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Assessing the impact of different tillage systems and land uses on CO₂-C emissions in Eastern Amazonia

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The production and emission of CO₂ in native, pasture and cultivated areas is a result of microbiological activity and mineralization of organic matter, and depends on favorable environmental factors, such as temperature, availability of water and of land use. The results of this work show that the no tillage system (NT) has the potential to mitigate 37.7% of C-CO₂ efflux from cultivation of soy compared to conventional tillage (CT). The temperature of the soil accounted for 65% of the variability of the flux of CO₂-C in CT. The variation of soil moisture explained 73 and 51% of the flux of CO₂-C in CT and NT, respectively. These results indicate that soil moisture and soil temperature were controlling factors of CO₂-C emissions from soil to atmosphere because these parameters directly affect soil microbial activity. The results also show that the active pasture had the highest outflows of soil CO₂-C to the atmosphere in relation to forests and degraded pasture in Western Pará. Furthermore, it was shown that both the pastures and forests have seasonality in the flux, which mainly related to precipitation patterns and water potential between soil and air. We observed a strong correlation between the efflux and soil moisture of both capoeira and in the pastures, as the soil temperature was a controlling factor of the active efflux only in the pasture. The average flux of CO₂-C obtained in pasture active was 218.9 mg C m⁻² h⁻¹ value of 40.7% higher than the primary forests and 155.5 mg C m⁻² h⁻¹. Finally, the results presented here suggest that the conventional tillage and pasture management are activities strongly associated to human enhance biogeochemical changes in the balance of carbon in these ecosystems, since the efflux of CO₂-C is related to soil primary productivity of these ecosystems.

Key words: Greenhouse effect, land use change, carbon cycle, soil CO₂-C efflux.

INTRODUCTION

The concentration of greenhouse gases (GHG) in the atmosphere has increased substantially in recent years as a result of anthropogenic activities. The atmospheric concentrations of carbon dioxide (CO₂) have all increased since 1750 due to human activity. In 2011, the

concentrations of these three gases were 391 ppm, 1803 ppb and 324 ppb, which exceeded pré-industrial levels by 40, 150 and 20%, respectively. The concentrations of CO₂, CH₄ and N₂O now substantially the highest concentrations recorded in the ice cores during the last

800.000 years. The average rates of increase in concentrations Atmospheres in the last century are unprecedented in the last 22.000 years (IPCC, 2014). CO₂ emissions are primarily due to activities such as burning fossil fuels, the burning of forests and the loss of soil humus.

About half of cumulative anthropogenic CO₂ emissions between 1750 and 2010 have occurred in the last 40 years. In 1970, cumulative CO₂ emissions from fossil fuel combustion, cement production and flaring since 1750 were 420 ± 35 GtCO₂. In 2010, that cumulative total had tripled to 1300 ± 110 GtCO₂. Cumulative CO₂ emissions from forestry and other land use since 1750 increased from 490 ± 180 GtCO₂ in 1970 to 680 ± 300 GtCO₂ in 2010 (IPCC, 2014).

World agriculture is responsible for issuing significant amounts of CO₂, CH₄ and N₂O to atmosphere contributing 11, 47 and 58% of the total anthropogenic emissions of these gases, respectively (IPCC, 2007). In Brazil, the participation of agriculture to the total of anthropic emissions is accentuated, being 75, 78 and 91% for CO₂, CH₄ and N₂O, respectively (Cerri et al., 2007) when considering the conversion of natural areas to agriculture.

Deforestation in tropical regions is a major cause of global changes. The conversion of forests to pastures affects the biogeochemical cycles, carbon fluxes to the atmosphere, terrestrial biodiversity and also the social and economic viability of traditional forest peoples (Salimon et al., 2011; Giacomini et al., 2006; Foley et al., 2003). As a result, new scenarios of changes in land use are encroaching on natural areas within the Amazon region, causing unpredictable changes that increase the intensity of the impacts of this new production cycle (Gardner et al., 2013).

The advance of the agricultural frontier on these natural areas by removing the natural vegetation cover and even the impact of the use of new production techniques and new forms of management can change microbial processes. The use and even the preservation of these natural resources and ecological functions, together with the much desired sustainable development, is still far from being achieved (Fearnside, 2015; Foley et al., 2007).

In Eastern Amazonia, the agricultural frontier has expanded bringing changes to a scenario that has already changed greatly from previous waves of development which also aimed to increase food production. The expansion of the agricultural frontier changes the entire structure of the region it occupies. Furthermore, the impacts are not restricted to cultivated areas, but due to climatological patterns of the region, the effects caused by the unplanned use of fertilizers and

pesticides are felt in the natural areas that surround these areas of production (Schlesinger, 1997). Forests and water bodies are affected by compounds emitted by farming areas and these have modified their ecological functions and natural processes. Within the region, the diversity of environments and climatic conditions makes it necessary to take measurements of the long-term dynamics of the mechanisms controlling the interactions between the biosphere and atmosphere (Fearnside, 2002, 2015; Foley et al., 2007; Nepstad et al., 2014).

These scenarios are alternated within the impact area and therefore also alter the process and the rates at which they occur. Within Western Pará State, a frontier for agricultural expansion has been established and few studies have been done to assess the impact on disturbed sites and its effect on these new centers of production in what were recently natural areas.

On a regional scale, knowledge about this type of land cover change and land use is fundamental to evaluate the functioning of an ecosystem and also for landscape management. Deforestation in the Brazilian Amazon is mainly related to the conversion of forests into pastures (Fearnside, 2016; Nepstad et al., 2014). After using these pastures or after planting for a few years, the soils of this region become less productive and the most common practice is the abandonment of areas, entering a stage of secondary secession, that lead to secondary forests.

Thus there are three main soil covers in the Amazon region: primary forests, pastures and agricultural fields. Some researches indicate the consequences of deforestation and conversion to pasture on carbon stocks in vegetation and soils also (Salimon et al., 2004). However, the flow of soil carbon to the atmosphere has been little studied in the Amazon, except in a few places in Pará (Davidson et al., 2000; Davidson et al., 2004; Trumbore et al., 1995; Sotta Doff et al., 2004, 2007; Vasconcelos et al., 2004; Keller et al., 2005) and Rondônia (Feigl et al., 1995). In view of this scenario, the present study aims to evaluate the impact of different types of soil cover on the CO₂ emissions from the soil to the atmosphere.

Of these sources of carbon to the atmosphere, CO₂ is the most important in terms of mass, especially through burning and respiration of roots and soil microorganisms. In the face of this scenario, it becomes essential to have a better understanding of the effect of different tillage systems linked to agricultural practices on the biogeochemical cycling of carbon in the soil (Sugihara et al., 2012).

It is presumed that changes in this cycle resulting from change in land cover and climate changes can lead changes on local, regional and global levels. In order to understand these consequences and to mitigate

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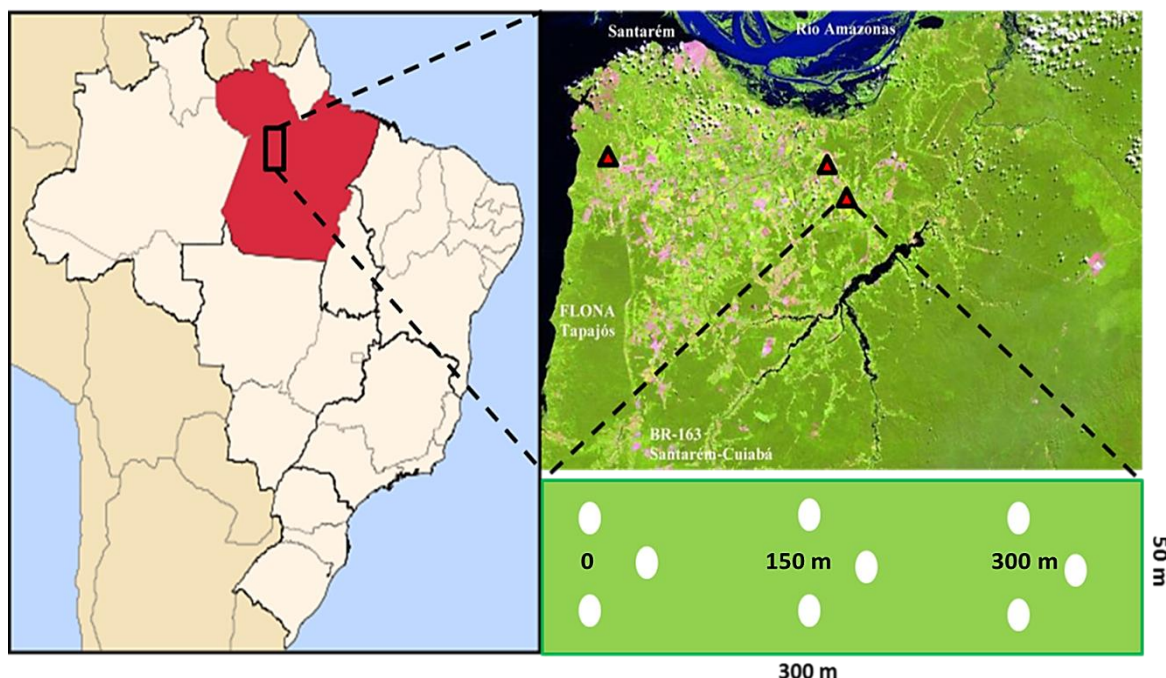


Figure 1. Area of study - triangles (measuring point) and rectangle in green (transect) blank circles (concentration chambers).

negative effects, the focus of this study was to examine C-CO₂ efflux from both forest and other forms of land use, such as secondary forest, grazing and agricultural areas.

MATERIALS AND METHODS

Study area

The study was conducted in Western Pará, on the Belterra plateau of the municipality of Santarém (Figure 1), in an agricultural field, secondary forests and degraded pasture situated 40 km from the PA-370 highway, whereas the active pasture is situated 25 km from the BR-163 highway. More details of the study sites are summarized in Table 1. These locations are characterized by a climate of type Ami-megathermal humid tropical climate, according to the classification of Köppen; the average annual rainfall is 2096 mm annual average temperatures range from 24 to 28°C. All soils are dystrophic yellow Oxisols. The Physical and chemical characteristics of clayey Yellow Latossols in Belterra municipality are summarized in the in Table 2.

The selection of the watersheds was performed considering the principal axes of heterogeneity in both the environmental and socioeconomic aspects. The main criterion for selection of individual watersheds was the total remaining forest cover (or conversely, the accumulated historical deforestation) and that the selected areas form a gradient of deforestation.

Sample design

Using a stratified sampling design allows a wide variety of rural properties to be represented in the landscape, covering both small and large producers and also all major types of land use and

management practices in the region. In the areas of secondary forest, mature (forest that has not suffered significant disturbances or been exploited or influenced directly or indirectly by humans), active (that was managed to achieve a balance between yield and quality of the fodder produced) and degraded pastures, the latter being (defined as demonstrating a loss of the ability to maintain biological productivity, accumulate significant biomass, to cover the soil surface), the factor seasonality was considered and sampling was done on subsamples (50 m × 300 m) of watersheds for nine months from February until November 2012 covering the dry and wet periods with two monthly samplings with 9 repetitions in each transect, except for the month of August, where the measures were not carried out due to equipment failures.

In the agricultural field the sampling was of short duration (≈ 10 min) between the periods and comparative analysis between CT and NT was made with one sampling (9 replicates) done before cultivation and during sowing. Sampling was also done at the time of crop planting with two samplings during the first week after planting and one sampling in the second week after planting implements change in rates of CO₂-C efflux from the soil.

For the biodiversity and environmental data each sample point is a standardized transect 300 m long by 50 m wide. Nine chambers were distributed along a transect with a dimension (50 m × 300 m) and three chambers were installed for each point (0, 150 and 300 m), with three placed on the soil surface distant 10 meters (Figure 1) relative to one another for the measurements of CO₂-C efflux, totaling nine chambers for each transect.

Sampling system

Measurements of CO₂ emitted by the soil were made using the methodology of dynamic chambers with a coupled infrared gas analyzer (IRGA) model Licor-820 (Figure 2). The response signals of the detectors were captured at a frequency of 5 seconds and flux

Table 1. Specification of the study watersheds and their respective transects (land use).

Watershed	Land use	Extension Area (ha)	History	Previous use	Geographic coordinates (Lat./Long.)
112	Agricultural field (Conventional tillage and no tillage)	380	≈ 10 of years soybean farming under conventional tillage	Pasture	-54°29'57.6 W/ -2°43'18.54 S
	Secondary forests	10	Secondary forests with ≈ 15 years	Pasture	-54°29'33.2 W/ -2°44'19.11 S
	Degraded pasture	50	≈ 3 years management minus	Mature forest	-54°29'57.5 W/ -2°44'20.87 S
129	Active pasture	150	Pasture ≈ 7 years	Mature forest	-54°46'35.4 W/-2°43'33.03 S

Table 2. Physical and chemical characteristics of clayey Yellow Latossols in Belterra municipality, Pará State. Two experimental sites.

HOR	Depth (cm)		g/kg of soil				pH		cmol _c kg ⁻¹ soil				Silt/ clay	Ki	%		P			
			Sand	ADA	Clay	C	Fe ₂ O ₃	H ₂ O	pH	Ca	Mg	K			S	Al	T	V	m	(mg/kg)
Typic Hapludox – coordinates: 02° 54'S and 54° 56'W																				
A1	0 -	11	30	640	890	19.8	61	3.7	-0.1	0.40	0.05	0.50	2.70	10.5	0.09	1.91	5	84	4	
AB	-	23	20	510	920	13.6	63	4.1	-0.3	0.30	0.03	0.45	2.10	7.8	0.07	1.86	5	84	2	
BA	-	45	20	0	930	9.6	66	4.3	-0.4	0.40	0.02	0.44	1.80	5.9	0.05	1.86	7	82	1	
Bw1	-	91	20	0	930	6.4	67	4.4	-0.4	0.30	0.01	0.32	1.70	4.4	0.05	1.88	7	85	1	
Bw2	-	160	10	0	930	4.2	67	4.7	-0.6	0.40	0.01	0.44	1.00	3.6	0.06	1.92	11	71	1	
Typic Hapludox – coordinates: 02° 45'S and 54° 54'W																				
O	3 -	0	160	50	680	55.9	41	4.8	-0.8	6.8	3.2	0.23	10.3	0.3	22.9	0.24	2.03	13	89	1
A1	0 -	15	100	50	820	18.1	49	4.5	-0.5	0.5	0.5	0.04	1.1	1.6	8.4	0.10	1.99	5	92	<1
AB	-	29	70	68	840	11.3	52	4.5	-0.5	0.4	0.02	0.44	1.7	6.4	0.11	1.98	1	90	<1	
BA	-	44	60	0	870	7.9	52	4.7	-0.6	0.50	0.02	0.53	1.5	4.6	0.08	1.94	1	88	<1	
Bw1	-	79	70	0	870	5.1	52	4.9	-0.9	0.40	0.01	0.42	1.3	4.0	0.07	1.94	1	91	<1	
Bw2	-	122	60	0	890	5.0	55	5.0	-1.0	0.40	0.01	0.42	1.3	3.5	0.06	1.92	1	-	-	
Bw3	-	200	50	0	880	4.0	54	5.0	-1.0	0.40	0.01	0.43	1.1	3.5	0.08	1.95	1	-	-	

was calculated by linear regression of concentration by time interval measurements.

Measurements were always conducted between 09:00 and 16:00 h. In order to evaluate whether the time of sampling was representative of soil respiration during the day, we also conducted samplings at 1 h intervals in pasture, mature and secondary forests, with nine flux measurements at each site and hour.

The flux was calculated from linear regression of the difference of CO₂ concentration over time. The measurements during the first minute were discarded from the regression to avoid any artifact of closing the chamber,

and only the data showing a linear increase in CO₂ concentration (usually during a 1 to 5 min interval) were used to calculate fluxes. The IRGA was calibrated every morning by using 'zero' air that had been run through a soda lime scrubber and by using certificated standard gas of 610 (±2%) ppmv of CO₂ (nitrogen as the balance gas).

CO₂ flow calculation

Soil respiration (*R_s*) was computed as the rate of change of the CO₂ concentration by time unit and area under the

region covered by the camera, as shown in the equation:

$$Rs = (C_n - C_{n-1}) / T_n \times (V/A) \quad (1)$$

where *R_s* = soil respiration (CO₂ μmol m⁻² s⁻¹); *C_{n-1}* = concentration (ppm) of CO₂ at the initial time (*n-1*); *C_n* = concentration (ppm) of CO₂ in the end time (*n*); *V* = chamber volume (m³); *A* = coverage area (m²); and *T_s* = time interval (s).

The calculation of the CO₂ flux described earlier was determined by means of a computer application (Licor - 2010) developed by Fagner (2010). These parameters

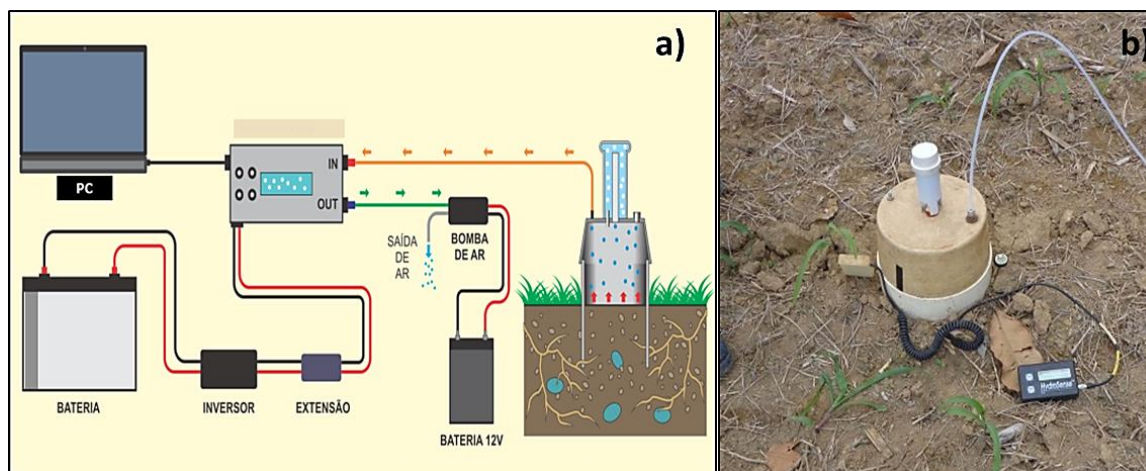


Figure 2. (a) Experimental arrangement and the (b) concentration chamber.

were inserted in Equation 1 in order to determine the flow of CO_2 from the soil. The average height of the chamber (cm) was obtained from three different points of the base ring. A conversion factor in the amount of 43.22 (this value is a conversion factor of the μmol unit to mg) was used to measure the efflux of $\text{CO}_2\text{-C}$ soil in $\text{mg CO}_2\text{-C m}^{-2} \text{h}^{-1}$.

Meteorological elements

To correlate the variation of soil CO_2 flux to the microclimate of the region parameters such as temperature of air and soil, soil moisture and precipitation were measured. For measurements of soil temperature a Taylor instruments digital thermometer was introduced into the soil to a depth of 5 cm, adjacent to the chamber. The same points were used for each sampling of soil CO_2 efflux.

Gravimetric soil moisture was measured at all points of measurements of CO_2 efflux at 10 cm depth using a soil auger. Samples were immediately placed in sealed plastic bags and weighed on the same day to obtain the wet weight of each soil sample and samples were dried at 105°C for approximately 48 h.

Waterfilled pore space (WFPS) was calculated as in the following equation:

$$\text{WFPS} = \% \text{Volumetric water} / \% \text{Soil porosity} \quad (2)$$

$$\% \text{Soil porosity} = 1 - (\text{soil bulk density} / 2.65)$$

where 2.65 is the assumed particle density.

Statistical analysis

Data were statistically analyzed with the software Statistica version 6.0 for Windows. Data were analyzed using ANOVA with site and season as fixed effects. Scheffe's (ou Tukey's) post hoc test was used to separate means, and a probability level of $\alpha = 0.05$ was used for all tests.

All data were analyzed for the distribution normality of data was checked by the Kolmogorov-Smirnov test and the tests showed that data were normally distributed.

The effect of and CO_2 emissions between conventional and no till systems was investigated by analysis of variance (ANOVA). When the ANOVA resulted in a significant effect ($p < 0.05$), the Tukey

multiple comparison test was used to separate means. The dependence of $\text{CO}_2\text{-C}$ efflux on temperature and soil moisture was evaluated from the significance of the correlation coefficients of linear regressions through the Pearson parametric test.

RESULTS AND DISCUSSION

Microclimate conditions in relation to no tillage and conventional tillage

The daily rainfall during the study period is presented in Figure 3. Dry soil is a favorable condition that ensures that soil preparation is carried out effectively, and for this reason dates wherein there was no precipitation (Figure 3) were recorded. There was no significant occurrence of drought, which maintained adequate levels of moisture in the soil, so it is assumed that this variable was not limiting to microbial activity responsible for the $\text{CO}_2\text{-C}$ efflux.

Comparison of CO_2 efflux between no tillage and conventional tillage

The no tillage system (NT) promoted less $\text{CO}_2\text{-C}$ efflux from the top soil ($p < 0.05$) than the conventional tillage system (CT). During all stages of tillage (plowing and harrowing, sowing and harvesting) there were higher levels of $\text{CO}_2\text{-C}$ efflux from the soil in the CT during the evaluation period, as shown in Reicosky et al. (1999) Figure 4. Throughout the measurement period greater efflux of $\text{CO}_2\text{-C}$ was observed in the system under CT (Figure 4) when compared with NT, averaging 196.1 ± 25.9 and $142.4 \pm 27 \text{ mg C m}^{-2} \cdot \text{h}^{-1}$, respectively (Table 3).

Similar values than those obtained in this work were reported in a study that evaluated the CO_2 emissions derived from plowing and harrowing, in which the

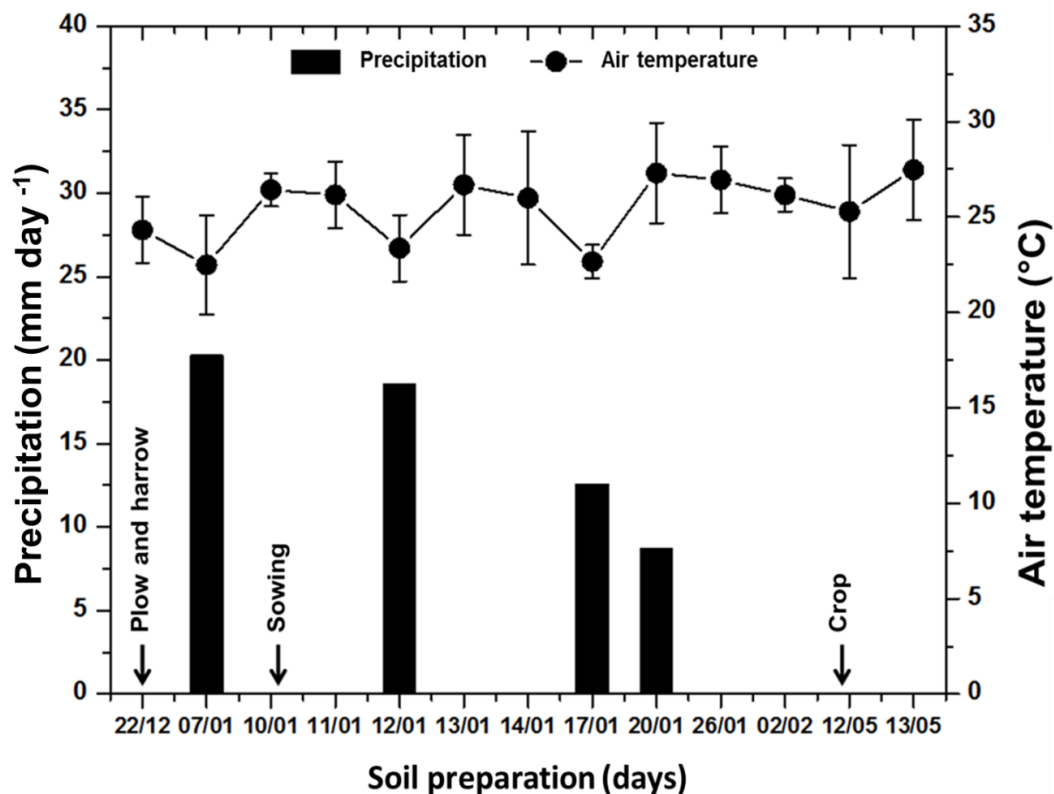


Figure 3. Distribution of day precipitation and variation of average air temperature during complete experimental period (22-Dec.-2010 to 13-May-2011).

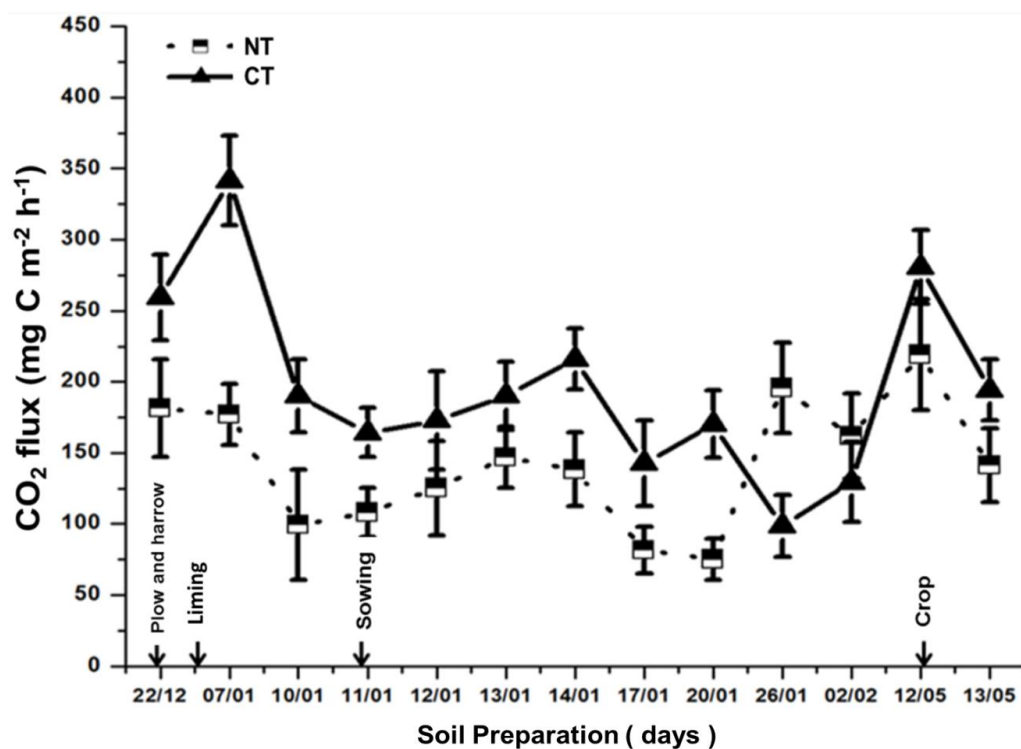


Figure 4. Soil CO₂-C efflux conventional tillage systems (CT) and no tillage (NT) in soybean/corn rotation. The bars indicate standard deviation.

Table 3. Mean values of CO₂-C (mg m⁻² h⁻¹) flux with standard deviation (SD), water filled pore space (WFPS%) and soil temperature (ST) at 5 cm depth under no-tillage and conventional tillage.

Date (Soil preparation)	No tillage				Conventional tillage			
	CO ₂ flux	SD	WFPS (%)	ST (°C)	CO ₂ flux	SD	WFPS (%)	ST (°C)
22 Dec. 2010	181.4	34.6	48.3	29.3	259.2	30.2	32.7	31.6
07 Jan. 2011	177.1	21.6	52.2	28.4	341.3	31.5	33.3	33.1
10 Jan. 2011	99.4	38.9	39.8	27.4	190.1	25.9	36.4	29.0
11 Jan. 2011	108.0	17.3	42.9	29.7	164.2	17.3	32.7	30.2
12 Jan. 2011	125.3	33.3	42.5	30.4	172.8	34.6	35.9	31.7
13 Jan. 2011	146.9	21.6	46.3	31.9	190.1	23.8	39.4	30.9
14 Jan. 2011	138.2	25.9	46.5	28.9	216.0	21.6	44.3	30.0
17 Jan. 2011	81.6	16.4	38.8	29.4	142.6	30.2	41.3	31.0
20 Jan. 2011	75.2	14.3	39.3	28.4	170.2	23.8	42.6	28.6
26 Jan. 2011	195.7	32.0	68.3	31.2	98.5	21.6	25.9	28.7
02 Feb. 2011	162.0	29.8	63.9	29.7	129.6	28.1	30.6	30.7
12 May 2011	219.0	38.9	64.3	31.8	280.8	25.9	30.1	29.7
13 May 2011	141.3	25.9	48.8	29.6	194.4	21.6	29.9	30.2
Media	142.4	27.0	49.4	29.7	196.1	25.9	35.0	30.4

average emissions of CO₂ efflux from the soil was greater in the CT treatment (La Scala et al., 2001).

It can also be seen in Figure 4 that the largest emission in CO₂-C efflux from the soil were recorded on 22-December-10 and 07-January-11 during soil preparation, with 250 and 345 mg C m⁻² h⁻¹ for the CT, respectively. These values occurred a few days after the execution of plowing and disking and application of limestone (CaCO₃ 4 t.ha⁻¹) on 07-January-11 generating a pulse (Figure 4) of CO₂-C of 341.3 ± 31.5 mg C m⁻² h⁻¹. This pulse was probably stimulated by liming and tillage from previous cultivation of soybean which possibly created favorable conditions for the decomposition and mineralization of soil C and therefore justifies the high efflux of CO₂-C (Anghinoni and Salet, 2000).

Subsequent soil tillage operations generated the highest value (341.3 mg C m⁻² h⁻¹) compared to the other days evaluated. In the seeding stage, the CO₂-C efflux values gradually increased in both NT and CT (Figure 4) which may be associated with intense autotrophic activity induced by application of fertilizer (NPK 308 kg.ha⁻¹) in this period.

Harrowing the soil breaks up the soil and frees the organic matter that can be found within the different soil aggregates, especially macroaggregates and microaggregates occluded within the macroaggregates (Six et al., 2000), making available the carbon within aggregates available for decomposition by microorganisms.

In temperate soils, the primary mechanism of protection of carbon in agroecosystems is the physical protection within aggregates. In tropical soils, on the other hand, such as Latosols, chemical protection may be the main mechanism of protection carbon (Zinnyl et al., 2005;

Denef et al., 2004). In this case, the impact of soil preparation of the efflux of CO₂-C may be less than the soils found in temperate biomes.

During soybean harvest (10-May-2011) CO₂-C efflux was measured in both management systems on subsequent days (12-May-2011), showing high values of efflux of CO₂-C. This pattern of emission of CO₂-C has been reported by some authors analyzing soybean several days after harvest (Fields, 2006; Oorts et al., 2007).

These high levels of emissions are apparently related to the higher concentrations of labile, C, which is consumed and used a substrate for growth of microbial populations (Dendooven et al., 2012). The roots of soybean remaining in the soil continue to emit CO₂-C during the process of decomposition, furthermore, and cutting of roots during the collection process can lead to increased efflux CO₂-C from the soil (Oorts et al, 2007; Varner et al., 2003).

Correlation between CO₂ efflux and soil temperature

The CO₂-C efflux from the soil is not influenced only by physical and biological processes in the soil, but also by environmental factors such as temperature and soil moisture, which are seen as important factors in controlling the rate of soil CO₂-C efflux. This study found a high coefficient of determination ($r^2=0.65$) and high significance ($P<0.01$) between the CO₂-C flux and soil temperature in CT, contrasting with the NT where there was no correlation between these variables (Figure 5a), indicating a more direct relationship of CO₂-C efflux in relation to soil temperature on, and that other factors

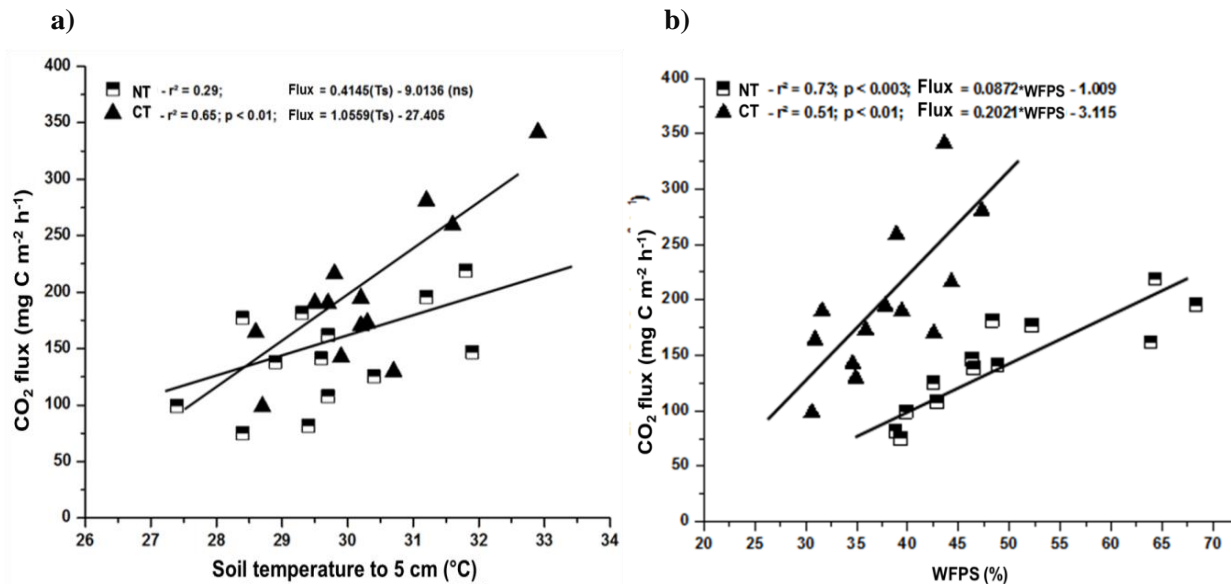


Figure 5. Correlation between the CO₂-C efflux and soil pores filled with water (WFPS) and soil temperature under conventional tillage (CT) and no tillage (NT) in soybean/corn rotational systems.

besides soil temperature may be influencing the efflux of CO₂-C soil in NT. Thus, the average daily temperature variation of the soil explained 65% of the variation in the soil CO₂-C efflux in CT.

Correlation between CO₂ efflux and soil temperature

In this case, the absence of ground cover in CT permitted direct incidence of sunlight and increased soil temperature, which, in turn, could have enhanced microbial activity, and thus the efflux of CO₂-C to the atmosphere (Moitinho et al., 2012).

Soil temperature as a factor controlling the CO₂-C efflux from the soil is an issue that has great importance, being used in analytical and statistical models in forecasting the emission of this gas from soils in various environments (Moncrieff and Fang, 2001). In the NT the input to the surface of organic debris decreased the incidence of direct sunlight on the ground and caused a consequent reduction in water loss (Salton and Mielniczuk, 1995) which acted to inhibit the increase in temperature CT ground and therefore to reduce the outflow of soil CO₂-C to the atmosphere.

The production of CO₂ in the soil is primarily a result of root and microbial activity which, when there is no limitation on other parameters (oxygen, moisture, pH, organic compounds, nutrients, etc.) is regulated by soil temperature.

Another important difference between CT and NT systems that influences production of CO₂ is microbial composition and its location in the soil profile, as highlighted by Vargas (2002).

These authors found largest populations of denitrifying organisms and fungi in soil layers in NT soil, and larger populations of aerobic microorganisms throughout the topsoil in CT.

These aspects are associated with the effects of soil management systems on the distribution of C and N throughout the soil profile (Steiner et al., 2012). However, physical changes triggered by tillage, and which reflect the ability of the soil to retain more or less water, have a strong effect on the composition and distribution of microorganisms in the soil profile (Bortolotto et al., 2015).

Correlation between CO₂ efflux and soil moisture

The NT system tends to have greater moisture and hence higher porosity filled with water (WFPS), accompanied by minor efflux of CO₂-C, relative to CT, and in the latter system, the soil moisture decreased drastically with tillage (Table 3). Soil moisture (WFPS) during the evaluation period explained 70 and 51%, respectively, in both systems (Figure 9) of the variability of the efflux of CO₂-C from the soil. This significant positive correlation ($p < 0.05$) for the NT system could be associated to the maintenance of residues in the soil, preventing direct incidence of solar radiation on the ground, and higher capacity for water storage in NT soil (Rethe et al, 2005; Costa, 2003) (Table 3), due to its larger stock of organic C, conditions which may explain part of the results obtained in the present study.

The CT also showed a significant linear correlation between CO₂-C efflux and soil moisture ($r^2 = 0.51$) (Figure 5b), which indicated greater dependence of CO₂-C

Table 4. Mean values of soil CO₂ efflux and standard deviation of the mean (spatial variation) in primary forest, secondary forests (n = 18), active pasture (n = 18) and degraded pasture (n = 18).

Year	Month	Precipitation	CO ₂ efflux (mg C m ⁻² h ⁻¹)		
			Secondary forest	Active pasture	Degraded pasture
2011	February	133.6	194.4 ± 17.3	315.4 ± 34.6	116.7 ± 21.6
	March	294.7	224.6 ± 38.9	302.4 ± 21.6	103.7 ± 34.6
	April	404.6	185.7 ± 30.2	345.6 ± 25.9	151.2 ± 30.2
	September	13.2	125.2 ± 21.6	116.6 ± 21.6	64.8 ± 25.9
	October	45.9	129.6 ± 30.2	103.7 ± 17.3	69.1 ± 21.6
	November	0	103.6 ± 38.9	129.6 ± 21.6	86.4 ± 34.6

efflux in soil CT on moisture, probably due to lack of crop residues on the soil surface, which increases its temperature. Some studies have shown that the CO₂-C efflux from the soil indicates that microbial activity in the soil increases exponentially or linearly with temperature and soil moisture and is used in mathematical models of ecosystems as a constant (Xu and Qi, 2001).

With respect to the effect of temperature and soil moisture on CO₂-C efflux (Ouyang and Zheng, 2000) emphasized that solar radiation is one of the important processes governing the diurnal cycles of soil temperature and water evaporation by controlling production rates from CO₂-C in the soil, and thus the CO₂-C emissions to the atmosphere from the soil (Reth et al., 2005).

Temporal variation of CO₂-C efflux between land uses

Effluxes CO₂-C atmosphere for soil generally varied between 60 and 350 mg C m⁻² h⁻¹ being greater in the wet period (Table 4). These values are within the same range of magnitude observed by other authors for the Amazon region, between 80 and 400 mg C m⁻² h⁻¹ (Salimon et al., 2004; Fernandes et al., 2002) and also in temperate ecosystems where efflux values ranged between 50 and 300 mg m⁻² h⁻¹ (Jarvis and Rayment, 2000; Savage and Davidson, 2001).

Seasonal variation of the CO₂-C efflux in different types of land use

The highest fluxes were recorded during the wet season (February-April) with the largest peak observed in April. The lowest fluxes, in turn, were found in September, one of the months where in the dry season is most pronounced (Figure 6 and Table 4).

A seasonal pattern similar to this was also reported by Davidson et al. (2000) in forests and grasslands in eastern Pará and also by Fernandes et al. (2000) in Rondônia. This may have occurred in response to changes in temperature and soil moisture, reflecting chemical changes that make up the respiratory

processes occurring simultaneously at different depths within the soil profile. According to these authors the spatial variability can probably be explained by the unequal distribution of roots in soil depths.

The variability of soil CO₂-C efflux soil during the year following seasonal rainfall influences with the soil moisture and therefore this seasonal pattern in CO₂-C efflux is strongly associated with the physical process of water percolating into the soil. This water will tend to occupy the pore spaces that are filled by the gas causing the immediate expulsion of CO₂ stored in the soil to the atmosphere (Smith et al., 2003). In April (wet season), the fluxes recorded in the active pasture were four times higher compared to September (dry season). The dominant species of grass has nearly all its biomass in the form of leaves and when this biomass is reduced in the dry season the photosynthetic rate also decreases. The same process probably occurs with root and microbial respiration in the rhizosphere, resulting in a reduction in total CO₂ efflux from the soil (Salimon et al., 2004).

Salimon et al. (2004) measured fluxes in pasture in the wet season in Acre, that were 4.5 times higher than in the dry season. In forests, however, seasonal variations were smaller being 2.1 to 2.7 in the mature forest and 1.6 to 1.7 in the secondary forest.

In the current study, the seasonal variation of flux was also high, with a 2.8 times greater flow in the rain than in the dry season. In native ecosystems, however, there was a much more pronounced seasonal variation, with fluxes 1.6 and 1.7 times higher in the wet season compared to the dry season, in secondary forests and degraded pasture, respectively. In pastures in the Brazilian State of Acre studied by Salimon et al. (2004), annual fluxes were 70% higher when compared with mature forest.

In April all values of CO₂-C efflux were higher than the average of the outflows in the dry season (September, October and November). In these months of the dry season, the points of measurement had low CO₂-C efflux (Figure 6). This suggests that at the start of measurements, increased humidity favored the CO₂-C production at all measured points.

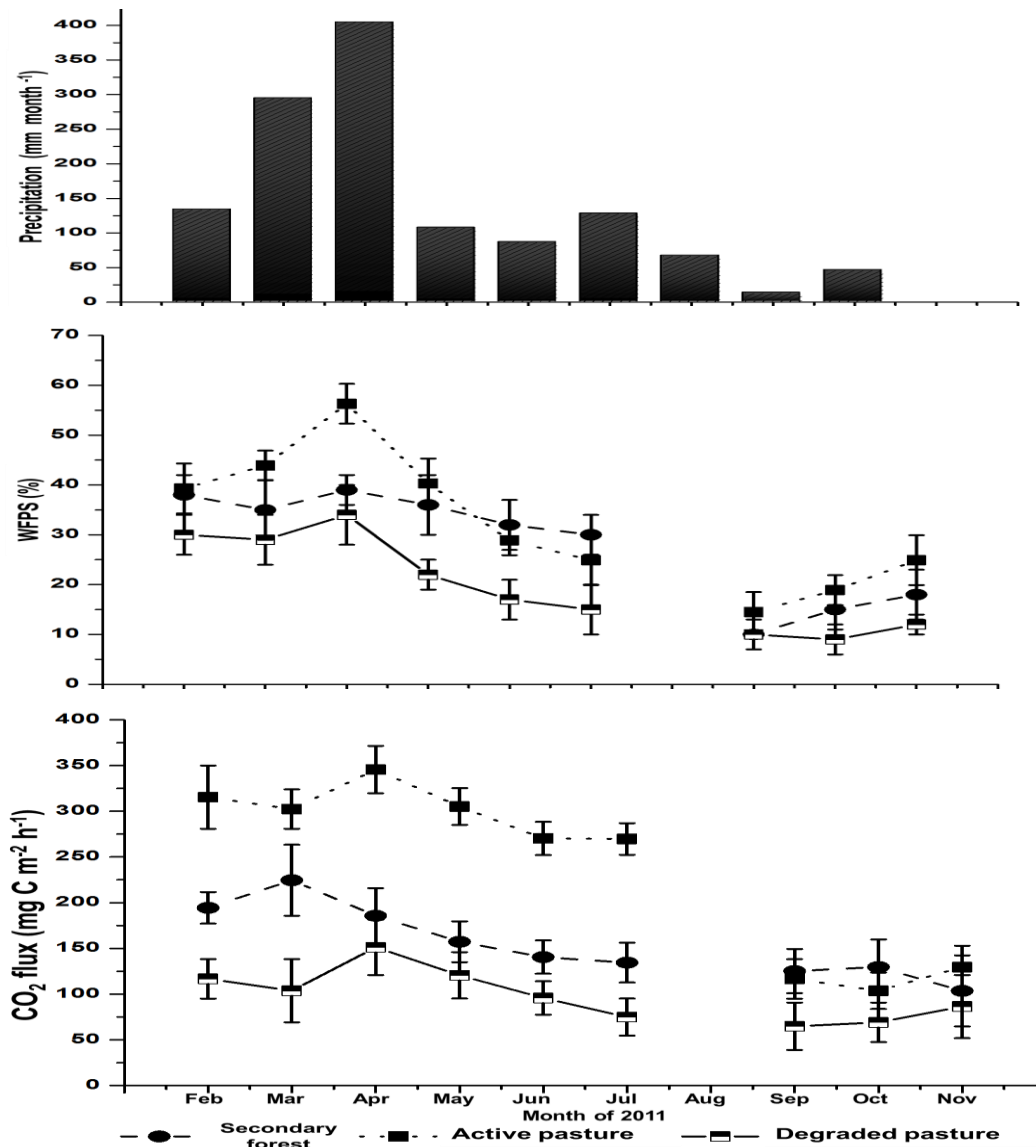


Figure 6. Seasonal variation of CO₂-C efflux from the soil, soil moisture and monthly rainfall. Error bars represent the standard spatial variation in secondary forest (n = 18), active pasture (n = 18) and degraded pasture (n = 18).

The possible increase in organic matter decomposition (with CO₂ production) may have altered the substrate thereby reducing CO₂-C emissions. Thus, the increase in humidity no longer showed homogeneous effect on CO₂ production. Incidentally, Davidson et al. (1998) and Savage and Davidson (2001) also find this pulse in CO₂-C emissions after the fast wetting of dry soil, similar to our study.

Although soil moisture (WFPS) was greater in pasture than in forest in the dry season (Figure 4), the largest reduction of the CO₂-C efflux from the soil in pastures indicates that grasses may be more sensitive to seasonal changes to water potential between the ground and air.

The surface soils under pasture are more clayey, but

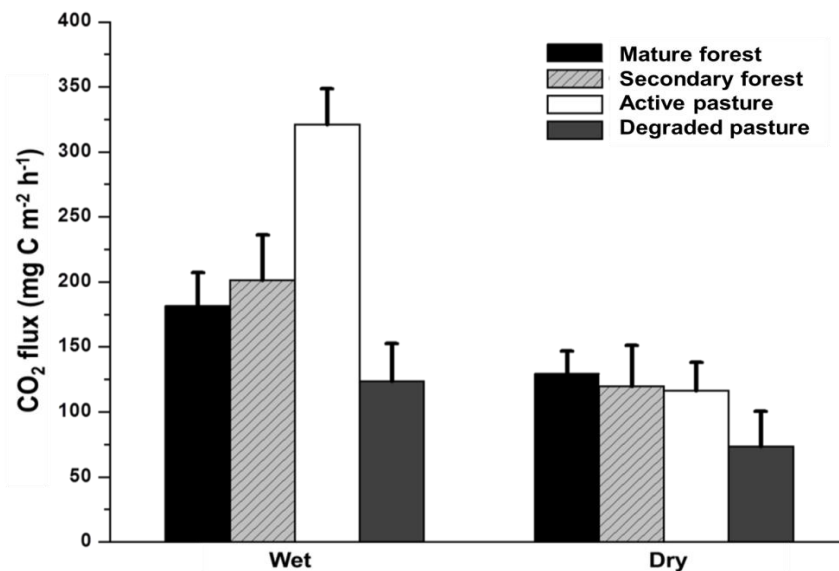
although there may be more water in the soil (Salimon et al., 2004), it may not be available to the plants. The forest vegetation has deeper roots, allowing access to deep soil water during the dry season, thereby reducing the seasonality of CO₂-C efflux in forests (Nesptad et al., 2008; 2014).

Therefore, the variation of water content in soil and the atmosphere should be primarily responsible for the seasonality observed and also the greater range of variation in the efflux soil of CO₂-C in active pasture. The influence of temperature on the soil CO₂-C efflux is minimal, since its range of variation is less than that observed in the flux due to rainfall.

Table 5. Average values of CO₂ efflux and standard deviations in mature forest, secondary forest, active pasture and degraded pasture active during the wet and dry season (mg m⁻² h⁻¹).

Seasonality	Land use			
	Mature forest	Secondary forest	Active pasture	Degraded pasture
Wet	181.4 ± 25.9 ^{aA}	201.6 ± 34.5 ^{aB}	321.2 ± 27.4 ^{aA}	123.8 ± 28.8 ^{aC}
Dry	129.6 ± 17.3 ^{bA}	120.0 ± 31.1 ^{bA}	116.6 ± 21.6 ^{bA}	73.4 ± 27.4 ^{bB}
Total average	155.5 ± 21.6	160.8 ± 32.8	218.9 ± 24.5	98.6 ± 28.1

*Different letters in the same column (lower case) and the same line (upper case) letters represent statistically significant differences (Tukey test, $\alpha = 0.05$).

**Figure 7.** Seasonal variation in CO₂-C efflux from the soil in mature forest, secondary forest, active and degraded pastures.

Comparison of CO₂ efflux between land uses

The values of soil CO₂-C efflux in secondary forest in the wet and dry periods varied between 168.5 and 216 mg C m⁻² h⁻¹ and 99.4 and 142.6 mg C m⁻² h⁻¹, and pasture values were between 254.9 and 311 mg C m⁻² h⁻¹ and 86.4 and 129.6 mg C m⁻² h⁻¹, and the degraded pasture values ranged between 121 and 172.8 mg C m⁻² h⁻¹ to 38.9 and 86.4 mg C m⁻² h⁻¹.

The lowest average value of CO₂-C efflux from the soil during the dry period was obtained in degraded pasture, and the highest was observed in the active pasture. For the wet season, meanwhile, the mean value of CO₂-C efflux from the soil was recorded in the active pasture and was lower in degraded pasture, as observed in Table 5.

The CO₂-C efflux from the soil, in general, is higher in the wet season, and soil moisture and temperature were the factors that primarily controlled the production of gas. In all types of soil cover statistically significant differences were observed relative to the seasonal factor (Table 5).

The active pasture had on average, higher CO₂-C efflux from the soil to the atmosphere in relation to forests and degraded pasture (Figure 7).

Pastures, on average, had higher CO₂-C efflux from the soil to the atmosphere than mature and secondary forests in the sampling period (Table 5). These results are similar but slightly higher than those from other studies conducted in the Southern and Western Amazon region (Salimon et al., 2004; Fernandes et al., 2002). Although, in Eastern Pará, Davidson et al. (2000), found that the forest had a greater flux than did a pasture.

Feigl (1994) working in a 13-year old pasture in the dry season, reported values between 91 and 182 mg C m⁻² h⁻¹, values that are close to those observed in the present study, for a similar period. Fernandes et al. (2002) also notes compatible values that are on average 100 mg C m⁻² h⁻¹ in the dry period and between 200 and 350 mg C m⁻² h⁻¹ in the wet season in pastures. Davidson et al. (2000) found values below 100 mg C m⁻² h⁻¹ during the dry period and between 200 and 400 mg C m⁻² h⁻¹ in the wet season.

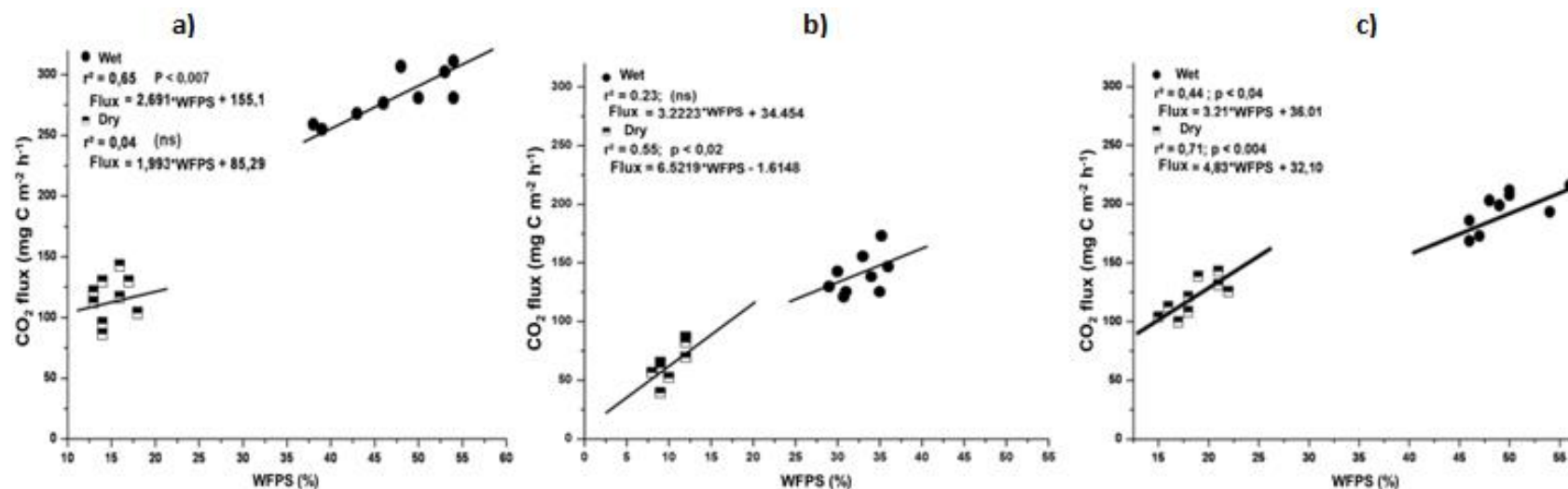


Figure 8. Correlation between the CO₂-C efflux from the soil and the percentage of pores filled by water (WFPS) during wet and dry seasons under the area of secondary forests (a), active pasture (b) and degraded pasture (c).

The discrepancy between the values observed in active pastures (Davidson et al., 2000) and the values of the present study, although both studies were conducted in the eastern Amazon, can be explained by fertilizer management in the active pasture of this study, which received 250 kg NPK ha⁻¹ that may have accelerated productivity and consequently induced the autotrophic component, thus increasing CO₂-C efflux from the soil to the atmosphere (Salimon et al., 2004; Fernandes et al., 2002).

Correlation between CO₂-C efflux and soil moisture in secondary forest, active and degraded pastures

In the dry period, the ratio of the efflux of CO₂-C and the percentage of pores filled with water was

significantly positive in the secondary forest ($r^2 = 0.71$, $p < 0.004$) and degraded pasture ($r^2 = 0.55$, $p < 0.02$), as can be shown in Figure 8b and c, respectively. In the wet season, in turn, only the secondary forest and active pasture showed statistically significant correlation ($r^2 = 0.44$, $p < 0.04$, $r^2 = 0.65$, $p < 0.007$) (Figure 8a), respectively.

Soil moisture interferes in the efflux of soil CO₂-C to the atmosphere through the supplement of nutrients that are available only to bacteria when dissolved in water films on the soil particles and also by the water content in the pores that controls the diffusion of gases through soil. When fully dry, the soil is composed only of solid particles and air. The total volume of space filled with air is called a pore. When there is drought conditions, soil particles lose their moisture films, hindering the diffusion of ions. This condition

facilitates the diffusion of gases, but alters the metabolism of bacteria and consequently the degradation of organic matter and the release of CO₂-C. When the amount of water contained in the soil increases, the total fraction of pores filled with water increases, restoring the diffusion of ions and hindering the diffusion of gases (Melillo et al., 2001).

Correlation between CO₂-C efflux and soil temperature in secondary forest, active and degraded pastures

In general the soil temperature varied little during the dry and wet seasons. The values of soil temperature at 5 cm depth in the different types of land cover were different, but there was a low temperature variation in both the wet and dry seasons.

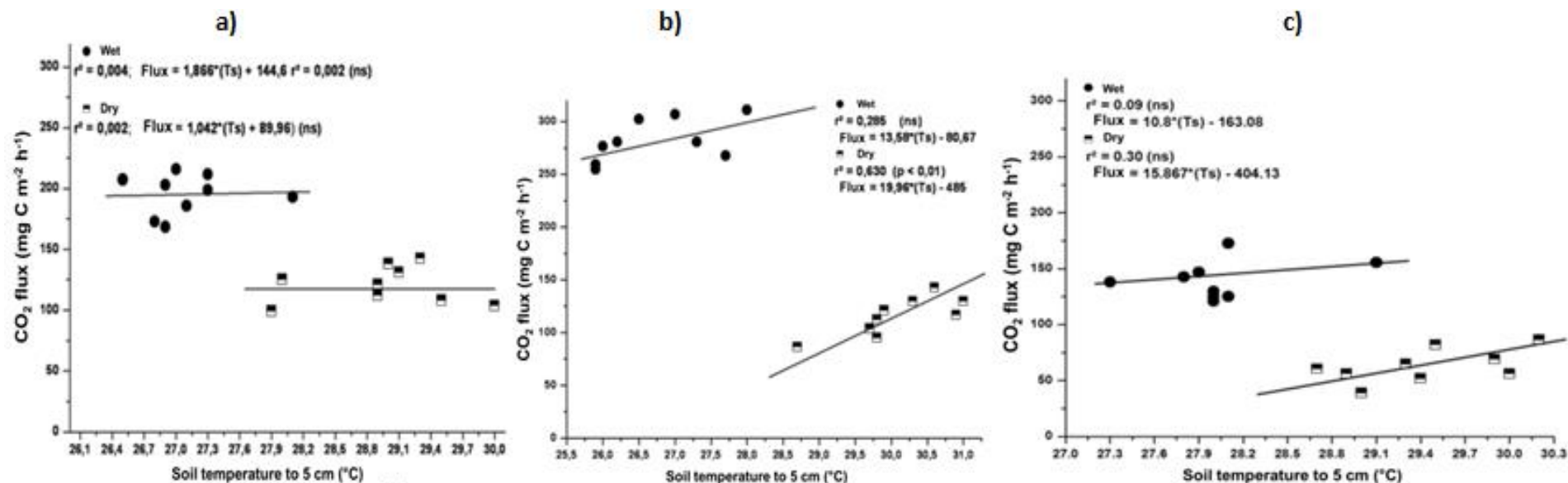


Figure 9. Correlation between the CO₂-C efflux from the soil and the soil temperature in the area of secondary forests (a), active pasture (b) and degraded pasture (c) during the wet and dry season.

The relationship between CO₂-C efflux and soil temperature, resulted in a significant linear relationship ($r^2 = 0.63$, $p < 0.05$) (Figure 9b) only in the area under active grazing as shown in Figure 8c.

In the area of secondary forest there was no pattern of dependence between the variation of the CO₂-C efflux and soil temperature, and this fact may indicate, hypothetically, that other parameters have exerted influence on variability of soil respiration in this area.

Some studies show that the microbial activity in the soil increases linearly with temperature (Bekku et al., 2003; Subke et al., 2003). On the other hand, high temperatures can influence the speed of enzymatic reactions of soil microbial communities, restricting their metabolic activity (Fang and Moncrief, 2001).

The data suggest a relationship between the efflux of CO₂-C and the temperature of the soil when there is high moisture. During the wet season, all plots studied showed a significant relationship between the efflux of CO₂-C and temperature. In the dry period, the portion under active pasture was the only one to show a significant relationship.

The dry season, showed higher soil moisture than other. It is possible that there is a minimum level of moisture in the soil so that the temperature increase causes an increase of microbial metabolism. In all plots studied soil temperature was not high, reaching a maximum of 33°C. This restriction precludes the possibility of enhanced microbial metabolism due to high temperatures.

Conclusion

With respect to the agricultural field with conventional tillage (CT) and no tillage (NT) systems

The results of this work show that the NT system has the potential to mitigate 37.7% of agricultural participation in CO₂-C efflux from soil-based cultivation of soy without the intense tillage as in CT. The soil temperature variation accounted for 65% of the variability of the flow of CO₂-C in CT. The variation of soil moisture explained 73 and 51% of variation in the flow of CO₂-C in NT and CT, respectively. These results indicate that moisture and soil temperature controlled emissions of CO₂-C soil to the atmosphere,

because these parameters directly affect the microbiological activity in the soil.

With respect to forest areas and pastures

The results also demonstrate that active grazing had the highest CO₂-C efflux from the soil to the atmosphere in relation to forests and degraded grasslands in the Western Region of Pará. Moreover, it was shown that both the pastures and forests exhibit a seasonality in this flow, which should be mainly related to precipitation patterns and water potential between soil and air.

There was a strong correlation between soil CO₂ efflux and soil moisture both in the pastures of secondary forests and soil temperature was a controlling factor in the efflux only in the active pasture. The mean value of the flux of CO₂-C obtained in the active pasture was 218.9 mg C m⁻² h⁻¹, a value 40.7% higher than in primary forest C (155.5 mg C m⁻² h⁻¹).

Finally, the results presented here suggest that conventional planting and the management of active grazing activities strongly associated with anthropogenic activities, leverage changes the in biogeochemical carbon balance of these ecosystems, since the CO₂-C efflux from the soil is related to primary productivity of these ecosystems.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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