paixão, R.; Ruivo, M.; Almeida, S., 2006. Landscape and climatic controls on spatial and temporal variation in soil CO₂ efflux in an Eastern Amazonian Rainforest, Caxiuanã, Brazil. *Forest Ecology and Management*, v. 237, (1-3), 57-64. doi:10.1016/j.foreco.2006.09.027.

Statsoft, 2011. *STATISTICA* (data analysis software system), version 7. (Accessed October 15, 2014) at: https://www.statsoft.com/

Tagore, M., 2017. O aumento da demanda do açaí e as alterações sociais, ambientais e econômicas: o caso das várzeas de Abaetetuba, Pará. Dissertação de Mestrado, Núcleo de Meio Ambiente, Universidade Federal do Pará, Belém. Retrieved 2020-20-03, from http://repositorio.ufpa.br/jspui/handle/2011/9548

Teles, M., 2018. Influência da estrutura da floresta na respiração do solo em diferentes sitios na Amazônia Central. Dissertação de Mestrado, Faculdade de Ciências Agrárias, Universidade Federal do Amazonas, Manaus. Retrieved 2020-10-04, from https://tede.ufam.edu.br/handle/tede/6822

Vezzani, F.; Mielenzuck, J., 2009. Uma visão sobre qualidade do solo. *Revista Brasileira de Ciência do Solo*, v. 33, (4), 743-755. https://doi.org/10.1590/s0100-06832009000400001.

Vincent, G.; Shahriari, A.; Lucot, E.; Badot, P.; Epron, D., 2006. Spatial and seasonal variations in soil respiration in a temperate deciduous forest with fluctuating water table. *Soil Biology and Biochemistry*, v. 38, (9), 2527-2535. https://doi.org/10.1016/j.soilbio.2006.03.009.

Wittmann, F.; Schongart, J.; Brito, J.; Wittmann, A.; Poldt, M.; Parolin, P.; Junk, W.; Guillaumet, J., 2010. Manual of trees from Central Amazonian varzea floodplains. INPA, Manaus, pp. 175-195.

Worbes, M., 1997. The forest ecosystem of the floodplain. In: Junk, W.C.; Guillaumet, J., 2010. *Manual of trees from Central Amazonian varzea floodplains*. INPA, Manaus, pp. 175-195.
World Meteorological Organization (WMO), 2019. Greenhouse gas bulletin: The state of the Greenhouse Gases in the Atmosphere Based on Global observations through 2018, v. 15 (Accessed March 20, 2020) at: https://library.wmo.int/index.php?lvl=notice_display&id=21620#.YF-jJK9KjIU.

Xavier, F.; Maia, S.; Oliveira, T.; Mendonça, E., 2006. Biomassa microbiana e matéria orgânica leve em solos sob sistemas agrícolas orgânico e convencional na Chapada da Ibiapaba-CE. Revista Brasileira de Ciência do Solo, v. 30, (2), 247-258. https://doi.org/10.1590/S0100-06832006000200006.

Zanchi, F.; Rocha, H.; Kruijt, B.; Cardoso, F.; Deus, J.; Aguiar, L., 2003. Medicação do efluixo de CO_2 do solo: monitoramento com câmaras automáticas sobre floresta e pastagem em Rondônia. In: Claudino-Sales, V.; Tonini, I.; Dantas, E. (Eds.), Anais VI Congresso de Ecologia do Brasil, Fortaleza, pp. 631-632.

Zanchi, F.; Waterloo, M.; Kruijt, B.; Kesselmeier, J.; Luizão, F.; Manzi, A.; Dolman, A., 2012. Soil CO_2 efflux in central Amazonia: environmental and methodological effects. Acta Amazonica, v. 42, (2), 173-184. https://doi.org/10.1590/S0044-59672012000200001.