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Carbon Storage in Equatorial Forest Soil-litter Systems as a Function of Management Intensity and Type of Vegetation Cover

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Authors' contributions

This work was carried out in collaboration between all authors. All authors participated of the samples collection, date and statistical analysis and wrote the first draft of the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

Aims and Place: The increase in greenhouse gas emissions in recent decades, especially CO_2, is attributed to the increasing burning of fossil fuels and the expansion of agricultural activities. Therefore, more information should be garnered about the mechanisms that control carbon storage, capture and sinks, while simultaneously seeking new management strategies to reduce atmospheric emissions. The main purpose of this research was to comparatively determine carbon storage in the soil and litter of three forest systems in the Western Amazon (Brazil): upland forest, shrublands and grasslands.
Duration of Study: Dry and rainy periods between 2005 and 2012.
Methodology: Diverse soil analysis including density, porosity, particle-size, total carbon (TC and TOC) were developed according to traditional methods. Multivariate analysis (MANOVA) and Tukey's test were applied to the results.
Results and Conclusion: Total C storage C ranged from 23 to 26 Mg ha^{-1} in the grasslands to 28 to 37 Mg ha^{-1} in the shrublands. These findings confirm the importance of seasonality for both litter production and carbon production and storage in the different landscapes. The conditions of land use and occupation were predominant factors that explain the different concentrations of total carbon and organic carbon in the areas under study. Additional studies are needed to determine the most efficient management of these landscapes.

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1. INTRODUCTION

Carbon, one of the most widely studied macronutrients in the last two decades, is present in all organisms and environmental compartments in both organic and inorganic forms. Under natural conditions, the planet's main carbon sinks, in descending order, are the earth's crust, ocean, soil, including the litter layer, atmosphere and plant biomass [1,2]. The rocky compartment of the earth's crust participates very little in the carbon cycle, hence, the soil and all residual vegetation on it play a major role in the earth's biogeochemical cycles, even though carbon concentrations in soils are much lower than in the rocky compartment. The atmosphere has the lowest carbon concentration among the aforementioned compartments, around 750 µg [1]. Nevertheless, it has attracted interest because of the increase in soil carbon dioxide efflux over the last 130 years, resulting in significant climate change.

Carbon, which is not a static element, circulates among the compartments, and there is a special relationship between the soil and the atmosphere. It is estimated that C from the atmosphere and captured by terrestrial flora through photosynthesis is 120 Pg year^{-1} [3]. Approximately 50% of the gross primary production (GPP) returns to the atmosphere as plant respiration [3], and another significant part remains as carbon efflux from decomposing organic matter and root respiration. After computing carbon losses to the atmosphere resulting from human activities, such as industrial and urban CO_2 emissions, forest fires, loss through agriculture and livestock, erosion, leaching of fertile soil and release of gases from lakes and dams, the soil still contains a carbon stock, which was estimated at 1576 Pg [1], especially in the top 30 centimeters of the layer, which is considered the most fertile and rich in organic matter and litter.

Organic matter (OM) is the main source of soil carbon, and in tropical and equatorial regions its physicochemical properties are essential to maintaining the health of terrestrial ecosystems. OM contributes to increase soil resistance to compaction, since organic compounds increase the cohesion between particles and aggregates, establishing organic cement in the compound [4]. Litter also plays an important role in supplying carbon to soil, and in ensuring the maintenance of moisture and reducing soil evaporation rates, protecting the fertile layers from heavy rains that cause erosion and leaching. OM volume and distribution are highly variable from one environment to another, depending directly on climatic factors (humidity, temperature and rainfall) and on the type of vegetation. In the Amazon region, environmental factors favor high production of litter and organic matter, and the decomposition rate in Amazonian soils is high, while the soil's nutrient storage capacity is low compared to that of soils in temperate climates.

The main objective of this study was to determine the level of carbon storage (total and organic carbon) in soil and litter in three distinct landscapes: 1) dense Upland Forest; 2) shrubland in an early stage of regeneration, hereinafter referred to as *Capoeira*; and 3) grasslands with predominantly herbage and shrub cover, hereinafter referred to as *Campina*. Based on the results, the loss of soil carbon in these environments and the carbon sequestration were estimated from the efflux into the atmosphere. The principal scientific contribution of that research was to show how corrects management strategies can reducing the CO_2 emissions by the Amazon Forest. Diverse researches has been done in the region with similar objectives [5-9].

2. MATERIALS AND METHODS

2.1 Study Area

The study area lies within the Western Amazon (2º45'-3º15'S and 60-60º30'W), and is home to a high diversity of terrestrial and aquatic organisms. According to the Köppen climate classification system, the climate in most of the study area is of the "*Am*" type, hot and constantly damp, i.e., a tropical monsoon climate with annual rainfall of 1200 to 2800 mm. The average temperature ranges from 25.5 to 27.5ºC, with relative humidity varying from 80 to 90% throughout the year. The rainiest months are from December to May and the driest from August to November. According to the EMBRAPA soil classification system [10], the soils in the upland forest region are predominantly dystrophic Yellow Latosol (LAd1), with medium to low levels of iron (Fe_2O_3) associated with concretionary Petric Plinthosols (LAd10) and patches of eutrophic to dystrophic Haplic TA Gleysols (GXve4) on the banks of the Negro River basin. The upland soils present a textural gradient, with the A horizon (surface) sandier than the B horizon, and low levels of organic matter, nitrogen and phosphorus. In the region comprising *Campina* vegetation and in the areas of *Capoeira* located in the municipality of Iranduba (state of Amazonas – AM), the soils are composed predominantly of allitic Red Ultisols and dystrophic Allitic Red Yellow Ultisols (PVal4), with insertions of dystrophic Haplic Plinthosols and dystrophic Red Yellow Ultisols (FXd4), also with patches of eutrophic to dystrophic Haplic TA Gleysols (GXve4) around the edges of the basins of the Negro and Amazon rivers. The ultisols are characterized by presenting textural gradient, with a clear separation between the horizons, usually less than 10% of Fe_2O_3 content, and moderately good drainage.

2.2 Description of the Landscape

The Upland Forest (ULF – site 1 in Fig. 1) is located in a higher region of the terrain (plateau or slope) and is characterized by its high species richness and diversity, with large trees and a permanent canopy varying from dense (compact) to open forest. The area of Capoeira (CPO – site 2 in Fig. 1) usually emerges as a result of opening a forest to extensive farming, grazing, occasional farming or mining, which is later abandoned because the soil has been exhausted or its resources extracted. In the initial stage of regeneration, Capoeira presents numerous grasses and ground ferns, and a few pioneer tree species. Depending on the restoration time, a new patch of forest may emerge with characteristics of primary or secondary forest. The Campina ecosystem (CAM – site 3 in Fig. 1) is characterized by scattered and low vegetation, which occurs in sandy soils of low fertility, especially in the region of influence of the Negro River basin [11], which also occurs in the Amazon River basin. Campina (grassy) vegetation may emerge as a result of forest fires, mainly due to water stress, presenting many fire resistant species. This property of grasslands, which is shared by the typical Cerrado vegetation, renders these landscapes less vulnerable to global warming, but does not make them immune to degradation resulting from human activities.

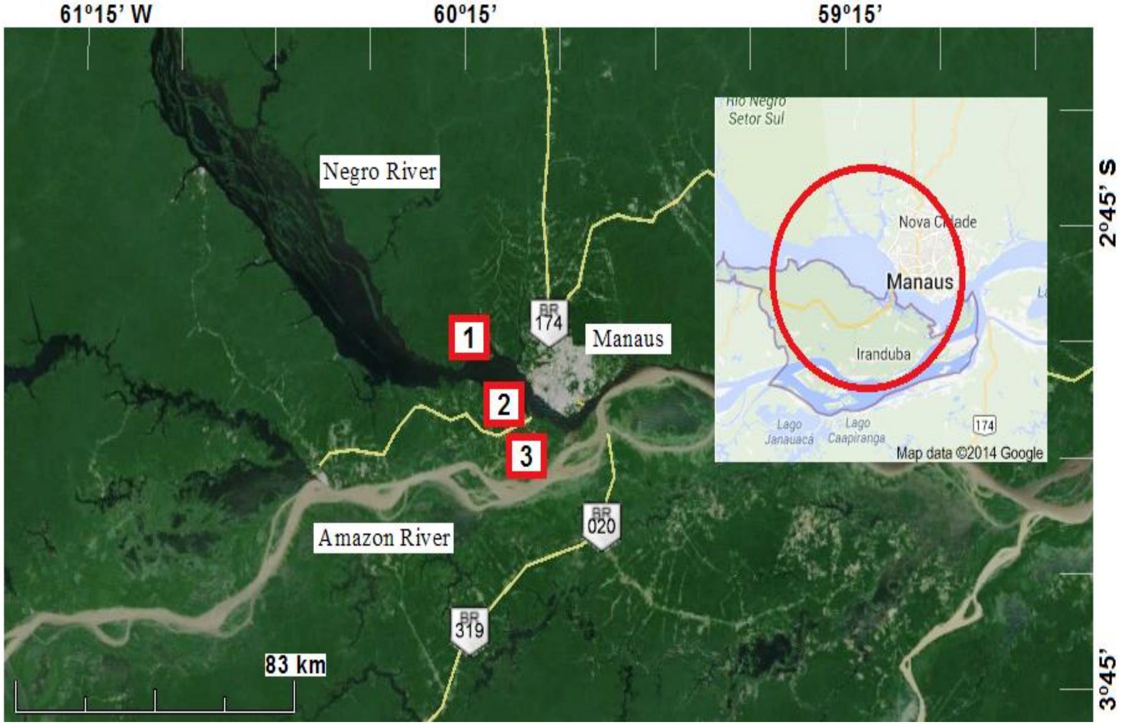

Fig. 1. Study areas in the Amazon River basin, Brazil. Legend: (1) Upland Forest–ULF; (2) Capoeira–CPO; (3) Campina–CAM
(Source: Google Earth, 4 Sep 2013)

2.3 Analytical Proceeds

Samples of surface soil (0.0-0.2 m) with litter were collected twice a year, during the dry (August to September) and rainy (January and February) periods between 2005 and 2012, from three distinct landscapes: Upland Forest, Capoeira and Campina (see Fig. 1). Ten randomly chosen 1 m^2 plots were established in each landscape for the collection of soil and plant material. All the plant material found within the plots was stored in paper bags and taken to the laboratory to be weighed and classified into predetermined fractions. The samples were then homogenized to remove representative subsamples for chemical analysis. The same procedure was adopted to obtain soil subsamples for analysis. Using portable electrodes, measurements of incident radiation (I0 $\mu E\ m^{-2}s^{-1}$), temperature (ºC) and air humidity (%) at 0.3 m above ground level, and soil temperature at a depth of 0.1 m were taken in each landscape. The measurements were taken at one hour intervals at different points to obtain a representative average of the area, starting at 08:00 AM and ending at 5:00 PM. The following properties were determined in the laboratory: (a) Plant material fresh and dry weight (%); (b) gravimetric moisture (GM%) and volumetric moisture (VM%) of the soils, based on the weight difference after oven drying at 105ºC (Eqs. 1 and 2); (c) density (kg dm^{-3}), based on the ratio of gravimetric to volumetric moisture (Eq. 3) and comparing the results with the calculated mass-to-volume ratio of soil collected with a 9.812 10^{-2} dm^3 metallic sampling cylinder (Eq. 4); (d) total soil porosity, based on the ratio of solids volume to saturation volume (Eq. 5); and (e) particle size analysis (%), based on wet fractionated sieving with sodium hexametaphosphate buffered with sodium carbonate, in addition to the carbon fractions. A sedimentation cylinder (Koettgen) was used to determine the particle size of the finest soils (fine silt and clay). The silt-clay ratio was used as an indication of the degree of soil weathering. To determine the carbon content, the soil samples were first ground, pulverized, and oven-dried at 50ºC for four days. The total carbon (TC%) content was determined in a LECO CNS analyzer by dry combustion at 1350ºC, and the values converted to the mass-to-area ratio. Total organic carbon (TOC%) was determined via wet oxidation of organic matter in potassium dichromate and sulfuric acid on a hot plate, and residual dichromate was titrated with a standard ferrous ammonium sulfate solution (Mohr's salt). Total inorganic carbon (TIC%) was calculated from the difference between TC and TOC. All the procedures of soil collection, storage and analysis followed the analytical protocols for soil analysis [12,13]. Carbon storage in litter (Mg ha^{-1}) was estimated based on the mass-to-area ratio of plant material, and carbon storage in soil (Mg ha^{-1}) at depths of 0.0 to 0.2 m was estimated based on the ratio between soil bulk density (mass/volume) and measured total C content. A land use impact factor (IF) was created, taking into account the percentage of sustainable use and the degree of landscape modification, and the following rule was established: minimum IF <5%, average IF between 40 and 50%, and maximum IF between 90% and 100% (landscape modification). It is a subjective analysis based on the conservation stage of the landscape. Fundamentally, data of Capoeira (shrublands) in different stages of regeneration as cited in [5,14], as well as direct observation, were utilized as reference for the IF analysis. The term "sustainable use" was applied to different degrees of conservation of the natural conditions of the landscape: the more preserved is the landscape higher is the sustainable use and vice-versa.

Equations:

$$GU\ (kg.kg^{-1}) = \left(\frac{a-b}{b}\right) where: a = wet\ mass; b = dry\ mass \tag{1}$$

$$VU\ (m^3.m^{-3}) = \left(\frac{a-b}{c}\right) where: c = volume\ of\ the\ sample \tag{2}$$

$$d\ (kg.dm^{-3}) = \frac{VU}{GU} \tag{3}$$

$$d\ (kg.dm^{-3}) = \frac{soil\ mass}{\text{cylinder volume}}\ where: volume = 9.812 \times 10^{-2}\ dm^3 \tag{4}$$

$$P = 1 - \frac{solid\ volume}{saturation\ volume} = 1 - \frac{d}{d_{\text{mineral}}} \quad where: d_{\text{mineral}} = 2.66\ g.cm^{-3} \tag{5}$$

The effect of seasonality and of the different types of soil/litter (dependent variables) on the variation of the different carbon fractions (TC, TOC, TIC) in the different landscape conditions (independent variables) was evaluated by multivariate analysis (MANOVA). Tukey's test was applied whenever a significant effect ($P \leq .05$) was observed. Linear regression analyses were performed to determine the degree of relationship between the physical and physicochemical parameters of the sampled soils.

3. RESULTS

The incident solar radiation (IO) near the soil surface (0.3 m) varied during the day from 18-27 average 22±2.7 μE $m^{-2}s^{-1}$ in upland forest (ULF) to 1009-2689 average 1686±535.8 μE $m^{-2}s^{-1}$ in Capoeira (CPO), and 315-504 average 395±55.5 μE $m^{-2}s^{-1}$ in Campina (CAM). The range of variation was very low in the dense forest (SD = 2.7) and significant in the Capoeira environment (SD = 535.8). Peak solar radiation during both the dry and rainy seasons was observed between noon and 2:00 PM (Fig. 2), and the different concentrations of radiation in each landscape directly influenced the air and soil temperature variations, as will be noted.

The daily variations in temperature and humidity (Fig. 3A) and soil (Fig. 3B) in the three landscapes under study confirmed the albedo effect, especially in the ULF. Temperature and humidity variations in the ULF were lower than in the CPO and CAM vegetation, reaching a difference of up to 26ºC in Capoeira soil and 17% of moisture in Campina soil, during the hours of strongest solar radiation (noon to 2:00 PM). This fluctuation influences the kinetics of decomposition of organic matter, since it regulates the greater or lesser presence of soil decomposing organisms (bacteria, fungi and different groups of worms). Moisture is a strong controlling factor of decomposition processes, even influencing the distribution of gases (O_2 and CO_2) in soil. Both excess and lack of moisture can reduce or even stop the process of conversion of organic matter into simpler inorganic elements, and thereby interfere in the continuity of nutrient cycling [15]. Seasonality is evident in this process of organic matter degradation because, during the rainy season, excess moisture in combination the high air temperatures inside dense tropical forests stimulates an increase in the kinetics of litter decomposition. Note that fluctuations in air temperature both throughout the day and comparatively among the three landscapes was not very evident (ULF 29±1.2ºC, CPO 34±2.4ºC and CAM 33±2.1ºC), considering the variations in soil temperature, which showed higher standard deviations (ULF 29±1.6ºC, CPO 42±8.2ºC and CAM 37±5.4ºC). The largest pointwise difference in air temperature was recorded between ULF and CPO at 2:00 PM (ΔT= 7.2ºC). The three landscapes are located at very similar latitudes and receive practically the same concentration of solar irradiation. The difference lies in the exposure of soil and in the higher evaporation in the areas with less plant cover, in both Capoeira and Campina, which ultimately influence the temperature and humidity of the lower air layers. In this regard, within the measured intervals, it was found that the average temperatures at the soil surface were consistently lower in the areas protected by plant cover compared to the areas with unprotected surfaces. Although soil moisture in the Campina is substantially higher than in Capoeira, thermal inversion in the soil of the two landscapes was not observed at any time during the day. This frequent finding is due to the fact that the specific heat of water is higher than that of dry soil, promoting greater accumulation of heat in wet soils.

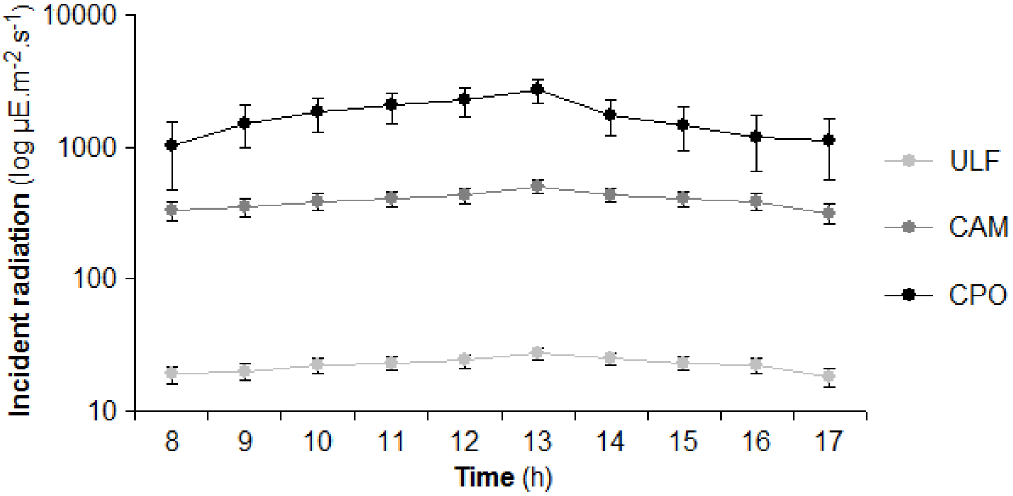

Fig. 2. Daily variation in incident solar irradiation in the Upland Forest (ULF), Capoeira (CPO) and Campina (CAM) landscapes in the period of 2005-2012 (n= 12)

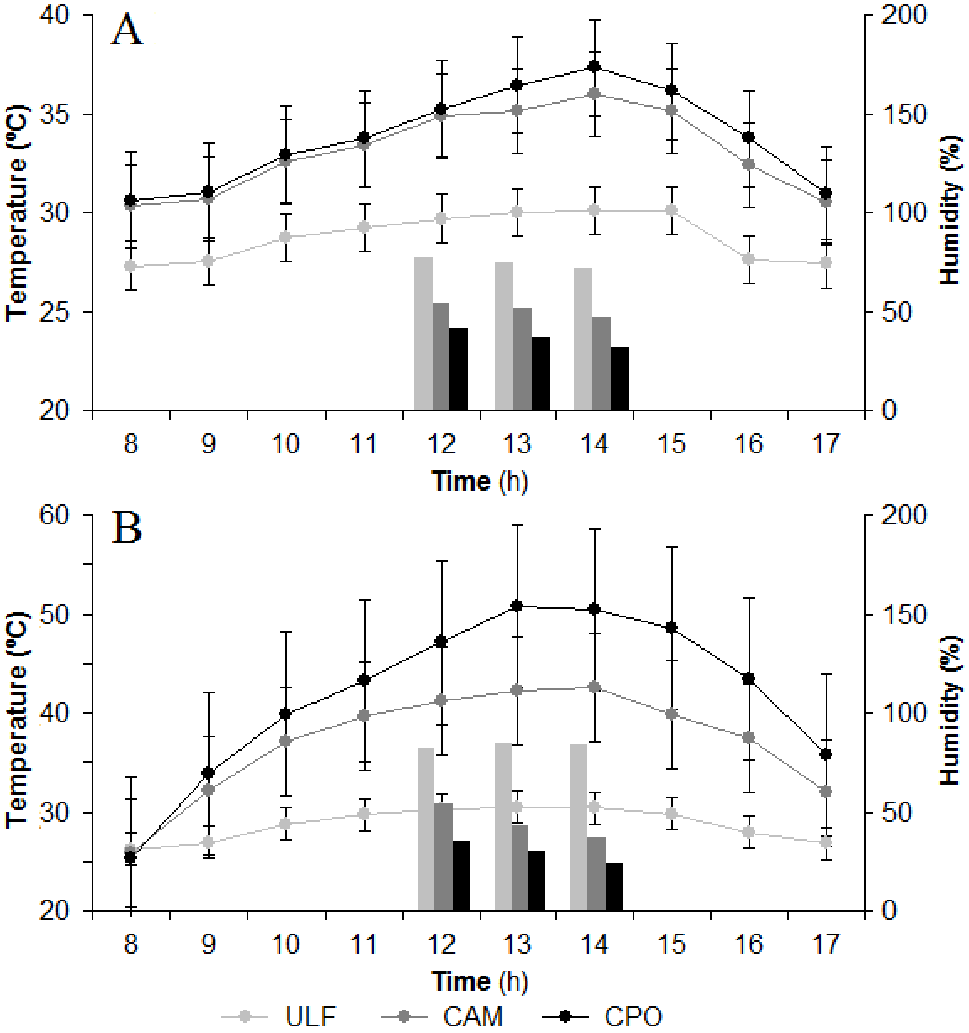

Fig. 3. Daily variation in temperature (line) and relative humidity (bars) a) of air, and b) of soil in the Upland Forest (ULF), Capoeira (CPO) and Campina (CAM) landscapes in the period of 2005-2012 (n= 12)

Table 1 describes the results of the analysis of the amount of carbon (%) in its full, organic and inorganic fractions in the soils of the plots in the three landscapes of western Amazonia under study. From the standpoint of seasonality, the average amounts of TC in the soils of the ULF, CPO and CAM were, respectively, 2.84±0.02, 1.90±0.02 and 1.97±0.02% during the dry season and 2.68±0.02, 2.51±0.06 and 1.76±0.02% during the rainy season. In general, the carbon levels in upland soils were higher than in the other landscapes. Factors such as the volume of plant material produced by dense forest, associated with Yellow Latosol type soils with patches of Gleysols with higher moisture content, may be contributing to increase the carbon level in this soil. The significantly higher porosity allows for greater water flow and higher water retention in the soil, regardless of hydrological period, and this factor may also be contributing to greater carbon sequestration in the upland soils (ULF). The analysis revealed significant differences in the carbon content of the three landscapes and a marked seasonality (Tukey $P \leq .05$), irrespective of the analyzed fraction. It could be suggested that carbon losses by leaching in the soil plots of the ULF are small in comparison to losses in CPO and CAM type soils, and in this case the volume of dead plant cover is presumably the major factor for this tendency.

Table 1. Mean values ± standard deviations of density, porosity, total carbon (TC), total organic carbon (TOC) and total inorganic carbon (TIC) in the soils of the three landscapes of western Amazonia in the dry and rainy seasons between 2005-2012

	Dry season			**Rainy season**		
	ULF	**CPO**	**CAM**	**ULF**	**CPO**	**CAM**
Density (kg dm^{-3})	1.01±0.05	1.52±0.13	1.36±0.05			
Porosity	0.62±0.01	0.43±0.05	0.49±0.02			
TC (%)*	2.84±0.04	1.90±0.02	1.97±0.02	2.68±0.02	2.51±0.06	1.76±0.02
TOC (%)*	2.52±0.04	1.46±0.07	1.50±0.02	2.33±0.03	1.36±0.01	1.68±0.06
TIC (%)*	0.32±0.01	0.44±0.05	0.46±0.04	0.35±0.05	0.83±0.01	0.39±0.01

**TC, TOC and TIC (n= 14)*

The average percentages of TOC estimated in surface soils (0.0-0.2 m) of the ULF, CPO and CAM were, respectively, 2.52±0.04; 1.46±0.07 and 1.50±0.02% during the dry season, and 2.33±0.03; 1.36±0.01 and 1.68±0.06% during the rainy season (Table 1). Following the same tendency observed for TC, the TOC concentrations found in this study showed a significant difference with respect to the hydrological period as well as the different land uses (Tukey $P \leq .05$). Organic carbon (TOC) was the predominant fraction of the total carbon in the analyzed soils, with an average TOC/TC proportionality ratio varying close to 87.7% in upland soils, 66.4% in Capoeira soils, and 76.9% in Campina soils. This variation is related to the volume of plant material and the frequency with which it is supplied to the soil through litter production, or through the introduction of dead organic matter (mulch) supplied by land management in certain landscapes. Litter volume is associated with the degree of density of the vegetation that covers the soil, while the frequency depends on seasonality, among other factors, particularly on the flood pulse in partially flooded plains, such as the Amazon floodplain. In Capoeira, which is considered a form of management used by traditional communities in the Amazon region, management involves cutting followed by burning of the plant material, which results in the rapid loss of macronutrients, especially carbon and phosphorus. Unfortunately, this practice is still very common in the Amazon region. In clearings recently abandoned, a way to replace organic carbon in the soil is to introduce a dead organic cover (mulch), which favors the development of decomposing microorganisms that increase soil fertility and also contribute to greater retention of the organic fraction through the soil microbial biomass. Moreover, this practice reduces the ecological restoration time of the native environment, allowing for increased moisture and soil porosity, which are important properties for the water flow in this compartment, and generally results in greater retention of CO_2 in the soil and in plant roots. The application of the land use impact factor (IF), which considered the percentage of sustainable use and the degree of modification of each landscape under study, demonstrated that the analyzed ULF plots showed an IF of less than 5%, while in the CPO the IF varied from 90% to 100% of alteration of the native landscape, and in the CAM it varied from 30% to 45%.

Table 2 describes the average TC content in the litter of the three landscapes in the Western Amazon, located between the basins of the Negro and Amazon rivers. The average TC concentrations in the ULF, CPO and CAM were, respectively, 49.0±1.1; 46.0±0.4 and 47.7±1.3% in the dry season, and 40.5±2.3; 44.2±0.8 and 44.5±0.2% in the rainy season. In general, the TC concentrations in the plots under study did not differ significantly within the same hydrological period (MANOVA $P > .05$), but differed between seasons (Tukey $P \leq .05$). This study did not take into account the successional stages of plant material that comprises the litter on each plot. However, it was observed that the freshly fallen leaf litter contains higher concentrations of certain nutrients (C, N, K and P) than the older leaves in stabilized litter. These findings are consistent with the earlier studies of Aprile et al. [5] in an upland forest and floodplain region near the city of Manaus. The high litter production in the plots could initially be explained by individual behavior, but this would increase not only the average but also its standard deviation, which was not the case here. Thus, it is concluded that this high litter production in the Capoeira plots is the result of a faster ecological restoration of this landscape after agricultural management activities.

Table 2. Mean values ± standard deviations (n= 14) of total carbon (TC) content in litter, and estimated storage (S) of litter and TC in the soils of the three landscapes of western Amazonia in the dry and rainy seasons between 2005-2012

	Dry season			**Rainy season**		
	ULF	**CPO**	**CAM**	**ULF**	**CPO**	**CAM**
TC (%)	49.0±1.1	46.0±0.4	47.7±1.3	40.5±2.3	44.2±0.8	44.5±0.2
S litter (Mg.ha^{-1})	8.2±0.3	0.2±0.1	0.8±0.1	6.0±0.6	0.1±0.1	0.5±0.1
S TC (Mg.ha^{-1})	28.0±0.4	28.2±0.3	26.1±0.3	26.4±0.2	37.2±0.9	23.3±0.3

Litter stocks were estimated from the mass-to-area ratio sampled in each plot (Table 2). The results indicated a distinctly larger stock of plant material in the upland forest, resulting from the higher density of the forest, with the presence of different stages of vegetative growth and different plant groups (herbs, grasses, shrubs and trees) in a condition of stability. The estimated mean values of litter stock in the ULF, CPO and CAM landscapes were, respectively, 8.2±0.3; 0.2±0.1 and 0.8±0.1 Mg ha^{-1} in the dry season, and 6.0±0.6; 0.1±0.1 and 0.5±0.1 Mg ha^{-1} in the rainy season. In addition to the significant difference in estimated litter stock in each landscape within the same hydrological period, a difference was observed in the stock between the dry and rainy seasons (Tukey $P \leq .05$), once again confirming the seasonality. The volume of litter stored in ULF was, on average, approximately 40 times higher than in CPO and 10 times higher than in CAM during the dry season, and 60 times higher than in CPO and 12 times higher than in CAM during the rainy season, demonstrating the importance of preserving densely forested areas in agricultural management programs to ensure the maintenance of the biogeochemical cycles. In this regard, seasonality was evidenced by the increased litter production in certain periods of the year, indicating that the presence/absence of rainfall has an influence on litter production, and therefore on carbon emissions into the atmosphere. The total carbon stock estimated in soils at depths of 0.0 to 0.2 m varied from 26.1 (CAM) to 28.2 (CPO) Mg ha^{-1} during the dry season, and in this case the average values showed no significant differences (MANOVA $P > .05$). Conversely, in the rainy season, the total carbon stock estimated for the same region and depth varied from 23.3 (CAM) to 37.2 (CPO) Mg ha^{-1}, and the estimated concentrations showed significant differences (Tukey $P \leq .05$). The higher TC stock estimated for the CPO during the rainy season (37.2 Mg ha^{-1}) may possibly be explained by the relationship between the soil bulk density and the higher moisture content in this landscape (Fig. 3B). The higher volume of water retained in the soil of Capoeira during the rainy season affected the transport of CO_2 through the soil pore spaces, as suggested by [16]. As the rains diminish, an increase should be expected in the carbon flux, thus reducing its storage in the soils of this compartment. The carbon stocks estimated in this study are close to those estimated by other authors in Amazon landscapes under different stages of management and conservation. For instance, Cerri et al. [17] estimated a carbon stock of 26.6 Mg ha^{-1} in dense forest soils and 21.1 Mg ha^{-1} in Capoeira soils under two years of cultivation, while Sampaio [14] reported an estimated stock of 24.1 Mg ha^{-1} in Capoeira soils under 22 years of cultivation.

4. DISCUSSION

The C balance in soils is directly proportional to the difference between the volume of C added to the soil by the photosynthetic activity of plants, including aerial and roots parts, and the volume of C emitted to the atmosphere resulting from the decomposition of organic matter. This calculation is also influenced by the volume of C stored in litter biomass and in the mulch in managed areas, both of which are conditioned by seasonality. In an ecologically balanced landscape, the volumes of stored and released CO_2 would be equivalent, resulting in equilibrium between plant respiration/ photosynthesis, including aerial and root parts, and microbiological activity. The difference would stem from the increase in aerobic decomposition rates of organic matter and the respiration of microorganisms and roots in situations of deforestation or inappropriate land use, including burning of vegetation. According to [6], the soils of tropical forests participate significantly in greenhouse gas flows, sometimes acting as a CO_2 source and at other times as a sink, and these flows are mediated especially by biochemical processes in the soil [18,19]. Changes in the temperature and humidity pattern

[18,20] and in soil porosity interfere in the amount of carbon stored in this compartment, altering the metabolic rates of microorganisms, which in turn interferes in the dynamics of soil carbon and greenhouse gas emissions into the atmosphere. This is an adverse mechanism of reaction to the ecological equilibrium of a given region. Several authors consider soil temperature and moisture the main abiotic factors responsible for regulating CO_2 emissions into the atmosphere [18-23]. The seasonality of soil moisture is able to control litter decomposition rates, increasing the loss of plant biomass by decomposition when it undergoes irrigation [24]. Aprile and Siqueira [15], who studied the kinetics of transformation of organic matter into humus, suggest that there is an optimum condition of temperature and humidity, especially at the tropical forest, for the transformation process not to be interrupted by the inhibition of microbial activity. In the present study, a Pearson correlation analysis applied to temperature and humidity confirmed the strong influence of these factors on the total carbon content of the soil in the three landscapes, which was calculated, for temperature, as r(ULF)= 0.998, r(CPO)= -0.885 and r(CAM)= 0.987, and for moisture as r(ULF)= 0.986, r(CPO)= -0.856 and r(CAM)= 0.898. It is possible that the negative values obtained for the Capoeira plots confirm there is an optimum temperature and humidity condition that favors the metabolic activity of microorganisms, and that the decomposition rate of organic matter would decline below or above this condition. Irrespective of the major factor that governs the CO_2 flux in the soil-atmosphere system, physical, chemical, physicochemical and biochemical processes act jointly in this balance, which has been disrupted by inappropriate soil management practices.

In the last decades there has been growing concern not only about the burning of areas of Capoeira but also about the deforestation and burning of large continuous areas for extensive agriculture in the Amazon region (to consult Google Images), causing irreparable loss of genetic heritage and also contributing decisively to regional and global climate change [7,8,25]. In this regard, alternative techniques to burning, such as cutting and grinding Capoeira vegetation, preserve soil structure and fertility, increasing the concentration of C, N and P for plants [26,27]. Protecting the soil by introducing mulch added or not to the volume of naturally produced litter, increases the availability of soil water (moisture) and provides and retains nutrients essential to plants. The result is a significant increase in the area of the root system in the surface layer, which can act jointly with the microbial biomass to regulate the capture-emission system of the CO_2 volume. FAO data indicate reductions of up to 30% in evapotranspiration rates when the soil is protected by plant cover [28]. The application of a layer of plant cover favors the formation of the CO_2 concentration gradient [29]. There is a consensus among researchers that the current model of land use and occupation in the Amazon region is harmful to species preservation, and also interferes directly in the kinetics of forest regeneration, changing the balance between carbon capture, storage and sinks in different landscapes of the region. Although the impact factor of land use is minimal in the ULF under study (IF<5%), there are areas of upland forest in the Amazon, especially in the southern peripheral region between the states of Pará, Mato Grosso and Rondônia, which have been the continuous target of deforestation for timber extraction and the creation of large tracts of pasturelands and monocultures. The expansion of forest fires has contributed to CO_2 emissions and soil depletion, with significant loss of moisture and declining contents of organic carbon. Among the three monitored areas, the Campina represented the portion of the Amazon rainforest with the lowest participation in the carbon stock in Amazonian soils. However, this finding may be due to the sample size, the age of the Campina, its degree of ecological restoration, or even the percentage of representativity of this landscape in the Amazonian context. Studies developed from satellite imagery analysis (data: INPE and Google Earth) show that areas previously used for grazing and agriculture, which were later abandoned, tend to recover faster as the degraded area is less. In the case of the Capoeira, this kinetic restore of the natural conditions is even greater [14,27], because of the diversity and interaction of herbaceous, shrub and tree. In this way, Capoeira have compared the two other landscapes studied a greater capacity for ecological restoration. The management intensity of each area is directly dependent on the degree of modification of the natural conditions. Studies of ecological restoration in different areas of managed vegetation [30,31] show that the higher sustainable practice better and faster is the resilience of the environment. In this case, with already mentioned, the variety of herbaceous and woody shrubs contributes to the kinetics restoration biological conditions of the soil. The results confirm that, especially in samplings from Capoeira areas.

Estimates of litter production are very importance for the calculation of greenhouse gas emissions caused by burning and decomposition of organic matter, contributing to a better understanding of the effects of deforestation on global warming. Litter is considered the main route of plant carbon transfer to soil, and the volume of C transferred depends on factors such as the quality, heterogeneity and age of litter, soil type, and the various physical and chemical properties that influence the decomposition kinetics, among them temperature and humidity, as mentioned earlier. Another important factor for the carbon flux is the concentration of nitrogen [32,33], particularly the C/N ratio, which, when low, facilitates microbiological activity in the decomposition. When these conditions are in ecological balance, according to Grace [34], the C stock in soil could be two to three times higher than the volume stored in the atmosphere. In this study, a higher stock of litter was observed during the dry season (Table 2), when decomposition processes are slower and consequently there is an accumulation of this layer on the ground. Both the stock and the higher pattern of accumulation during the dry season confirm the findings reported by [9,35], who found contents of approximately 8.25 Mg $ha^{-1}year^{-1}$ in plots of dense forest close to Manaus.

Among the various land use and occupation practices, the traditional Amazonian family farming communities use the model of opening clearings in the forest for direct planting. The main characteristic of this practice involves cutting down and burning the natural vegetation, which stimulates the loss of soil fertility by leaching, erosion, soil compaction and volatilization of nutrients. Sommer [27] studied stages of plots of Capoeira in the northeast of the state of Pará and estimated a loss of 21.5 Mg ha^{-1} of C and 45 to 70% of K, Ca and Mg due to burning in a seven year old Capoeira landscape. In addition to loss of soil fertility, another problem that has emerged is the withdrawal of C in the form of CO_2 from soils, especially soils without plant cover, contributing to the increase in greenhouse gas emissions. The CO_2 flux from tropical forest soils may represent from 50% to 80% of all CO_2 emitted by the ecosystem [33,36], and these percentages cannot be ignored. Thus, we believe that more studies are needed to determine whether the carbon balance in tropical forests, particularly in the Amazon forest, is in equilibrium or if it has behaved primarily as a carbon source or sink, interfering in the global weather patterns.

5. CONCLUSION

The comparative analysis of the daily variation in temperature and soil moisture in the three landscapes under study confirmed that the presence of organic matter on the ground increases soil water retention, reduces soil temperature, leaching and erosion, and favors the continuous release of carbon into the environment. The findings of this study confirm the importance of seasonality in carbon production and storage in the soil-litter system, especially temperature and moisture. The degree of land use and occupation was a crucial factor to explain the different concentrations of TC and TOC in the monitored landscapes. Improper landscape management, including selective logging and burning, intensifies the loss of soil carbon to the atmosphere, which is evidenced by the decline in TC levels, especially in the Campina, and is also detrimental to productivity, a fact revealed by the reduction of organic carbon content in the soil.

CONSENT

All the authors accepted the terms for publication, and we agree that, if the manuscript is accepted for publication, we'll transfer the copyright-holder of the manuscript to BJECC and SDI, including the right of total or partial reproduction in all forms and media. We informed also that if accepted, the manuscript will not be published elsewhere including electronically in the same form, in English or in any other language, without the written consent of the copyright holder.

ETHICAL APPROVAL

It is not applicable.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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