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Greenhouse gas emissions and soil carbon dynamics in the Brazilian oil palm production

Leidivan Almeida Frazão

Thesis presented to obtain the degree of
Doctor in Science. Area: Soils and Plant Nutrition

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CONTENT

RESUMO

Emissões de gases do efeito estufa e dinâmica do carbono do solo na produção de palma no Brasil

A palma (dendê) tem sido apontada como uma das oleaginosas mais viáveis para a produção de biodiesel no Brasil. Esta cultura tem sido cultivada nas regiões norte e nordeste em plantios comerciais e sistemas agroflorestais. Como é uma planta perene, é importante entender como o cultivo intensivo pode alterar a dinâmica da matéria orgânica do solo a longo prazo. O objetivo deste trabalho foi determinar as emissões de gases do efeito estufa nas principais fases do sistema produtivo e as mudanças nos estoques de carbono do solo sob cultivo da palma. Amostras de solos e gases do efeito estufa foram coletadas em áreas tradicionais de produção no Brasil. No Pará (fazenda Agropalma) foram selecionadas áreas derivadas de pastagem e Floresta Amazônica, enquanto na Bahia (fazenda Opalma e Lamego) foram selecionadas áreas derivadas de Mata Atlântica. Primeiramente foram avaliadas as mudanças nos estoques de carbono do solo sob sistemas comerciais e agroflorestais de cultivo. Os resultados indicaram que a variabilidade na dinâmica do carbono do solo em áreas de plantio de palma pode ser explicada por vários fatores, como as variações temporais e espaciais, e uso da terra anterior à instalação dos palmares. Os estoques de carbono do solo, após as correções pelas diferenças na densidade e teores de argila do solo, decresceram até 46% nas áreas derivadas de pastagem e aumentaram 18% na área derivada de Floresta Amazônica. Os estoques de C do solo aumentaram até 23% nos plantios comerciais derivados de Mata Atlântica e decresceram 30% quando foi adotado o sistema agroflorestal. As emissões de óxido nitroso (N_2O) pelo solo derivadas da aplicação de fertilizantes nitrogenados foram 10 vezes maiores na produção de plântulas do que nos plantios jovens e adultos, entretanto, esta fase representa apenas 3,8% do ciclo de vida da planta. De forma geral, as emissões de gases do efeito estufa nos diferentes estágios de produção não foram maiores do que para outras culturas no Brasil. A decomposição dos resíduos culturais também contribuiu para as emissões de gases do efeito estufa para a atmosfera. A pegada de carbono associada a produção do óleo de palma pela Agropalma foi aproximadamente 0,7 kg CO_2 equivalente por kg de óleo produzido, dos quais 70% estão associadas ao manejo de efluentes industriais nas lagoas anaeróbicas, que emitem uma grande quantidade de metano (CH_4) para a atmosfera. O manejo correto do efluente pode resultar nas reduções das emissões de gases do efeito estufa, e consequentemente, diminuir a pegada de carbono associada a produção do óleo de palma na região Amazônica. Os resultados encontrados neste estudo poderão ser usados para fazer avaliações mais complexas como a avaliação do ciclo de vida do biodiesel derivado do óleo de palma no Brasil.

Palavras-chave: Carbono orgânico do solo; Dióxido de carbono, Óxido nitroso, Metano, Fertilização nitrogenada, Pegada de carbono; Sistema espontâneo da palma; Sistema comercial da palma

ABSTRACT

Greenhouse gas emissions and soil carbon dynamics in the Brazilian oil palm production

Oil palm has been considered one of the most favorable oilseeds to biodiesel production in Brazil. The crop has been cultivated in the north and northeast regions under commercial plantations and agroforestry systems. As the oil palm is a perennial crop, it is important to understand how the intensive cultivation affects the dynamic of soil organic matter in the long term. The goal of this work was to determinate the greenhouse gas emissions associated to the main production steps and the changes on soil organic carbon under oil palm plantations. Soil and greenhouse gas samples were collected in traditional production areas in Brazil. Commercial plantations derived from pasture and Amazon rain forest were selected in Pará State (Agropalma farm), while areas derived from Atlantic rain forest and agroforestry system were selected in Bahia State (Opalma farm and Lamego). At first, changes on soil carbon stocks were evaluated in the commercial plantations and agroforestry systems. The variability of soil carbon dynamics in the production areas can be explained by several aspects such as temporal and spatial variations, and prior land use. The soil carbon stocks, after corrections for differences in density and clay content, decreased till 46% in areas derived from pasture and increased 18% in an area derived from Amazon rain forest. The soil carbon stocks increased till 23% in areas derived from Atlantic rain forest and decreased 30% when agroforestry system was adopted. The soil nitrous oxide (N_2O) emissions from N fertilizer application were 10 times higher in the seedlings production than in juvenile and mature plantations, however this step represents 3.8% of the plant cycle. In general, the observed greenhouse gas emissions at different stages of oil palm production are not large than other agricultural crops in Brazil. The decomposition of plant residues also contributed to greenhouse gas emissions to the atmosphere. The carbon footprint associated to oil palm production at Agropalma farm was approximately 0.7 kg CO_2 equivalent per kg of crude palm oil produced, and 70% this value is associated with the management of effluent in the anaerobic ponds emitting a large amount of methane to the atmosphere. The correct treatment of the effluent can result in reductions of greenhouse gas emissions, and consequently, decreasing the carbon footprint associated to palm oil production in the Amazon region. The results founded in this study may be used to improve the biodiesel life cycle assessment derived from palm oil produced in Brazil.

Keywords: Soil organic carbon; Carbon dioxide; Nitrous oxide; Methane; Nitrogen fertilization; Carbon footprint; Oil palm spontaneous system; Oil palm commercial system

1 INTRODUCTION

The use of fossil fuel has contributed over decades to the increase of greenhouse gases (GHG) in the atmosphere. So, concerns about climate changes are growing and have converged to global policies for reductions of GHG emissions. The use of biofuels, especially ethanol and biodiesel, are seen as a cleaner alternative to fossil fuels. The biodiesel has the same properties of fossil diesel, but can reduce net emissions of carbon dioxide (CO_2).

The agricultural cultivation of oilseeds has increased in the last decade due the demand of raw material for biodiesel production. However, the cultivation systems should not be associated with increasing of deforestation to be environmentally sustainable. In Brazil, there is a large agricultural area capable of being included in this process, particularly previous deforested areas in the Amazon region and improper areas to grain cultivation in the Northeast region. In this context there is the incentive for sustainable extraction of native species and the encouragement to cultivate perennial crops. The oil palm (*Elaeis guineensis* Jacq.) has received greater focus by the National Program for Production and Use of Biodiesel (PNPB). This oilseed is cultivated in the southern coast of Bahia state and North region, and Pará State is the largest producer of oil palm in Brazil.

Previous studies have demonstrated that the type of vegetation in place before the land is converted to a biofuel plantation exerts a significant effect on the soil carbon stock and over all biofuel GHG budget. However, the field measurement of GHG emissions and the soil carbon stocks in oil palm production focusing the potential to reduce the carbon footprint associated to biodiesel production was not performed in Brazil yet.

So, the goal of this research was to determinate changes on soil carbon stocks and the GHG emissions in the conversion of native forest and pasture to oil palm production in Brazil. The commercial cultivation systems adopted at Pará and Bahia States were evaluated as well as the spontaneous system adopted by small farmers at the last one.

Field measurements were performed on both traditional regions of palm oil production in Brazil. At first, some areas were chosen in Pará State to assess changes in soil C stocks under oil palm plantations derived from Amazon rain forest and pasture (*Chapter 2 – Soil carbon stocks and changes after oil palm introduction in the Brazilian Amazon*). After that, other areas were chosen in Bahia State to evaluate the soil carbon stocks under oil palm plantations derived from Atlantic rain forest and adopting an Agroforestry system (*Chapter 3 – Soil carbon stocks under oil palm plantations in Bahia State, Brazil*). Some experiments were carried out at Pará State to evaluate the soil GHG emissions derived from decomposition of plant residues and use of fertilizers in commercial oil palm plantations (*Chapter 4 – Soil Greenhouse gas emissions from oil palm production in the Amazon Region*). Finally, the carbon footprint associated to agricultural phase, extraction and transportation of crude palm oil produced in a commercial farm at Pará State (*Chapter 5 – Carbon footprint in the crude palm oil supply chain: Brazilian Amazon case study*) was evaluated.

This insight about GHG emissions and soil carbon stocks under different scenarios of oil palm production in Brazil provides valuable information to be used in life cycle assessments of biodiesel production using this oil seed as raw material.

2 SOIL CARBON STOCKS AND CHANGES AFTER OIL PALM INTRODUCTION IN THE BRAZILIAN AMAZON

Abstract

The Brazilian Amazon has about 70 million hectares of potential area for oil palm cultivation, but a small fraction has been effectively cultivated and about 80% is located in Pará State. Oil palm plantations are derived from native rain forest and pasture, and can modify the soil organic carbon (SOC) dynamics. The aim of this study was to evaluate the changes in SOC after the conversion of forest and pasture into oil palm production in the northeast Amazon Region. Soil samples were collected in March 2008 and September 2009 in five areas: Forest (NARF), Pasture cultivated for 55 years (PAST), Oil palm cultivated for 4 years (OP-4), 8 years (OP-8) and 25 years (OP-25). Soil sampling was carried out in oil palm areas in March 2008 to evaluate the spatial variability of C and nitrogen (N) contents in relation to oil palm base (trunk). In September 2009 soil sampling was carried out to evaluate the differences in soil C stocks between the avenues (inter-rows) and frond piles in oil palm areas, and compare the total C stocks with natural forest and pasture system. Soil C contents were higher in the region next to the oil palm base (0.6 m) 22% at OP-4, 33% at OP-8 and 38% at OP-25 than the average for 5 distances, indicating that the increment in soil organic matter must have been largely derived from root material. The soil C stocks were higher in frond piles 9% at OP-4, 4% at OP-8 and 26% at OP-25 than in the inter-rows, due to inputs of soil organic matter by pruned fronds. The soil C stocks in oil palm areas, after corrections for differences in density and clay content, decreased to 46% of the pasture soil C content and increased 18% of the native forest soil C content. The results found here may be used to improve the life cycle assessment of biodiesel derived from palm oil.

Keywords: Amazon; C stocks; Forest to oil palm conversion; Pasture to oil palm conversion

2.1 Introduction

As biodiesel production expands in Brazil and oil palm has been cited as the main raw material, it is critical to understand the environmental consequences of the cultivating system. Oil palm is a perennial plant of African origin which came to Brazil in the sixteenth century and has adapted to the southern coast of Bahia. In addition to this state, northern Brazil is showing favorable weather conditions for the cultivation of this oilseed (LOPES; STEIDLE NETO, 2011). The state of Pará is the largest producer of palm oil in Brazil with 60,000 hectares cultivated in 2008, representing 80% of the cultivated area (ISTA, 2009). Brazil is a small producer when compared to others countries such as Malaysia and Indonesia, but has about 70 million hectares of potential area for cultivation of oil palm in Brazilian Amazon (BARCELOS; SANTOS; RODRIGUES, 2002).

One potential impact of biofuel cultivation is the storage or release of soil organic carbon (SOC). Brazil has a large agricultural area capable of being included in the production of raw material for biodiesel, particularly in the Amazon region and some states in the

Northeast of the country. As the land-use-change and land management can modify the SOC dynamics (LAL, 1997; SIX et al., 2002), management systems which increase soil C stocks and reduce soil C losses are essential for sustainable development.

Soil organic carbon is an important component in the life cycle assessment of biofuel production (ADLER; DEL GROSSO; PARTON, 2007, ANDERSON-TEIXEIRA et al., 2009). Increases in SOC produce a host of advantages including increased productivity and crop quality, improved water and nutrient retention, decreased runoff of both sediment and pollutants, and increased soil biodiversity (LAL, 2004). The SOC sequestration is affected by crop management decisions, which impact the quantity and quality of crop residue added to the soil and the rate of decomposition (PAUSTIAN et al., 2000; JARECKI; LAL, 2003). Crops have different requirements for energy inputs from crop planting, soil tillage, fertilizer and pesticide application, and harvest (WEST; MARLAND, 2002). Oil palm is adapted to humid tropical conditions of the Amazon region, protects the soil from erosion and increases the soil organic matter (SOM) promoting the recycling of nutrients (VEIGA; FURLAN JUNIOR; KALTNER, 2001).

Soil organic carbon is more variable in space and time in oil palm plantations than most other crops (HARON; BROOKES; ZAKAIA, 1998). Following planting, growth of ground cover legumes is encouraged (both for erosion control and nitrogen fixation) except in a circle approximately 1.2 m diameter around the palm base which is kept weed-free using herbicides. About 70% of the root system is concentrated within a circle of 2.0 m around the palm base and in the first 40 cm soil depth. The ground cover is suppressed by canopy closure at about 6 to 8 years. During the crop phase (from about 8 to 25 years) above-grounds inputs are highly heterogeneous because fronds, which are progressively pruned to facilitate harvesting of fruit bunches, are piled one between every two palm rows. Fruit bunches are generally removed using micro tractors Agrale which can promotes soil compaction in the inter-rows (BRITO et al., 2006). In this study the area around the inter-rows and frond piles constitute about 80% and 20% respectively of the ground surface. The palm are planted in a staggered design, 9 m apart at a density of 143 oil palms ha^{-1}, each tree being located at the tip of 9 m equilateral triangle.

During the economic life of the plantation (about 25 years) the palm inter-rows therefore receive much lower organic matter inputs than the region near the plant and the frond piles and should, therefore, approach different equilibrium contents of soil organic matter over a different period of time.

Given the difficulty of determining the SOC dynamics in the short term for such heterogeneous systems, the objective of this study was to measure the C stocks in different ages of oil palm plantations, investigated as a possible soil carbon stocks accumulation or decline within different areas derived from pasture and forest.

2.2 Material and Methods

2.2.1 Description of the study area

The study was carried out at the Agropalma Farm (48°46’W, 2°27’S), a conventional commercial farm with an area of 107,000 ha in the city of Tailândia, Para State, Brazil (Figure 1).

Figure 1 – Location map of the study area in the Agropalma Farm, Para State, Amazon region, Brazil

The native vegetation of the region is tropical rainforest. According to Köppen (1900) the climate is classified as Afi (tropical monsoonal), where precipitation occurs all year long and the month with least rainfall is more than 60 mm. The mean annual rainfall for the previous 20 years was 2,500 mm year^{-1} and the mean temperature was 26.6^{o} C (Figure 2). Mean temperature for the warmest and coolest months varies by less than 3 ^{o}C and mean annual relative humidity is 89%.

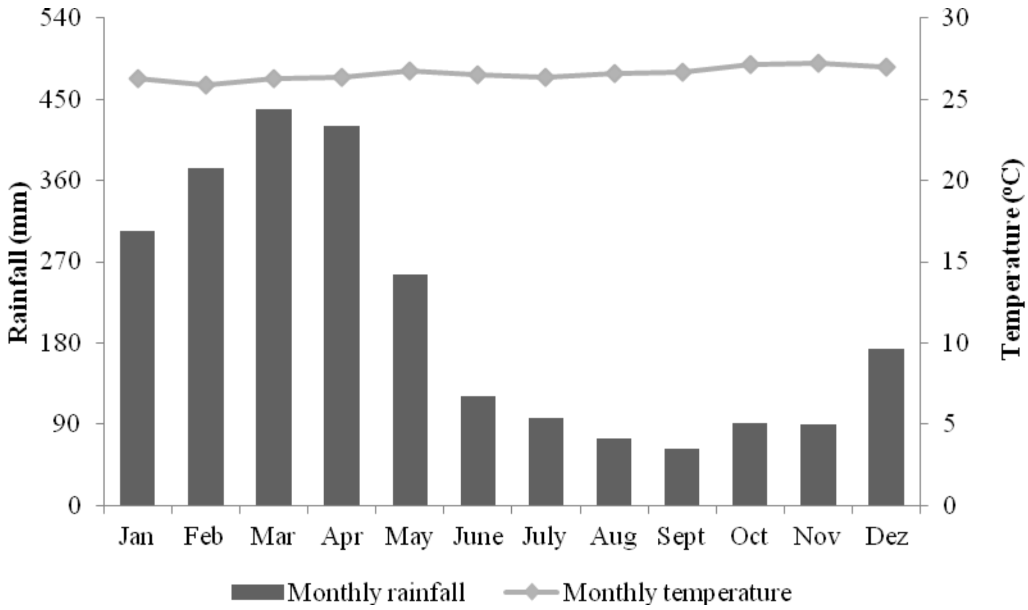

Figure 2 - Monthly rainfall and temperature distribution for the 25-year (1984-2009) in the Agropalma farm, Pará State, Amazon region, Brazil

The mean altitude of the region is 49 m and the soil had medium clay content (18 to 29%) and classified as “Latossolo Amarelo distrofico tipico” in the Brazilian System of Soil Classification (EMBRAPA, 2006), and an Oxisol (Xanthic Hapludox) in the USDA classification (USDA, 1999).

2.2.2 Conversion of native vegetation and pasture into oil palm cultivation

Before 1999 the native areas of the farm were cleared yearly for oil palm planting. But, for environmental reasons, the company decided to stop with deforestation and incorporating new areas previously occupied by pasture. According to Sommer, Denich and Vlek (2000), the land-use-change from forest to pasture in north-eastern Pará began in the 1950s, so we consider that the pasture area was occupied for 55 years with *Brachiaria humidicola* (Rendle) Schweickerdt.

Five different sites were considered in this study: native Amazon rain forest (NARF), used as first reference area; pasture system (PAST), used as a second reference area; oil palm plantation derived from pasture cultivated for 4 (OP-4) and 8 years (OP-8); and oil palm plantation derived from native rain forest cultivated for 25 years (OP-25). Table 1 shows the bulk density, clay content, pH H_2O, CEC, available P and Base Saturation (BS) in the 0-30 cm soil layer.

Table 1 – Soil bulk density (BD), clay content, pH, CEC and Base saturation (BS) in the study areas (0-30 cm) located at Agropalma farm, Para State, Amazon region, Brazil

Area	Plantation age (y)	BD (mg dm^{-3})	Clay (g kg^{-1})	pH H_2O	Available P (mg dm^{-3})	CEC (mmol$_c$dm^{-3})	BS (%)
NARF		1.26	280	4.4	4.2	33	18
PAST		1.35	200	4.2	4.5	30	16
OP-4[a]	4	1.29	290	4.0	4.3	36	16
OP-8[a]	8	1.29	250	3.8	3.9	36	13
OP-25[b]	25	1.34	180	4.0	4.2	25	14

Available P was determined by ion exchange resin method
[a] Areas derived from pasture
[b] Area derived from native Amazon rain forest

2.2.3 Soil sampling and analysis

The soil sampling was carried out in March 2008 (wet season) and September 2009 (dry season) in each area of approximately 1 ha (100 x 100 m) based on a completely randomized sampling design with five pseudo replicates in each area. We are considering those as pseudo replicates, since they came from the same evaluated areas.

As the oil palm plantation is a heterogeneous system, in March 2008 the soil samples were collected to determine the spatial variability of soil carbon in the same area. To accomplish this evaluation soil samples were collected in five profiles 0.6, 1.2, 2.5, 3.5 and 4.5 m away from the oil palm base at 0-10, 10-20 and 20-30 cm soil depth (Figure 3).

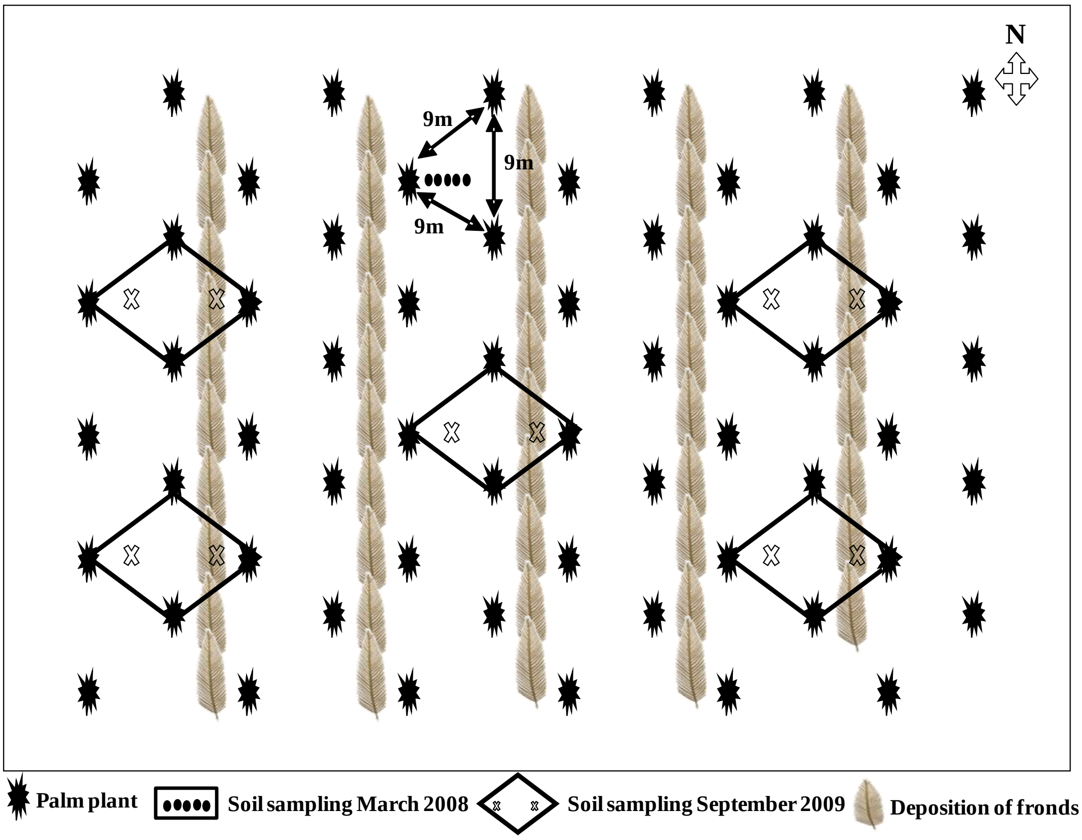

Figure 3 - Experimental design to soil sampling in oil palm plantations at Agropalma farm located in - Para State, Amazon region, Brazil

The second soil sampling (September 2009) was carried out in five profiles 3.5 m away from the oil palm base in the inter-rows and under the frond piles at 0-5, 5-10, 10-20 and 20-30 cm depths in each site (Figure 3). Similarly, soil samples were also collected in five profiles in the NARF and PAST systems.

These samples were air-dried and sieved with a 2 mm mesh to remove stones and root fragments before analysis. Sub-samples were ground to a fine powder to pass through a 100-mesh sieve before total carbon determination. Total carbon was measured by dry combustion on Carbon Analyzer – LECO® CN-2000 (furnace at 1350 °C in pure oxygen). For determination of density (ρ), samples of undisturbed areas were collected using a steel cylinder (5 x 5 cm). Samples from the 10-20 and 20-30 cm soil layers were taken from the middle part of the corresponding layer.

2.2.4 Soil C stock calculation and density and clay adjustments

For each soil layer, carbon stocks were calculated by multiplying the concentration of the C (g g^{-1}) by ρ (kg m^{-3}) and layer thickness (m). As samples were collected from fixed layers, the stock calculation needed to be adjusted for variations in BD after land use changes.

Therefore, the methodology described in Ellert and Bettany (1996) and Moraes et al. (1996) was used to adjust soil C stocks to an equivalent soil mass. In order to calculate C stocks in an equivalent soil mass, the depth of the considered area was adjusted, i.e., the depth of the cultivated areas containing the same soil mass as the corresponding layer (0-30 cm) in native vegetation (the reference area).

We attempted to account for small soil variations in clay content between the study areas by using the hypothesis proposed by Moraes et al. (1996) that for each soil type there is a close relationship between clay and carbon contents and no changes in clay content occurs after oil palm establishment. This correction is based on the equation1.

$$C\ (corrected) = \frac{C\ (measured) \times Clay\ (reference)}{Clay} \qquad (1)$$

Where Clay (reference) is the mean clay content for each soil layer, including the forest site.

It has been suggested that soil texture plays a role in determining the amount of organic matter in soil (PARTON et al., 1987, FELLER et al., 1991, MORAES et al., 1996). Variation in soil C content is more closely related to the variation in soil texture than to others parameters like land-use-changes and climate. Soil C variation is linear for those where clay content is less than fifty percent (FELLER et al., 1991).

2.2.5 Statistical analysis

The statistical analysis of data was performed on a completely randomized sampling design, with the assumption that the studied areas -had the same topographic, edaphic and climatic conditions. Data from soil C stocks under different areas were analyzed for variance (ANOVA) to determine land use effects. A Tukey test was used to test for significant ($p \leq 0.05$) differences among treatments. All statistical analyses were performed using the SAS program, version 9.2.

2.3 Results and discussion

2.3.1 Spatial variability of soil C and N contents in relation to oil palm base

It was found horizontal differences in the carbon levels on the oil palm inter-rows (OP-4, OP-8 and OP-25) where fluctuations in the soil organic matter were observed in different distances from the palm base (Table 2). C and N contents were higher in the region near de palm base and this result must largely be due to root inputs (HARON; BROOKES; ZAKAIA, 1998).

The carbon contents were decreasing as we moved away from the base of the plant. These results can be attributed to adverse soil conditions such as poor drainage in the inter-rows and soil compaction due to traffic of agricultural machines. According to Yahya et al. (2010), as the oil palm has an adventitious root system, the use of machines during the harvesting and cultural managements could contribute to the gradual deterioration of soil physical conditions that restrict the growth and functions of roots.

At 0.6 m from the oil palm base the C content was higher than average in the three areas evaluated at 0-10, 10-20 and 20-30 cm. The C levels were 22, 33 and 38% higher than average levels in OP-04, OP-08 and OP-25, respectively. Different results were found at 3.5 m from the oil palm base, where the C values were 1, 6 and 15% lower than to average levels in the same areas. To assess C stocks in total area (inter-rows and frond piles) will need to consider these adjustments.

The soil C levels were increasing with the age of the oil palm in the soil surface layer (0-10 cm), in agreement with the results found by Haron, Brookes and Zakaia (1998) in study areas in the West of Malaysia. Different results were found by Sommer, Denich and Vlek (2000), where agricultural use of soils with oil palm plantation caused a reduction of soil C throughout the profile. The considerably lower SOC content of the top soil of the oil palm plantation was probably caused by repeated removal of the ground cover.

It is important to emphasize that these results refer to soil sampling performed in the inter-rows where the transit of agricultural implements occurs during the fertilizer application and harvesting of fruit bunches. Such as reported by Lal (2004), when these agricultural activities are adopted, part of soil carbon is removed from soil and it is lost to the atmosphere as CO_2.

Table 2 - Soil carbon (C) and nitrogen (N) contents in the oil palm plantations under different distances from the palm base in Agropalma farm, Para State, Amazon region, Brazil

Oil palm Areas	Distance	0-10 cm			10-20 cm			20-30 cm		
	(m)	C	N	C/N	C	N	C/N	C (%)	N (%)	C/N
		---- % ----			---- % ----			---- % ----		
OP-4[a]	0.6	1.14	0.09	12.7	1.05	0.09	11.7	0.72	0.07	10.1
	1.2	0.92	0.09	10.2	0.79	0.07	11.3	0.60	0.06	10.8
	2.5	0.98	0.09	10.9	0.70	0.06	11.7	0.55	0.05	10.9
	3.5	1.04	0.09	11.6	0.67	0.06	11.2	0.57	0.06	10.3
	4.5	0.92	0.09	13.1	0.67	0.05	13.4	0.64	0.06	10.8
	Mean	1.00	0.09	11.7	0.78	0.07	11.8	0.62	0.06	10.3
OP-8[a]	0.6	1.37	0.09	15.2	1.01	0.07	14.4	0.63	0.04	11.5
	1.2	1.08	0.08	13.5	0.55	0.04	13.8	0.49	0.04	13.3
	2.5	1.01	0.08	12.6	0.53	0.04	13.3	0.46	0.04	11.0
	3.5	1.01	0.08	12.6	0.66	0.05	13.2	0.48	0.04	12.4
	4.5	0.98	0.08	12.3	0.67	0.05	13.4	0.50	0.05	13.0
	Mean	1.09	0.08	13.2	0.68	0.05	13.6	0.51	0.04	12.3
OP-25[b]	0.6	1.82	0.11	16.5	1.16	0.09	12.9	0.81	0.06	13.5
	1.2	1.31	0.09	14.6	0.98	0.07	14.0	0.72	0.06	12.0
	2.5	0.99	0.07	14.1	0.78	0.06	13.0	0.70	0.05	14.0
	3.5	0.89	0.06	14.8	0.68	0.05	13.6	0.65	0.05	13.0
	4.5	0.82	0.06	13.7	0.57	0.04	14.3	0.52	0.04	13.0
	Mean	1.17	0.08	14.8	0.83	0.06	13.6	0.68	0.05	13.1

[a] Areas derived from pasture
[b] Area derived from native Amazon rain forest

In inter rows there is no deposition of the oil palm fronds and soil C inputs are derived from root material and crop residue from legume nitrogen fixing spread out in the inter row of oil palm plantation (*Pueraria phaseoloides*). This fact explains the small increase in C levels over time. To determine the total soil C in the oil palm plantations is need to consider the inputs of plant material (fronds) and the soil carbon stocks in areas under frond piles which represent 20% of the oil palm plantation.

The C/N ratio in the top soil (0-10 cm) of soils ranged from 10.2 to 15.2 (Table 2). Means values for the sites of 11.7, 13.2 and 14.8 increased as a function of stand age, according to the results found by Haron, Brookes and Zakaia (1998).

2.3.2 Soil carbon stocks in inter-rows and frond piles in the oil palm plantations

As mentioned in section 2.3.1, to determinate the total soil C stocks is necessary to evaluate the areas of the inter-rows and frond piles. Due to time and spatial variability in soil organic matter in the inter-rows (0-10 cm) and considering that soil sampling was carried out at 3.5 m away from the oil palm base, we performed an adjustment in the C contents about 1, 6 and 15% for OP-4, OP-8 and OP-25 areas, respectively.

The mean bulk density (0-30 cm) was 1.29 cm^{-3} in OP-4 and OP-8, and 1.34 cm^{-3} in OP-25 (Table 1). Oil palm areas derived from pasture (OP-4 and OP-8) show the bulk density slightly higher than oil palm area derived from forest (OP-25) in all soil layers evaluated.

The C stocks were higher in the frond piles than in the inter-rows (Table 3). We found values 9, 4 and 26% higher in frond piles than in the inter-rows in OP-4, OP-8 and OP-25, respectively. It has been estimated that approximately 10 t ha^{-1} y^{-1} dry matter of fronds are cut in mature oil palm plantations (NG; THAMBOO; SOUZA, 1968; CHAN; WATSON; LIM , 1980). The frond piles in these systems, representing 20% of the area, therefore receive inputs of 4.8 t C ha^{-1} y^{-1} (taking the C content as approximately 48% of frond mass).

Table 3 - Soil C stocks (Mg ha^{-1}) in the oil palm plantations under inter-rows and frond piles in Agropalma farm, Para State, Amazon region, Brazil

Soil depth (cm)	OP-4[a]	OP-8[a]	OP-25[b]
	Inter-rows		
0-5	6.9±0.9Ab	5.4±1.5ABb	4.4±0.6Bb
5-10	7.0±0.4Aa	5.0±0.7Ba	4.1±0.3Cb
10-20	10.2±0.4Aa	8.8±1.0Aba	8.7±0.2Bb
20-30	9.4±0.5Aa	7.8±1.0Ba	8.2±0.4Ba
0-30	**33.4±0.3**Ab	**27.0±2.0**Ba	**25.4±1.1**Cb
	Frond piles		
0-5	8.6±1.3Aa	7.9±1.5 Aa	6.8±1.5 Aa
5-10	7.8±0.6 Aa	5.0±1.0 Ba	5.6±1.4 Ba
10-20	10.5±0.4 Aa	7.4±0.9Ba	9.3±0.9 Aa
20-30	9.5±0.9 Aa	7.1±0.6 Ba	7.9±0.6 Baa
0-30	**36.3±1.4**Aa	**27.4±2.6**Ba	**29.6±3.7** Ba
	Total		
0-5	7.2±0.9 A	5.9±1.5 B	4.9±0.8 B
5-10	7.1±0.4 A	5.0±0.6 B	4.4±0.4 B
10-20	10.2±0.4 A	8.5±0.7 B	8.9±0.3 B
20-30	9.4±0.4 A	7.7±0.8 B	8.1±0.2 B
0-30	**34.0±0.5** A	**27.1±1.6** B	**26.3±1.5** B

The values represent the mean (n=5) ± standard deviation. Means within each row of the same site (Inter-rows, Frond piles and Total) followed by the same capital letter are not significantly different by the Tukey test ($p<0.05$). Means between sampling sites (Inter-rows and Frond piles) within same treatment and depth followed by the same small letter are not significantly different by the Tukey test ($p<0.05$).
[a] Areas derived from pasture
[b] Area derived from native Amazon rain forest

Frond inputs in immature stands increase linearly up to 8 years (HARON et al, 1998). The soil C stocks do not, however, reflect the large cumulative inputs of organic matter to the frond piles indicating that decomposition of this material is largely taking place on the soil surface.

To estimate the C stocks per hectare we consider that the inter-rows and frond piles represent 20 and 80% of the total area planted with oil palm. We observed that the C stocks were decreasing with the age of oil palm, with 33.8, 26.3 and 24.7 t ha^{-1} in OP-4, OP-8 and OP-25 areas, respectively. So, we have to consider the differences in bulk density and clay content between the areas. The correction of these data is described in section 2.3.3.

2.3.3 Adjustments in soil carbon stocks under forest, pasture and oil palm areas

The evaluated areas show differences in the clay contents (Table 1). The mean bulk density (0-30 cm) was 1.26 g cm^{-3} in NARF (Table 1). Soils under pasture and oil palm had increased soil BD in the surface and deeper. Table 4 shows the adjustments in soil C stocks by bulk density and clay contents.

The pasture system showed the highest carbon stocks, as related other studies in the Amazon region (FEARNSIDE; BARBOSA, 1998; CERRI et al., 2003; ZINN; LAL; RESCK, 2005; GARCIA-OLIVA et al., 2006). Our results showed an increase of 25% in total soil C (corrected by bulk density). Considering the adjustment by clay content the pasture system increasing about 21 t C ha^{-1} (82%) in soil after 55 years of introduction. Increased soil C concentrations in surface horizons are a common consequence of pasture formation after forest has been cleared in the Amazon basin (BONDE et al., 1992; MORAES, 1995; TRUMBORE et al., 1995; MORAES et al., 1996; NEILL et al., 1997; BERNOUX et al., 1998). In this situation, pasture was not subjected to extremes of burning regimes or overgrazing.

Table 4 - Total soil carbon stocks (Mg ha^{-1}) in the equivalent layers of 0-30 cm and in the soil equivalent clay under Native Amazon rain forest (NARF), pasture (PAST) and oil palm plantations (OP-4, OP-8 and OP-25) in Agropalma farm, Para State, Amazon region, Brazil

Area	Soil C stock (Mg ha^{-1}) Adjustments (0-30 cm)	
	Soil Equivalent layers	Normalization for the mean clay content
NARF	30.2±3.4B	25.6±2.9C
PAST	38.5±4.0A	46.7±4.8A
OP-4[a]	33.2±0.5B	28.1±0.4B
OP-8[a]	26.6±1.6C	25.3±1.5C
OP-25[b]	22.7±1.4D	30.3±1.8B

The values represent the mean (n=5) ± standard deviation. Means within each column followed by the same capital letter are not significantly different by the Tukey test ($p<0.05$).
[a] Areas derived from pasture
[b] Area derived from native Amazon rain forest

C stocks in oil palm areas (OP-4 and OP-8) decreased by 46% of the pasture stock. Pasture grasses have the potential to introduce large amounts of organic matter into the soil (FISHER et al., 1994; BODDEY et al., 1996; REZENDE et al., 1999; GUO; GIFFORD, 2002). When these areas were converted to oil palm, the C stocks tended to return to the levels found in the forest. The frond residues added to soil in oil palm plantations promote an input of soil organic matter less than the residue input and root decomposition of pasture (LAMADE; DJEGUI; LETERME, 1996).

In the area derived from forest, establishing oil palm increased soil C stocks by 18 % over 25 years. According to Maia et al. (2010), perennial crops had a minimal impact on soil organic C stocks, suggesting these systems maintain about 98% of the SOC found under native vegetation. Our results can be due the management of oil palm that reduce tillage intensity, maximize residue return and promotes the absence of water stress because precipitation occurs throughout the year. These management decisions have been suggested to increase the soil organic C stocks (WEST; MARLAND, 2002; OGLE; BREIDT; PAUSTIAN, 2005; ZINN; LAL; RESCK, 2005).

2.4 Conclusions

The dynamics of soil organic C under oil palm plantations is variable due the inputs of litter from aboveground and the increments derived from root material. The highest soil C stocks were found under frond piles and the regions where the root density is higher (0.6 m way from the oil palm base).

The SOC concentrations do not reflect the large cumulative inputs of soil organic matter to the frond piles indicating that decomposition of this material is largely taking place on the soil surface.

Oil palm plantations derived from forest show an increase on soil C stocks, in contrast with the areas derived from pasture. The pasture establishment was associated with significant changes in soil organic matter that resulted in an increase in soil C stocks.

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3 SOIL CARBON STOCKS UNDER OIL PALM PLANTATIONS IN BAHIA STATE, BRAZIL

Abstract

The oil palm (*Elaeis guineensis* Jacq.) is a perennial plant of African origin which came to Brazil in the sixteenth century and has adapted to the southern coast of Bahia State. Brazilian Atlantic coast has about 850,000 hectares of potential area for oil palm cultivation that can be found areas within agroforestry system and commercial plantations. Different oil palm cultivations derived from native rain forest can modify the soil organic carbon (C) dynamics. So, the aim of this study was to evaluate the changes in soil organic carbon (SOC) stocks after the conversion of Atlantic forest into oil palm production in Bahia State, Brazil. Soil samples were collected in four areas: Native Atlantic Rain Forest (NARF), Oil palm cultivated as spontaneous system (OPSP), Oil palm cultivated during 23 (OP23) and 35 years (OP34). Soil samples were carried out in oil palm areas in May 2008 to evaluate the spatial variability of C and nitrogen (N) contents. In February 2009 soil samples were carried out to assess the differences in soil C stocks between the avenues (inter-rows) and frond piles in oil palm areas, and compare the total C stocks with native forest and spontaneous system. We found the highest soil C contents in the region next the oil palm base (1.22% in OP23 and 1.49% in OP34), indicating that the increment in soil organic matter must have been largely derived from root material. The soil C stocks were higher in frond piles (1.7 times in OP23 and 2.6 times in OP34) than in the inter-rows, due to inputs of soil organic matter by pruned fronds. The soil C stocks adjusted for a mass equivalent to the 0-30 cm layer under native forest in OPSP were similar to NARF, but the normalization for the mean clay content indicated a decrease in soil C stocks in OPSP. We found SOC storage of 34.7 Mg ha^{-1} and 66.6 Mg ha^{-1} under OP23 and OP34, respectively, indicating an increase of soil C stocks in oil palm plantations over time.

Keywords: Atlantic forest; Spontaneous system of oil palm; Forest to oil palm conversion; Residue inputs on soil

3.1 Introduction

About 75% of terrestrial carbon is found in the soil, which contains about 1550 Pg of soil organic carbon (SOC) and 750 Pg of soil inorganic carbon (BATJES 1996; CERRI et al., 2006). However, land use change has been shown decreasing in the amount of SOC (CADISCH et al. 1996; DESJARDINS et al. 1994; KOUTIKA et al. 1999). The use and management of soil can strongly influence the emissions and fixation of soil carbon (JACKSON et al. 2000; JANDL et al. 2007; LAL, 1997; SIX et al., 2002).

The production of oilseeds is increasing due the growing demand of raw material for biodiesel production. In Brazil, there is a large agricultural area capable of being included in this process, particularly in the Amazon region and in some states of the Northeast of the country. Oil palm (*Elaeis guineensis* Jacq.) has received greater focus by the National Program for Production and Use of Biodiesel. Brazil has appropriate technology to increase the planted area with this perennial crop that produces up to 5 t of oil ha^{-1} yr^{-1}; it can be planted in areas already suited for other uses such as pastures (FURLAN JÚNIOR et al., 2004).

The oil palm, a major source of vegetable oil, was first seen as shifting cultivation in West Africa and came to Brazil in the sixteenth century. This type of spontaneous system can sustain plant, bird and mammal diversity at 50–70% of undisturbed forests (CURRENT; LUTZ; SHCERR, 1998; DE FORESTA; MICHON, 1994; IPCC, 2000). In Brazil, large plantations of African palms exist in North and Northeast regions. Pará State, located at Amazon region, is the largest producer of oil palm, representing 80% of the cultivated area (ISTA, 2009). The Southeast Bahia State (Northeast region) has an exceptional diversity of soil and weather appropriated for the African palm cultivation, with an available area of 854,000 hectares (MELO; OLIVEIRA, 2006). It is common to find areas with spontaneous system and plantations of oil palm. This crop requires about 2000 mm of rainfall annually, temperatures greater than 24°C and deep soils (SANTOS, 2005).

The intensive land use has negative effects on both the environment and on agricultural productivity when conservation practices are not adopted (CERRI et al., 2004; FOLEY et al., 2005). Regarding the environment, the reduction of soil organic matter (SOM) amount is accompanied by increased GHG emissions in the atmosphere, and consequent increase in global warming (KNORR et al., 2005). These changes on SOM occur, for example, in the breakdown and destruction of soil with losses to erosion, reducing the availability of nutrients in plants and lower water storage capacity. These are some factors which reflect negatively on agricultural productivity, and consequently, on food production as well as the sustainability of the soil-plant-atmosphere (KNORR et al., 2005; LAL, 2003; SIX et al., 2004). So, management systems which increase soil C stocks and reduce soil C losses are essential for sustainable development.

According to Araújo et al. (2004) some studies document the levels of SOC in the native Atlantic Forest and in the agricultural ecosystems that followed deforestation. These levels require documentation in order to establish the level of SOC decline and the rehabilitation that must occur if the levels are to be brought back to pre-deforestation levels. Spontaneous system may represent a significant role in that rehabilitation.

The objective of this study was to measure the soil C stocks in different ages of oil palm plantations located in Bahia State, Brazil, investigating the possibility of SOC stocks accumulation or reduction among different areas derived from forest and areas characterized as spontaneous system.

3.2 Material and Methods

3.2.1 Study areas

The study was carried out at Opalma Farm and Lamego Spontaneous System (13°27'S, 39°05'W), located in the city of Taperoá in Bahia State, Brazil (Figure 1).

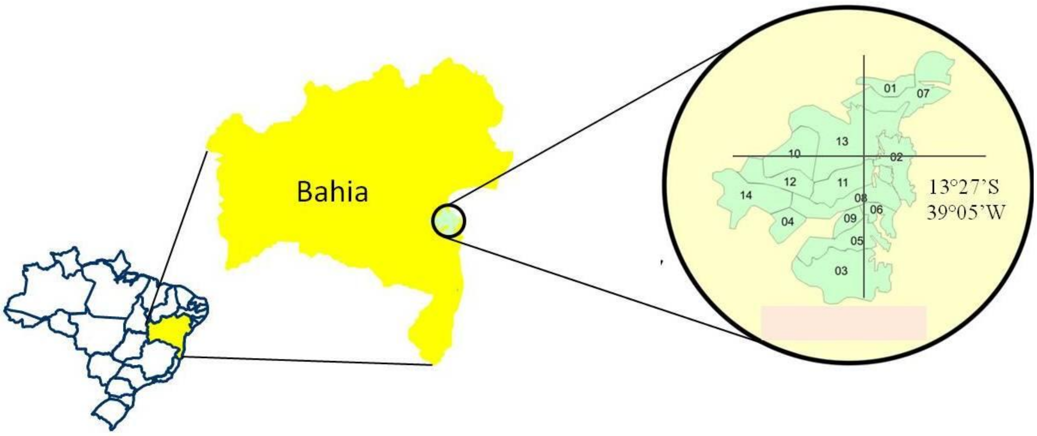

Figure 1 – Location map of the study areas in Taperoá, Bahia State, Brazil

According to Koppen classification (1900), the climate is classified as Aw. The annual mean rainfall over the last 20 years was 2000 mm $year^{-1}$ and the mean temperature was 25.3^{o} C. The mean altitude of the region is 15 m a.s.l. and the soil is well drained with medium clay content (16-26%) and classified as "Latossolo Amarelo distrofico tipico" in the Brazilian System of Soil Classification (EMBRAPA, 2006), and an Oxisol (Xanthic Hapludox) in the USDA classification (USDA, 1999).

The oil palm was established in this region after the clearing of Atlantic Rain Forest. But there is also a Spontaneous system (extractive system) located at Taperoá. The dispersion of the oil palm occurs through birds, and the plants are distributed along the native forest. This system was evaluated in order to determine the impacts of the oil palm introduction into the native Atlantic Rain Forest.

Four different sites were considered in this study: Native Atlantic Rain Forest (NARF), reference situation with native soil conditions; Spontaneous System (OPSP), extractive system where the oil palm was spread out along the native forest; Oil palm plantation derived from native rain forest cultivated for 23 years (OP23); Oil palm plantation derived from native rain forest cultivated for 34 years (OP34). Table 1 shows the bulk density, clay content, pH H_2O, available P, cation exchange capacity (CEC) and base saturation (BS) in the 0-30 cm soil layer.

Table 1 - Bulk density, clay content, pH, available P, CEC and base saturation in the study areas located at Taperoá, Bahia State, Brazil

Area	Plantation age (y)	Bulk density (mg dm^{-3})	Clay (g kg^{-1})	pH H_2O	Available P (mg dm^{-3})	CEC ($mmol_c dm^{-3}$)	BS (%)
NARF	-	1.14	180	4.3	2.8	119	4
OPSP	-	1.13	230	4.4	4.4	68	4
OP23	23	1.32	160	5.1	2.5	48	7
OP34	34	1.28	160	5.0	1.0	76	10

Available P was determined by ion exchange resin method

3.2.2 Soil sampling and analysis

Soil sampling was carried out in May 2008 (Opalma Farm) and February 2009 (Opalma Farm and Lamego) based on a completely randomized sampling design.

The palm are planted in a staggered design, 9 m apart at a density of 143 plants ha^{-1}, each tree being located at the tip of 9 m equilateral triangle. As soil organic carbon is more variable in space and time in oil palm plantations than most other crops, in May 2008 the soil samples were collected to determine the spatial variability of soil carbon in the same areas (OP23 and OP34). To accomplish this evaluation soil samples were collected in five profiles 0.6, 1.2, 2.5, 3,5 and 4.5 m away from the oil palm base at 0-5, 5-10, 10-20 and 20-30 cm soil depth (Figure2). Soil samples were also collected in five profiles in the native system (NARF).

During the harvest phase of oil palm at Opalma farm, above-grounds inputs are highly heterogeneous because fronds, which are progressively pruned to facilitate harvesting of fruit bunches, are piled between palm rows. The inter-rows and frond piles areas constitute about 80% and 20% respectively of the ground surface. So, the second soil sampling (February 2009) was carried out in five profiles 3.5 m away from the oil palm base in the inter-rows and the frond piles at 0-5, 5-10, 10-20 and 20-30 cm depths in each site (Figure 2).

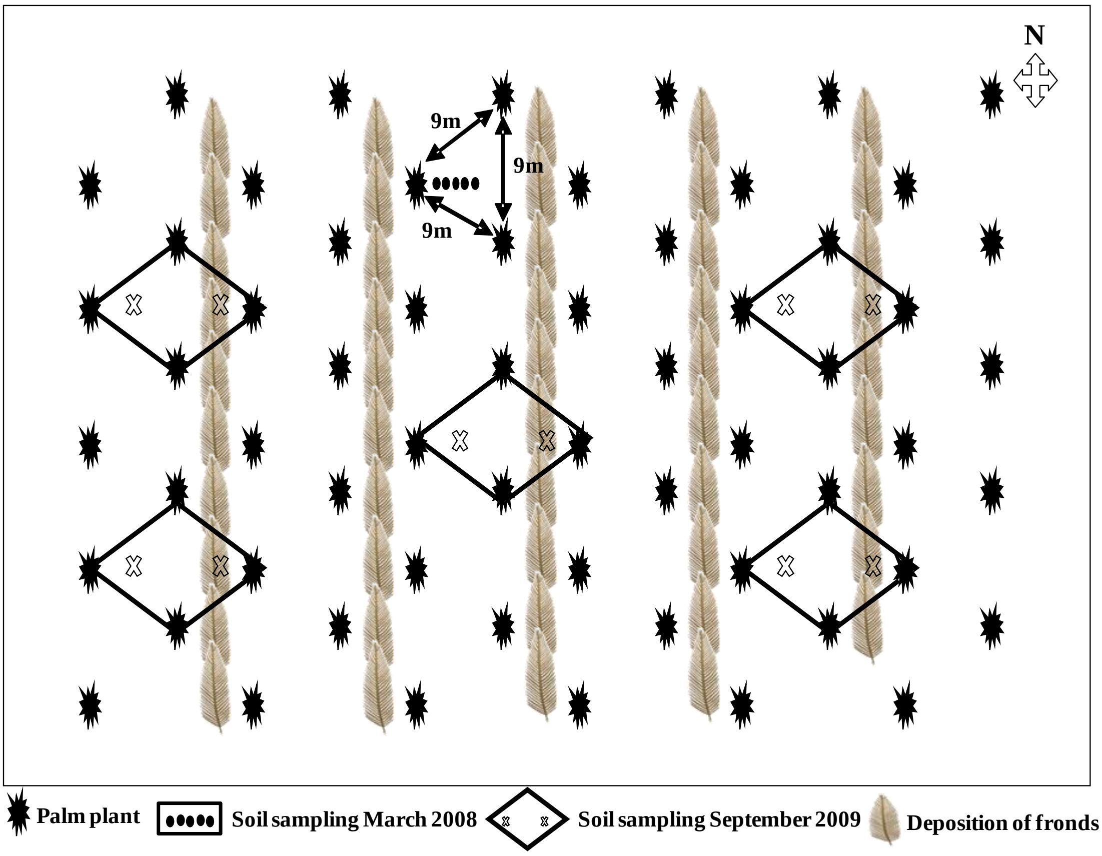

Figure 2 - Soil sampling design - in oil palm plantations at Opalma farm located in Taperoá, Bahia State, Brazil

To evaluate the soil organic carbon in the OPSP, three hectares were selected for soil sampling in February 2009. Each hectare was divided into 25 points 25 meters apart from each other. After that, five points were randomly selected to be sampled in each hectare (Figure 3). The soil sampling was carried out in profiles at 0-5, 5-10, 10-20 and 20-30cm.

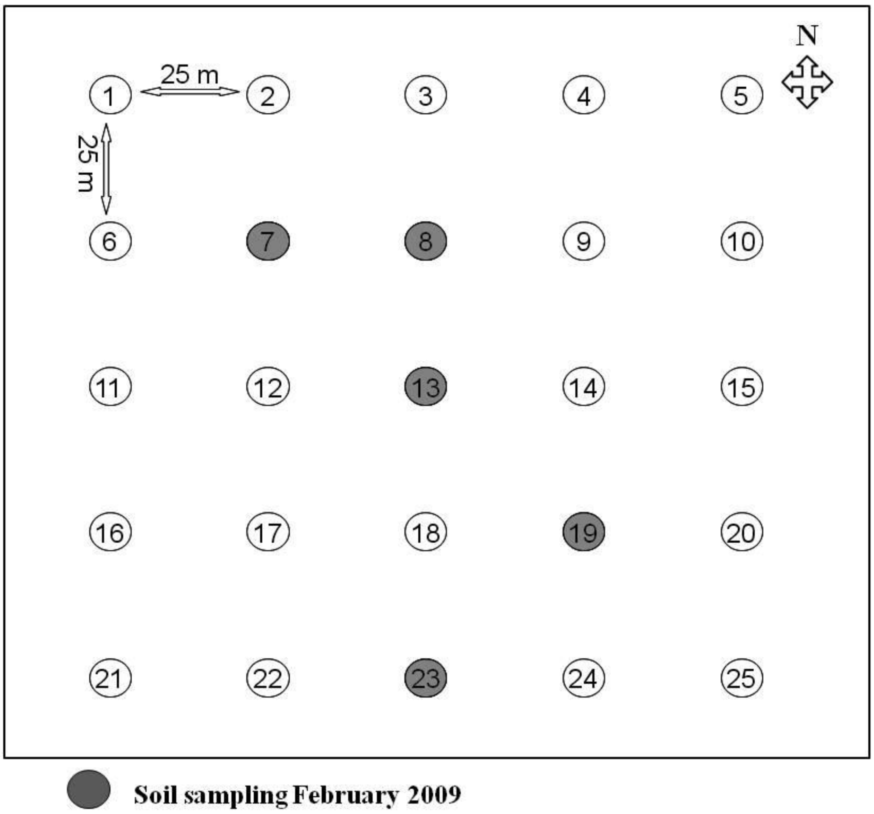

Figure 3 - Soil sampling design in spontaneous system of oil palm located at Taperoá, Bahia State, Brazil

The soil samples were air-dried and sieved with a 2 mm mesh to remove stones and root fragments before analysis. Sub-samples were sieved with 100 mesh and ground to a fine powder before total carbon determination. Total carbon was measured by dry combustion on Carbon Analyzer – LECO® CN-2000 (furnace at 1350 °C in pure oxygen). Bulk density (ρ) was measured from each pit and each layer with a volumetric (100 cm^3) steel ring.

3.2.3 Soil C stock calculation and density and clay corrections

For each soil layer, we calculated the carbon stocks by multiplying the concentration of the C (g g^{-1}) by bulk density (BD) (kg m^{-3}) and layer thickness (m). As samples were collected from fixed layers, the stock calculation needed to be adjusted in order to compare equivalent soil mass among the land uses. To do so, we used the variations in BD of each land use changes. Therefore, the methodology described in Ellert and Bettany (1996) and Moraes et al. (1996) was used to adjust soil C stocks to an equivalent soil mass. In order to calculate C stocks in an equivalent soil mass, the depth of the considered area was adjusted, i.e., the depth of the cultivated areas containing the same soil mass as the corresponding layer (0-30 cm) in native vegetation (the reference area).

We attempted to account for small soil variations in clay content among the study areas by making the hypothesis proposed by Moraes et al. (1996) that for each soil type there is a close relationship between clay and carbon content and no changes in clay content occurs after oil palm establishment. This correction is based on the equation 1.

$$C\ (corrected) = \frac{C\ (measured) \times Clay\ (reference)}{Clay} \qquad (1)$$

Where Clay (reference) is a mean clay content for each soil layer, including the forest site.

3.2.4 Statistical analysis

The statistical analysis of data was performed on a completely randomized sampling design, with the assumption that the areas studied had the same topographic, edaphic and climatic conditions. Data from soil C stocks under different areas were analyzed for variance (ANOVA) to determine land use effects. A Tukey test was used to test for significant ($p \leq 0.05$) differences among treatments. All statistical analyses were performed using the SAS program, version 6.

3.3 Results and discussion

3.3.1 Soil carbon and nitrogen contents in Spontaneous and Native Systems

Soil C and N contents were similar in both the agroforestry and native systems ($p<0.05$), with contents decreasing in soil depth (Table 2). Thus, it can be inferred that the input of soil organic matter in the native systems is similar to spontaneous system of oil palm over time. Gama-Rodrigues, Gama-Rodrigues and Barros (2008) evaluated the carbon and nutrient cycling in two plantation systems of forest species native in the Atlantic Forest. The results found in mixed-tree stands proved to be the best plantation system, in view of the more efficient biochemical and biogeochemical cycling and better balanced of carbon and nutrients.

Table 2 - Soil carbon and nitrogen content in native and spontaneous systems located at Taperoá, Bahia State, Brazil

Depth	NRAF[a]			OPSP[b]		
(cm)	C (%)	N (%)	C/N	C (%)	N (%)	C/N
0-5	1.93±0.16	0.12±0.01	15.6±0.37	1.82±0.25	0.12±0.02	16.69±0.58
5-10	1.53±0.27	0.10±0.02	15.2±0.70	1.55±0.19	0.10±0.02	16.24±0.31
10-20	1.33±0.11	0.09±0.01	14.6±0.38	1.23±0.13	0.08±0.01	17.02±0.65
20-30	1.23±0.18	0.08±0.01	14.4±0.89	0.98±0.18	0.06±0.01	16.21±0.75

[a]The values represent the mean (n=5) ± standard deviation
[b] The values represent the mean (n=15) ± standard deviation

According to Gama-Rodrigues and Barros (2002) the process of carbon and nutrients cycling between agroforests and natural forest allows to evaluating the changes due to management applied and to inferring the sustainability of forest sites. In low fertility soils, the quantities of carbon and nutrients found in soil, litter and biomass are important to balance of nutrients and can be used as indicators to the availability of plant nutrients (ZAIA; GAMA-RODRIGUES, 2004).

The small farmers in the spontaneous system of oil palm have adopted the management regime where they preserve all plant residues on site, including the residues from manual weeding. As observed by Araújo et al. (2004) in a study at Brazilian Coastal Tableland, the agricultural procedures adapted by small farmers in this area are an example of how spontaneous system can promotes the maintenance of soil organic carbon.

3.3.2 Soil carbon and nitrogen contents in oil palm plantations

We found that the older system contained the highest C contents in the region nearest the plant (Table 3). This result can be attributed to higher inputs of organic matter due the large concentration of roots which has accumulated large amounts of carbon (LAMADE; DJEGUI; LATERME, 1996). Oil palm has an adventitious root system and the most important part (tertiary and quaternary roots) is concentrated mostly in the upper 30 cm from the soil surface (YAHYA et al., 2010).

Lamade, Djegui and Laterme (1996) pointed out that the equilibrium of the soil organic carbon stock in an oil palm plantation over 14 years old was reached when the total amount of carbon returned to the soil by plant residue was equal to the amount of carbon in the soil mineralized by heterotrophic respiration. Our average values showed that there was a small increase of C contents in the soil of the oil palm cultivated areas over time. Haron, Brookes and Zakaia (1998) also reported increases in soil organic carbon with stand age and the authors attributed this increase due to root inputs.

Table 3 - Soil carbon (C) and nitrogen (N) contents in the oil palm plantations under different distances from the palm base in Taperoá, Bahia State, Brazil

Depht (cm)	Oil palm cultivated for 23 years (OP23)						Oil palm cultivated for 34 years (OP34)					
	0.6[a]	1.2	2.5	3.5	4.5	Mean	0.6	1.2	2.5	3.5	4.5	Mean
							C (%)					
0-5	1.55	1.26	1.09	1.13	1.06	1.22	3.82	1.00	0.87	0.83	0.95	1.49
5-10	1.27	1.13	1.09	1.14	1.17	1.16	2.74	1.02	0.91	0.91	0.94	1.30
10-20	1.15	0.92	0.90	0.83	1.03	0.97	1.91	0.80	0.84	0.90	0.94	1.08
20-30	0.82	0.65	0.61	0.60	0.72	0.68	1.43	0.65	0.93	0.76	0.80	0.91
							N (%)					
0-5	0.08	0.06	0.07	0.06	0.06	0.07	0.17	0.06	0.05	0.04	0.06	0.07
5-10	0.07	0.07	0.07	0.07	0.07	0.07	0.14	0.06	0.04	0.05	0.06	0.07
10-20	0.07	0.06	0.06	0.06	0.07	0.06	0.10	0.05	0.05	0.05	0.06	0.06
20-30	0.07	0.05	0.04	0.05	0.04	0.05	0.08	0.04	0.04	0.05	0.05	0.05
							C/N					
0-5	19.4	21.0	15.6	18.8	17.6	18.5	22.5	16.7	17.4	20.8	15.8	18.6
5-10	18.1	16.1	15.6	16.3	16.7	16.6	19.6	17.0	22.8	18.2	15.7	18.6
10-20	16.4	15.3	15.0	13.8	14.7	15.1	19.1	16.0	16.8	18.0	15.7	17.1
20-30	11.7	13.0	15.3	12.0	18.0	14.0	17.9	16.3	23.3	15.2	16.0	17.7

[a]Distances from the oil palm trunk (m).

The mean for total soil N was similar in OP23 and OP34. The overall mean for total N across the two plantations age and soil depth was 0.06% N. The C/N ratio of soils ranged from 11.7 to 22.8 (Table 3). Means values of C/N ratio increased as a function of stand age, corroborating to the results found by Haron, Brookes and Zakaia (1998).

3.3.3 Soil carbon stocks in oil palm plantations in relation to native and spontaneous system

Oil palm areas (OP23 and OP34) showed the mean bulk density (0-30 cm) slightly higher (1.32 and 1.28 g cm^{-3}, respectively) than native forest and spontaneous system (1.1 cm^{-3}) (Table 1). The use of soil with oil palm resulted in an increase of soil bulk density in the surface and deeper layers. Yahya et al. (2008) also found the increase in soil bulk density and decrease in soil porosity in oil palm plantations at Malaysia. According to the authors, mechanization in oil palm plantations such as the use of machines for cultural practices could contribute to the gradual deterioration of soil physical conditions.

The frond residues added to soil in oil palm plantations promote an input of soil organic matter over time. The study areas located at Opalma farm evidenced higher C stocks due the frond inputs (Table 4). Other studies had also reported improvement of organic C in soils under oil palm plantations that had received application of palm residues (BAKAR et al, 2011; HARON; BROOKES; ZAKAIA, 1998). Soil C stocks (0-30 cm) under frond piles at OP23 and OP34 were 1.7 and 2.6 times higher than inter-rows, respectively (Table 4).

Frond piles and inter-rows in oil palm system represent respectively 20% and 80% of the area; therefore we consider these area proportions to calculate the soil C stocks per hectare. Within the top 30 cm of the soil profile we found 38.5±2.8 Mg C ha^{-1} in OP23 and 66.6±10.4 Mg C ha^{-1} in OP34, resulting in increase of C stocks over time. Our results can be due the management of oil palm that reduce tillage intensity, maximize residue return and promotes the absence water stress because precipitation occurs throughout the year.

Table 4 - Soil C stocks (Mg ha^{-1}) in the oil palm plantations under inter-rows and frond piles in Taperoá, Bahia State, Brazil

Depth	Inter-rows		Frond piles		Total	
(cm)	OP23	OP34	OP23	OP34	OP23	OP34
0-5	6.9±0.8Bb	10.7±2.7Ab	12.8±4.2Ba	23.3±5.9Aa	8.1±1.4B	13.2±2.5A
5-10	5.1±0.6Bb	11.8±2.7Ab	12.5±2.4Ba	25.6±3.1Aa	6.5±0.9B	14.6±2.A
10-20	12.4±0.5Ab	17.8±4.8Ab	19.7±4.2Ba	37.6±6.9Aa	13.8±0.7B	21.8±4.0A
20-30	9.2±0.4Bb	14.4±3.9Ab	12.7±3.0Ba	27.4±7.4Aa	9.9±0.8B	17.0±2.5A
0-30	33.5±1.2C	43.1±2.9C	57.7±11.1A	113.9±20.6A	38.5±2.8B	66.6±10.4B

The values represent the mean (n=5) ± standard deviation. Means within each column of the same site (Inter-rows, Frond piles and Total) followed by the same capital letter are not significantly different by the Tukey test ($p<0.05$). Means within each row and different sites (Inter-rows and Frond piles) of the same treatment (OP23 and OP34) followed by the same small letter are not significantly different by the Tukey test ($p<0.05$).

As already mentioned the evaluated areas showed small differences in the clay contents (Table 1) and bulk density. Table 5 shows the adjustments in soil C stocks for bulk density and clay contents. After the correction for bulk density, i.e. equivalent soil mass, the carbon stocks under OPSP did not differ statistically from the NARF. However, after the correction for clay content we found differences between the systems.

Table 5 - Soil carbon stocks (0-30 cm), Mg ha^{-1}, in the equivalent layers and normalization for the mean clay content under Native Atlantic rain forest (NARF), Spontaneous system (OPSP) and oil palm plantations (OP23 and OP34) in Taperoá, Bahia State, Brazil

(cm)	NARF	OPSP	OP23	OP34
0-5	10.5±0.9	9.8±1.3	8.1±1.4	13.2±2.5
5-10	7.5±1.3	8.6±1.0	6.5±0.9	14.6±2.0
10-20	15.7±1.3	13.9±1.5	13.8±0.6	21.8±4.0
20-30	14.8±2.2	11.7±2.1	5.9±0.5	11.5±1.7
0-30[a]	48.5±3.3B	44.0±5.2B	34.3±2.7C	61.1±9.6A
0-30[b]	53.5±3.6B	37.1±4.4C	34.7±2.8C	66.6±10.5A

[a]Soil C stocks adjustment for the soil equivalent mass
[b] Normalization of Soil C stocks for the mean clay content
The values represent the mean (n=5) ± standard deviation. Means within each row followed by the same capital letter are not significantly different by the Tukey test ($p<0.05$).

The clay content in OPSP was 5% higher than NARF (Table 1), so the normalization for the mean clay content showed a decrease in C stocks in this system. It is has been suggested that soil texture represents an important role in determining the amount of organic matter in soil (PARTON et al., 1987, FELLER et al., 1991, MORAES et al., 1996). Variation in soil C content is more closely related to the variation in soil texture than to others parameters like land-use and climate (SIX et al., 2002). According to Feller et al. (1991) soil C variation is linear for those where clay content is lower than fifty percent.

The OP23 area showed decrease in C stocks when compared with native system, agreeing with the results found by Sommer, Denich and Vlek (2000). However, OP34 area showed the highest C stocks among the areas evaluated with an increase of 80% of the amount of SOC storage found under native vegetation. The IPPC guidelines (2006) reported that perennial cropping systems do not appear to have a negative effect on SOC storage following land use change from native vegetation. In the case of oil palm plantations, we can suggest that mature stands may create a significant increase in SOC storage following conversion from native rainforest. Thus, more research with different ages of oil palm plantation is needed to understand the point where the SOC storage is equal or higher than under natural conditions.

3.4 Conclusions

The spontaneous system with oil palm can promotes a decrease of the soil C stocks, even adopting a management system without soil disturbance and preserving all plant residues on site.

The inputs of frond from aboveground during the life of plantations and the increments derived from root material promote the variability in the dynamics of SOC in oil palm plantations resulting in an increase in soil C stocks over time.

The results suggest that the oil palm cultivation may be increasing the SOC with land use change from native vegetation to cropland management in the Atlantic Coast region of Brazil. So, under the environmental point of view, the use of this oilseed can be seen as a viable alternative as raw material for biodiesel.

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4 SOIL GREENHOUSE GAS EMISSIONS FROM OIL PALM PRODUCTION IN THE AMAZON REGION

Abstract

As biodiesel production expands in Brazil to substitute the fossil fuel, oil palm has been cited as the main raw material. So, it is critical to measure the greenhouse gas (GHG) emissions associated to its production. The objective of this work was to evaluate the N_2O, CO_2 and CH_4 emission rates associated to the agricultural phase from the nursery till juvenile and mature stands of oil palm cultivated in the Brazilian Amazon region. The GHG fluxes from the soil were measured in August 2010 in two different sites (1 hectare plot): in the first site we collected GHG samples after nitrogen (N) fertilization (nursery and juvenile phases); in the second site we collected GHGs samples in the experiment after fertilization (mature phase) and in the frond piles (local of crop residue deposition). We found higher N_2O fluxes in the nursery (values reaching 77.2 mg N_2O ha^{-1}) than in juvenile and mature stands (mean values of 6.0 mg N_2O ha^{-1}). The emission factor from N fertilizer showed highest values in the nursery (7.95%) and this result was attributed to the substrate used in the production system. The ammonium sulfate applied in juvenile and mature stands showed emission factor lower than the values proposed by IPCC (1%). The CO_2 fluxes ranged at each crop stage during the evaluated period but we didn't find difference between the treatments evaluated from N fertilizer applied. The CH_4 fluxes were higher in the treatments were N fertilizer was applied. Decomposition of frond piles showed N_2O, CO_2 and CH_4 fluxes for the period evaluated of 22.12 µg m^{-2} h^{-1}, 83.46 mg m^{-2} h^{-1} and 11.55 µg m^{-2} h^{-1}, respectively. Our results indicate that seedlings production is the stage with highest GHG emissions associated to oil palm production. However, this step represents 3.8% of the plant life cycle and the emissions are not significant when analyzing the application of fertilizers during 25 years in the juvenile and mature plantations.

Keywords: Carbon dioxide; Methane; Nitrogen fertilizer; Nitrous oxide; Plant material decomposition

4.1 Introduction

The atmospheric concentrations of the three main greenhouse gases (GHGs) – carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) – have increased rapidly in the last few decades, which is a phenomenon associated to anthropogenic activities (Mosier et al., 1991; 1998). To prevent or slow down the increase in concentrations of GHG, some mitigation decisions need to be made (ADLER; DEL GROSSO; PARTON, 2007). Among a number of strategies proposed by Pacala and Socolow (2004) for mitigation of carbon (C) based on the use of new technologies, the use of biofuels has been cited as one of the most viable alternatives.

It is estimated that 75 % of CO_2, 94 % of N_2O, and 91 % of the CH_4 emissions in Brazil come from agricultural activities (LIMA et al., 2006). An accurate assessment of the productive chain of biodiesel should be conducted under an environmental approach. An important issue that should be taken into account is the use of fossil fuels used in the production of biodiesel that increase the emission of GHG to the atmosphere. Regarding the agriculture cultivation, the largest emissions of greenhouse gases are N_2O, CO_2 and CH_4 from soil, in addition to the CO_2 emissions from agricultural machinery (DEL GROSSO ET AL., 2001; ROBERTSON; PAUL; HARWOOD, 2000; WEST; MARLAND, 2002). As biodiesel production expands in Brazil and oil palm has been cited as the main raw material, it is critical to understand the environmental consequences of the cultivating system.

The estimation performed by Instituto Brasileiro de Geografia e Estatística (IBGE, 2008) indicates that it will be necessary to expand the agricultural areas by 2.56 million of hectares till 2013 to accomplish the demand for biodiesel. This is, although, an estimate considering the four main plants (soybean, castor bean, oil palm and sunflower) among several others. Oil palm cultivation represents 18 % of the estimated area. Besides a GHG emissions comparative analysis between biodiesel from palm oil and fossil diesel, is also necessary to consider the GHG emissions in the agricultural cultivation of oil palm.

Estimates for Brazil indicate that land-use and agriculture respond for 81% of the total national emissions of greenhouse gases (TEIXEIRA; MURRAY; CARVALHO, 2006). Part of this contribution is explained by nitrous oxide (N_2O) emitted from N fertilizers and crop residue (PRINN, 2004). Compared to CO_2, N_2O has a much smaller impact on annual greenhouse gas emissions from agriculture, approximately 6% against 66% for the former. However, it should be considered that whilst some agricultural practices may promote soil C accumulation, the capacity of soil to accumulate C is finite (SIX et al., 2002), and theoretically N_2O emissions will always occur when fertilizers and crop residues are added to the soil (JANTALIA et al, 2008).

The cultivation system based on bioenergy varies according to the length of the plant life cycle: productivity, efficiency of energy conversion, demand for nutrients, inputs of carbon in the soil, losses of nitrogen (N), and other characteristics; all of them resultant from management operations. Those factors affect the magnitude of the components which contribute to the net fluxes of GHGs (ADLER; DEL GROSSO; PARTON, 2007, 2007).

The objective of this study was to measure the soil GHG emissions associated to the seedlings production, juvenile and mature phases of oil palm cultivated in the Brazilian Amazon region.

4.2 Material and Methods

4.2.1 Study area

The study was carried out at Agropalma Farm, in the city of Tailândia, Pará State, Brazil. The climate was classified as tropical monsoonal (Afi) (KÖPPEN, 1900). The mean annual rainfall for the previous 20 years was 2,500 mm $year^{-1}$ and the mean temperature was 26.6^{o} C.

The mean altitude of the region is 49 m and the soil was well drained with medium clay content and classified as an Oxisol (Xanthic Hapludox) in the USDA classification.

4.2.2 Experimental design

We evaluated the GHGs emissions after ammonium sulfate ($(NH_4)_2SO_4$) application in the nursery, juvenile and mature phases of oil palm cultivation. Moreover, the GHG emissions from the decomposition of crop residue added to soil (frond piles) were measured. The experiments were conducted at two sites (1 ha plot) with juvenile (site 1) and mature stands (site 2). All measurements reported here were taken at least 20m from the edge to guard against edge effects.

4.2.2.1 GHG measurements after fertilizer application in the nursery

The oil palm seedlings grown in a polyethylene plastic bag until 15 months. After that they are planted in the soil. To cultivate the seedlings the substrate consist of 30% of organic compost from industrial oil extraction (fiber and shell) and 70% of superficial soil layer (horizon A). In the seedling nursery there is an irrigation system that guarantees the wetting of the substrate when necessary. The fertilizer application in the nursery is divided into 13 applications, and to measure the GHGs emissions we used the minimum and maximum doses from N applied in the substrate without plant, as described in the treatments below:

SN1: Control treatment, without N application;

SN2: Minimum N dose applied in the substrate (1.8 g N per plant per application);

SN3: Maximum N dose applied in the substrate (5.4 g N per plant per application).

Measurements of GHGs emissions after the fertilizers application in the substrate for seedlings production were made using the static chamber technique with two-piece static polyvinyl chloride plastic chamber (STEUDLER et al., 1989). The chambers were inserted 5 cm into the soil at site 1 and then we applied the substrate and the N fertilizer into the camera 1 day before the first measurements. To study the effect of irrigation on the trace gas fluxes from substrate after fertilizer application, 8 mm of water was added into the chamber to simulate the irrigation every day after taken the GHGs samples. At each treatment three chamber bases were installed along at randomly selected points along a 50m long transect and they remained in place during the entire monitoring period.

4.2.2.2 GHG measurements after fertilizer application in the juvenile and mature stands

To measure the GHG emissions after fertilizer application in oil palm stands we consider the incidence of solar radiation and precipitation in the inter rows of the culture where the fertilizer is applied. The ground cover is suppressed by canopy closure at about 6±8 years. We selected 1 ha plot to install the experiments in areas with juvenile (before start the harvesting operations) and mature (after start the harvesting operations) stands of oil palm. By determining differences between the two plots before and after rainfall, treatment effects are clearly identified as rends of pretreatment similarities and differences between plots begin to diverge after the treatment begins. Each dose of N fertilizer consist one different treatment as described below:

JN1: Control treatment in the juvenile stand, without N application;

JN2: Representative N dose applied in 1-year old juvenile stand (108 g per plant or 15.4 kg per hectare);

MN1: Control treatment in the mature stand, without N application;

MN2: Representative N dose applied in 3-years old mature stands (165 g per plant or 24 kg per hectare);

MN3: Representative N dose applied in 8-years old mature stands (360 g per plant or 51 kg per hectare);

MN4: Representative N dose applied in 17-years old mature stands (480 g per plant or 69 kg per hectare).

Measurements of GHG emissions after the fertilizers application in the each site were made using the static chamber technique with two-piece static polyvinyl chloride plastic chamber (STEUDLER et al., 1991) that were inserted 5 cm into the soil. At each treatment three chamber bases were installed along at randomly selected points along a 100m long transect and they remained in place during the entire monitoring period. The N fertilizer was applied into the camera 1 day before the first measurement.

4.2.2.3 GHG measurements due the decomposition of plant material added to soil

During the crop phase of oil palm (from about 8 to 25 years) above-grounds inputs are highly heterogeneous because fronds, which are progressively pruned to facilitate harvesting of fruit bunches, are piled between palm rows. In this study the area extend the frond piles constitute about 20% of the ground surface. It has been estimated that approximately 10 t ha^{-1} y^{-1} dry matter of fronds are cut in mature oil palm plantations (CHAN; WATSON; LIM, 1980; NG; TAMBOO; SOUZA, 1968).

To measure the GHGs emissions in frond piles at site 2, five static chambers ($1m^2$) with two-piece were inserted 10 cm into the soil. The chamber cover was fitted on to an aluminum base (volume of 140L) equipped at the top with a water channel (height of 0.05 m) to ensure a good seal between the base and the cover. The chambers had a thermometer with outside display for monitoring the temperature inside the chamber, and an internal fan to homogenize the chamber atmosphere before sampling. In the top, the chambers were equipped with a rubber septum to take air samples. The chambers were inserted into the soil 2 days before the first measurement and remained in place during the entire monitoring period.

4.2.3 GHG Sampling

The GHG samplings were collected throughout August 2010. Fluxes were measured once a day between August 5th and 24th. Air samples were manually taken from closed flux chamber. Air samples from chamber headspace were taken simultaneously in the treatments, beginning at 9 a.m. by a syringe (polypropylene, 20 mL) at 0, 5, 10 and 20 min after closing the chamber in the areas where fertilizers were applied, and at 0, 10, 25 and 40 min after closing the chamber in the frond piles. Ambient air (at 1 m above the ground), inside chamber air and soil temperature at 2, 5 and 10 cm depth were measured during each incubation. Barometric pressure was measured at the beginning of each incubation.

The syringes were immediately disposed in a cooler box, where they were kept at low temperature, and dispatched the lab (i.e., the Environmental Biogeochemical Lab, Nuclear Energy Centre, University of Sao Paulo) for analysis of GHG concentrations by gas chromatography (GC - Shimadzu 2014). The concentrations of the N_2O were determined using a electron capture detector (ECD). The CO_2 and CH_4 concentrations were determined using a flame ionization detector (FID). The fluxes of each gas were calculated by measuring alteration in concentration as a function of incubation time.

4.2.4 N_2O emission factor calculation from N-fertilizer

N_2O emission factor from nitrogen fertilizer (EF_{fert}) was calculated according to the methodology proposed by the IPCC (2006) (Equation 1).

$$EF_{fert} = \left(\frac{\Sigma_{N2O} - \Sigma_{Co}}{Nappl.} \right) \qquad (1)$$

Where: Σ_{N2O} is the N_2O emissions from each treatment; Σ_{Co} is the N_2O emissions from the control; *Nappl* is the amount of N-fertilizer applied.

4.2.5 Statistical analysis

The statistical analysis of data was performed on a completely randomized sampling design. Data of GHGs from soil were analyzed for variance (ANOVA). A Tukey test was used to test significant ($p \leq 0.05$) differences among treatments. All statistical analyses were performed using the *Statistical Analysis System* (SAS), version 9.2.

4.3 Results and discussion

4.3.1 Rainfall and temperature during the study period

Mean daily rainfall (mm), soil and air temperature (^{o}C) were measured in the study areas (sites 1 and 2) during the period of study (Figure 1).

The total rainfall was 46 mm during de GHGs sampling and the occurrence of rain was observed in three days, ranged from 4.9 to 29.9 mm (Figure 1A). August is characterized by low rainfall in the Amazon Region, so it is a good period for fertilizer application. Mean daily temperatures showed normal averages for August and ranged from 27.2 to 30.1^{o}C during the study period (1A).

It has been found that rainfall may have important effects on climate change by altering soil emissions of CO_2, CH_4 and N_2O (Prather et al., 1995). The soil GHG emissions caused by direct effects of land-use-change (KIRKMAN; GU; AMMANN, 2002; VERCHOT, DAVIDSON; CATTÂNIO, 2000) as well as the effects of precipitation (GARCIA-MONTIEL et al., 2003; WICK et al., 2005) have been studied in the Amazon region. However, studies determining the influence of precipitation in the GHG emissions after fertilizer application are more common in the Cerrado region (CARVALHO et al., 2006; METAY et al., 2007).

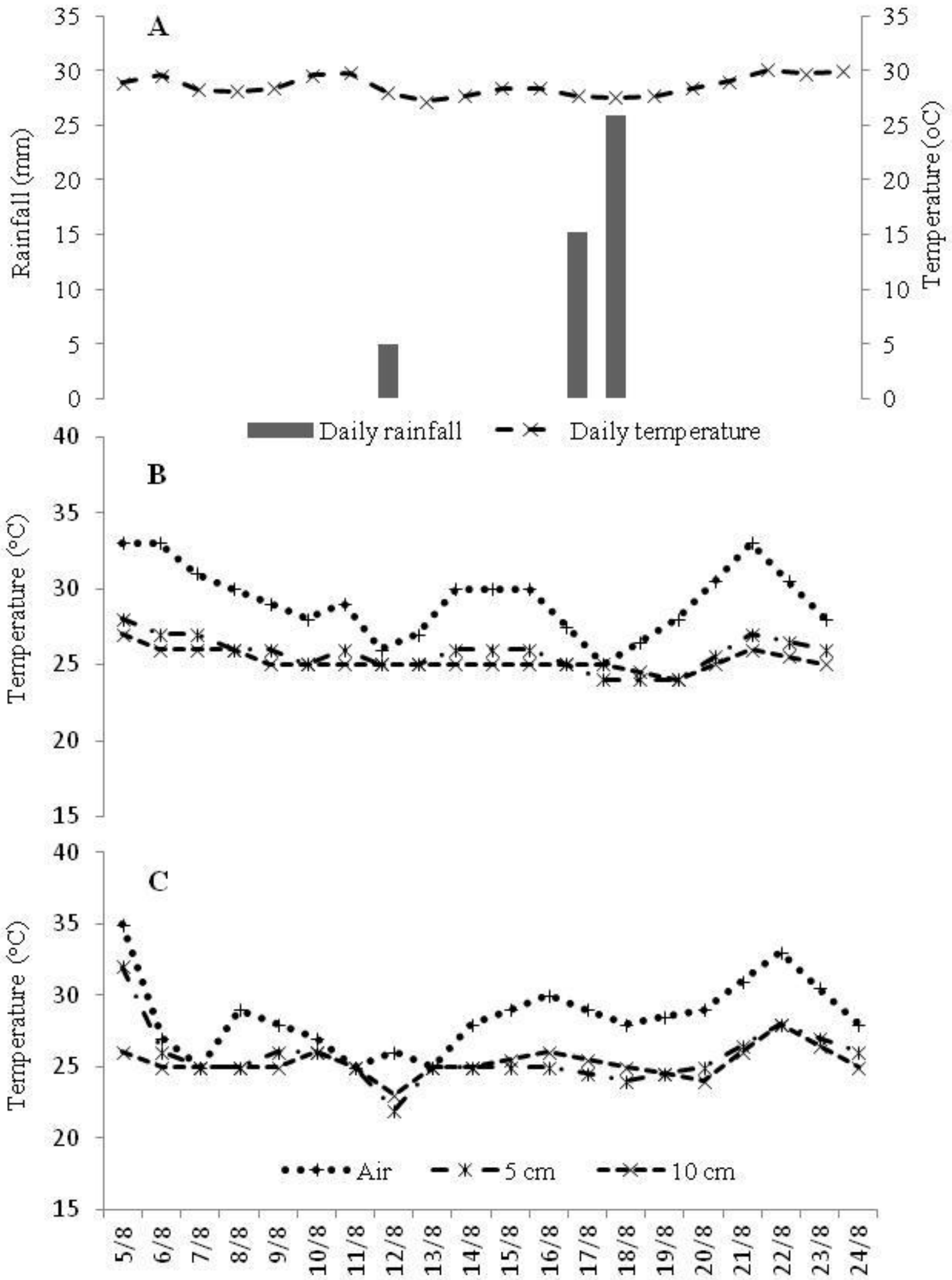

Figure 1 – Rainfall and mean daily temperature (A), and air, 5cm and 10 cm temperature at site 1 (B) and site 2 (C) during the GHGs sampling in the period of study at Agropalma Farm, Pará State, Brazil

GHGs samples were collected earlier in site 2, so the air temperatures were lower than in site 1. The soil temperature during GHGs sampling showed low variations between the days evaluated and we found the highest averages at 5 cm depth (Figure 1 B, C).

4.3.2 GHGs fluxes in different stages of oil palm cultivation

4.3.2.1 Soil N_2O fluxes and emission factor from fertilizer application

Nitrous oxide (N_2O) emissions in the nursery were directly proportional to the amount of N fertilizer applied at substrate (Figure 2A). SN3 showed the highest fluxes during the period of evaluation reaching 565 μg N_2O m^{-2} h^{-1} ($p<0.01$) on August 17th. The short-term nature of N_2O pulses following fertilization support the arguments by Mosier (1989) and Veldkamp and Keller (1997) that frequent measurements are important to capture high N losses by gases emissions in the first weeks following N application. We found an increasing in N_2O emissions until 15 days after fertilizer application. After that the emissions were decreasing until reaching the initial values. The highest values for all treatments occurred when there was rainfall in the study area. The cumulative emission for the period evaluated was ranked the fallowing order: SN3 (0.566±0.207 kg N ha^{-1}) > SN2 (0.206±0.021 kg N ha^{-1}) > SN1 (0.075±0.011 kg N ha^{-1}). The cumulative N_2O emission was directly related to the added N (r^2 = 0.93).

In the nursery, the GHG emissions come from substrate and fertilizer application. The substrate used is composed of 30% of fiber and nutshell which are mixed with 70% of soil from surface layers. The shells are an average of 5% of the fruits of oil palm and have 20% humidity. The mesocarp fiber represents approximately 12% of fresh fruit bunch with humidity ranging from 15% to 30% (SINGH et al., 1989). The substrate showed high C content (57 g kg^{-1}) and these by-products of oil palm have 4 g kg^{-1} of N, 1.4 g kg^{-1} of P_2O_5 and 1.9 g kg^{-1} of K_2O (FERREIRA; BOTELHO; VILLAR, 1998). So, we can suggest that the higher N_2O emissions observed in the evaluated treatments is largely attributed to use of by-products in the substrate. In general we observed a higher variability in N_2O emissions after N application, but the N_2O fluxes were higher when circumstances combine larger rainfall and fertilization (Figures 1 and 2A). The relationship between increasing moisture levels and higher rates of denitrification was determined in the field by Davidson et al. (2000) and these short-term N_2O responses to fertilizer additions usually occur in tropical agricultural and agroforestry systems (DAVIDSON; MATSON; BROOKS, 1996).

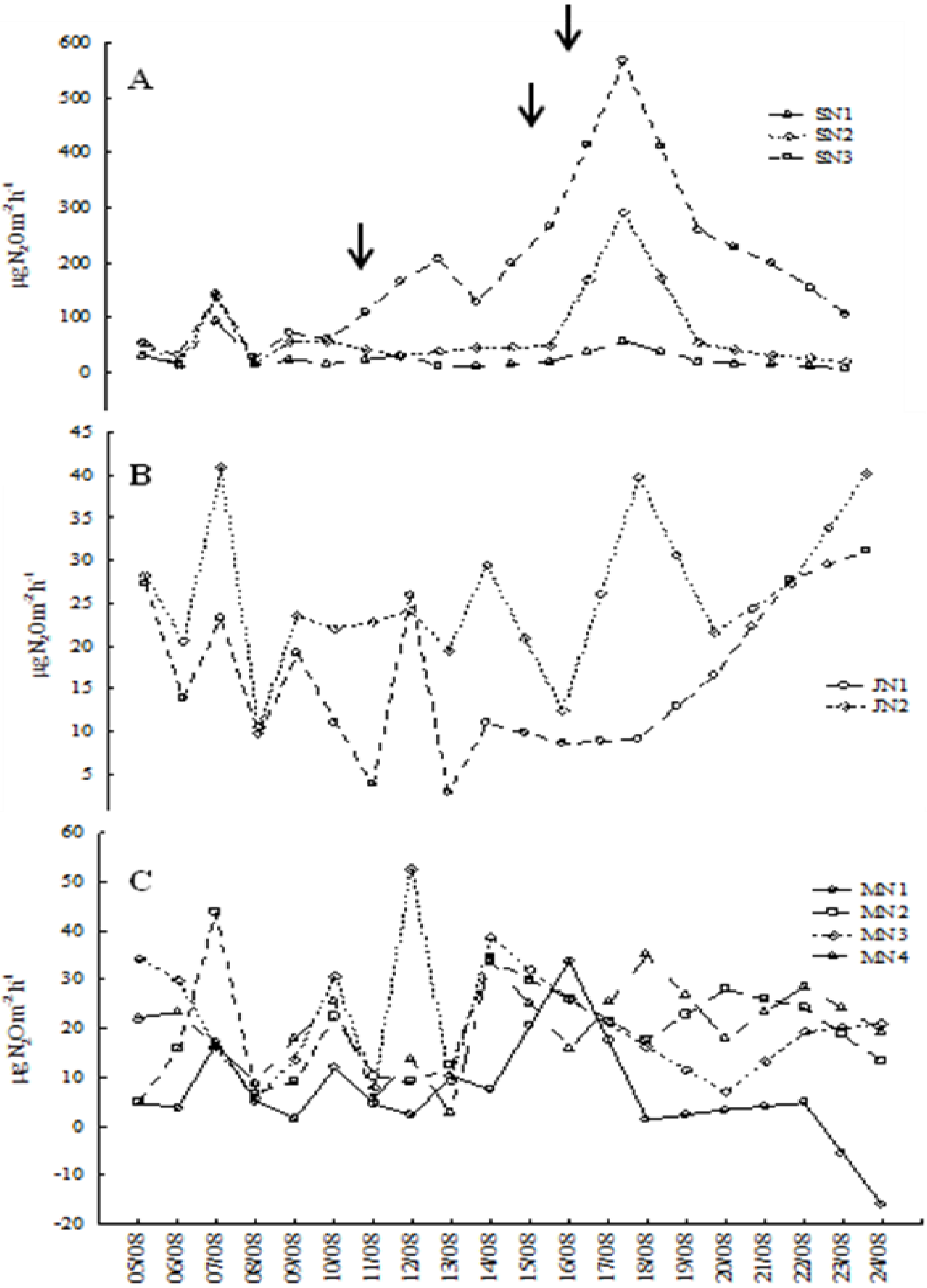

Figure 2 - Nitrous oxide (N_2O) fluxes from the substrate (seedlings production) and soil (juvenile and mature stand) after fertilizer application in Agropalma Farm, Pará State, Brazil. The values represent the mean (n=3) and ↓ represent the occurrence of rainfall during the period of evaluation.

In the juvenile stands we evaluate the soil N_2O emissions after N fertilization (Figure 2B). The N_2O fluxes were higher in JN2 than JN1 (control treatment) in the most part of the evaluated period ($p<0.01$). We found N_2O fluxes ranging from 2.95 µg m^{-2} h^{-1} (JN1) to 40.90 µg m^{-2} h^{-1} (JN2). The cumulative soil emissions during the evaluated period was higher ($p<0.01$) in JN2 (0.074±0.022) than in JN1 (0.045±0.01 kg N ha^{-1}).

In the mature stands we evaluated the soil N_2O emissions after fertilizer application (Figure 2C). We observed large variations in the soil N_2O fluxes during the evaluated period, ranging from 4.83 µg m^{-2} h^{-1} (MN1) to 52.51 83 µg m^{-2} h^{-1} (MN3). We didn't found difference between the treatments with different N doses applied (MN2, MN3 and MN4), but all of them showed higher cumulative emissions ($p<0.01$) than the control treatment (MN1). The cumulative emission was ranked in the following order: MN3 (0.061±0.006 kg N ha^{-1}) = MN4 (0.060±0.018 kg N ha^{-1}) = MN2 (0.059±0.015 kg N ha^{-1}) > MN1 (0.022±0.011 kg N ha^{-1}).

The mean of soil N_2O fluxes in the juvenile and mature oil palm stands were lower than in the nursery phase (Figures 2 A, B, C). As the amount of fertilizer applied in the seedlings was lower than in the plantations we can to confirming that the highest N_2O fluxes observed in the seedling experiment is due the interaction between the fertilizer applied, by-products in the substrate, and humidity due the daily irrigation. The influence of precipitation on the N_2O fluxes showed the relationship between soil moisture and an increase in aerobic sites (METAY et al., 2007). These results were similar those found by Signor (2010) in order to confirming that N_2O is formed mainly by denitrification which requires anaerobic conditions.

There is no clear the correlation between N application and N_2O fluxes from soil because the higher variability is to be observed shortly after each fertilization. The results found here are consistent with other studies under tropical (NOBRE, 1994; METAY et al., 2007) and temperate conditions (MOSIER, 1989).

It was calculated the emission factor (EF) from N fertilizer applied at substrate (seedlings production) and soil (juvenile and mature stands) (Table 1). Ammonium sulfate was the nitrogen source used in all growth stages of oil palm. Our results showed the highest emission factor values in the nursery phase where the by-products from industry were used to compound the organic substrate.

Table 1 - Soil nitrous oxide (N_2O) fluxes and emission factor (EF) measured after N fertilization (ammonium sulfate) in different growth stages (seedlings, juvenile and mature stands) in Agropalma farm, Para State, Brazil

Growth stage	N dose kg ha^{-1}	N_2O fluxes ($mg\ N_2O\ m^{-2}$)	Emission factor (%)
SN2	0.25	20.7±1.5	6.38
SN3	0.77	77.2±30.9	7.95
JN2	15.4	4.5±3.2	0.60
MN2	24.0	5.9±0.7	0.50
MN3	51.0	6.2±0.7	0.24
MN4	69.0	6.0±1.1	0.21

The measured EF ranged from 0.21% to7.95% in the evaluated steps of oil palm production. Considering the plant life cycle, the seedlings production, juvenile and mature plantations represent 3.8%, 11.6% and 84.6% of total, respectively. So, we founded an EF from N fertilizer in oil palm production of 0.58%.

According to the IPCC (2006), 1% of the fertilizer applied in cropping systems is emitted to atmosphere. These results are consistent with other data from tropical sites where the N_2O emissions from fertilizer ranged from 0.01% to 4.9%, derived from different soils and source of N fertilizer, and some application rates far greater than those of the present studies (CRILL et al., 2000; METAY et al., 2007; STEUDLER et al., 2002; VELDKAMP; KELLER; NUÑES, 1998; WEITZ et al., 2001). Our results suggest that ammonium sulfate is an important source of N for growing of oil palm from the point of view of reducing N_2O emissions associated with the cultivation process.

4.3.2.2 Soil CO_2 fluxes in different stages of oil palm cultivation after fertilizer application

Carbon dioxide (CO_2) fluxes in the nursery (Figure 3A) ranged from 35 mg m^{-2} h^{-1} (SN1) to 210 mg m^{-2} h^{-1} (SN3) during the evaluated period and highest mean values were found on SN3 ($p<0.01$). The cumulative emission for the period evaluated was 86.61±19 kg C ha^{-1} on SN1, 95.56±8.64 kg C ha^{-1} on SN2 and 106.05±3.44 kg C ha^{-1} on SN3 and these results wasn't statistically different ($p<0.05$). In the juvenile stand (Figure 3B) the fluxes ranged from 24.15 to 131.51 mg m^{-2} h^{-1} on JN1 and 27.26 and 90.61 mg m^{-2} h^{-1} on JN2, but we didn't found difference ($p<0.01$) between the treatments on the cumulative emissions to the evaluated period (58.79±6.21 kg C ha^{-1} in JN1 and 61.84±10.22 kg C ha^{-1} in JN2).

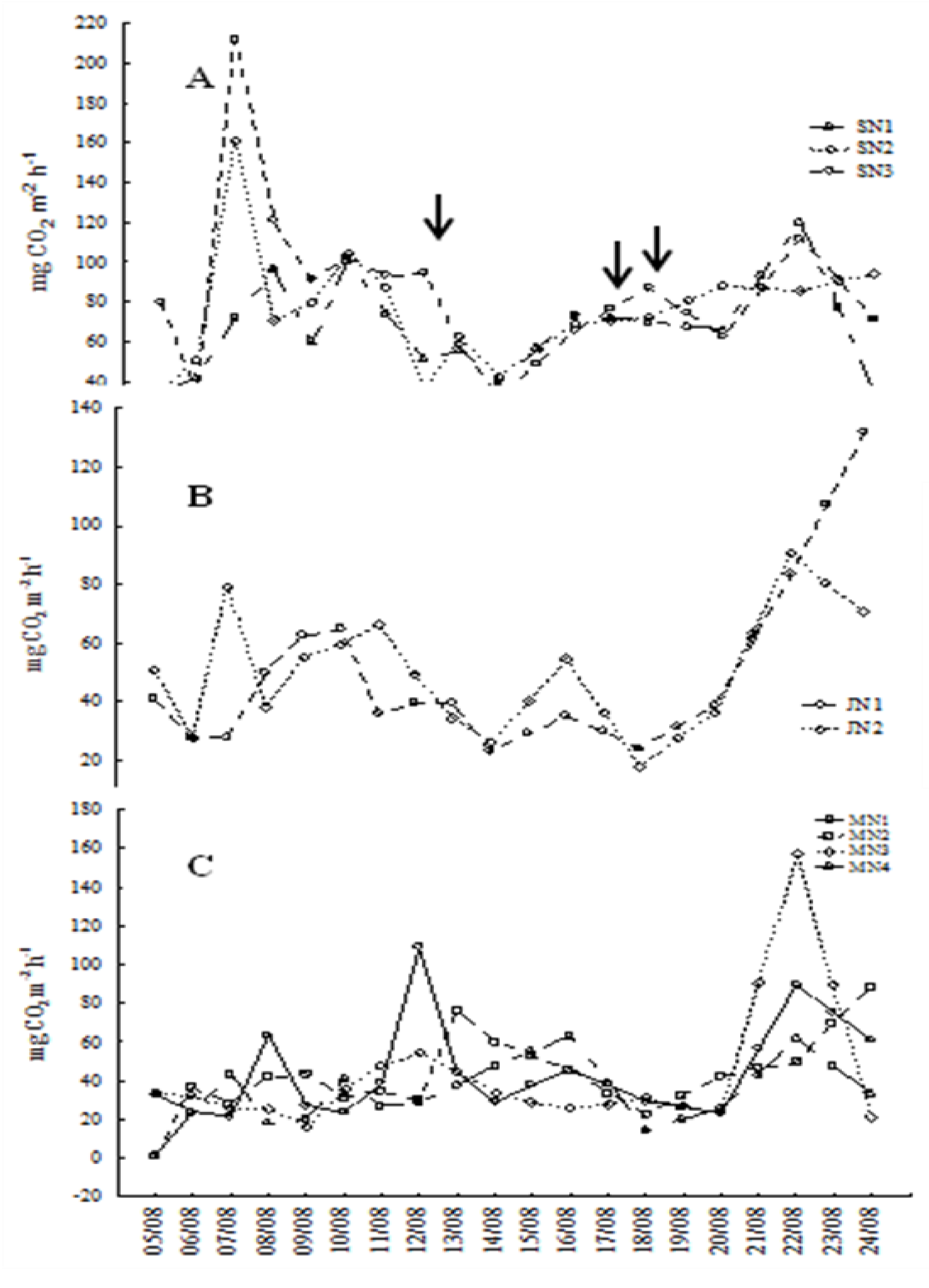

Figure 3 - Carbon dioxide (CO_2) fluxes from the substrate (seedlings production) and soil (juvenile and mature stands) after fertilizer application in Agropalma farm, Pará State, Brazil. The values represent the mean (n=3) and ↓ represent the occurrence of rainfall during the period of evaluation

In the mature stand (Figure 3C) the CO_2 fluxes showed variations between the studied period (1.39 to 157.60 mg CO_2 m^{-2} h^{-1}), but we didn't found difference in the accumulated emissions for the treatments evaluated ($p<0.01$). The cumulative values were 54.58±1.33 kg C ha^{-1} (MN1), 54.03±6.54 kg C ha^{-1} (MN2), 55.41±16.82 kg C ha^{-1} (MN3) and 45.55±5.34 kg C ha^{-1} (MN4).

The soil CO_2 emissions due the N fertilization were higher in the seedlings production than in juvenile and mature stands, and this result can be attributed to respiration rates from substrate (HUANG et al., 2004). Although there are interactions between the CO_2 fluxes and the input of N via mineral fertilizers, soil water availability is the most important factor to determining the CO_2 emissions rates (FERNANDES, 2008). The non-influence on CO_2 emissions as a consequence of N fertilization has been reported in other studies (ADVIENTO-BORBE et al., 2007; ELLERT; JANZEN, 2008; SÁNCHEZ-MARTÍN et al., 2008; SIGNOR, 2010).

4.3.2.3 Soil CH_4 fluxes in different stages of oil palm cultivation after fertilizer application

We found soil methane (CH_4) fluxes in the nursery (Figure 4A) ranging from -62 µg m^{-2} h^{-1} (SN3) to 82 µg m^{-2} h^{-1} (SN2), and the cumulative emission for the period evaluated was higher ($p<0.01$) in SN1 (0.106±0.029 kg C ha^{-1}) than in SN2 (0.046±0.006 kg C ha^{-1}) and SN3 (0.058±0.007 kg C ha^{-1}). The positive CH_4 emissions were observed because we added 8 mm of water into the chamber to simulate the irrigation every day after taken the GHGs samples.

The soil CH_4 fluxes in juvenile stands (Figure 4B) ranged from -59.51 µg m^{-2} h^{-1} (JN1) to 87.67 µg m^{-2} h^{-1} (JN2) and the cumulative emissions was higher ($p<0.01$) in JN2 (0.116±0.025 kg C ha^{-1}) than in JN1 (0.05±0.016 kg C ha^{-1}). We found fluxes in mature stands (Figure 4C) ranging from -67.60 µg m^{-2} h^{-1} (MN3) to 99.19 µg m^{-2} h^{-1} (MN2). The cumulative emissions were lower in MN3 (0.010±0.03 kg C ha^{-1}) than in the others treatments (0.106±0.23 kg C ha^{-1} in MN2, 0.098±0.005 kg C ha^{-1} in MN1 and 0.078±0.017 kg C ha^{-1} in MN4).

The cumulative CH_4 emissions reported in our results was positive for the evaluated period, agreeing with others studies that reported reductions in CH_4 consumption with N fertilization (MOSIER; DELGADO, 1997; STEUDLER, 1989). According to Flessa and Ruser (2002), weekly measurements are sufficient to provide reliable estimates of the CH_4 fluxes. The variability of CH_4 fluxes reported in this study not seems to be clearly dependent on rainfall, in agreement with results reported by Metay et al. (2007).

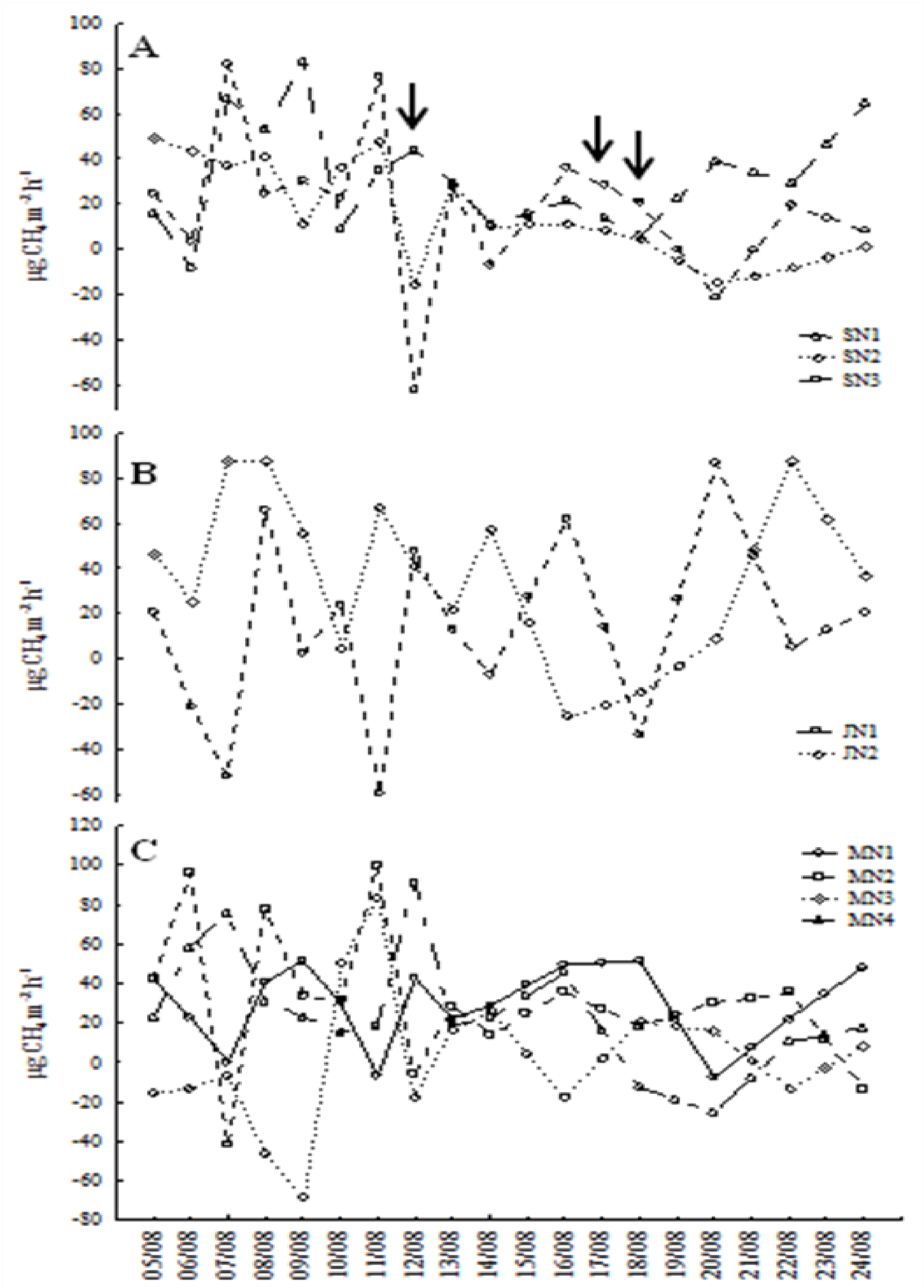

Figure 4 - Methane (CH_4) fluxes from the substrate (seedlings production) and soil (juvenile and mature stand) after fertilizer application in Agropalma farm, Pará State, Brazil. The values represent the mean (n=3) and ↓ represent the occurrence of rainfall during the period of evaluation

The Oxisol studied has good draining properties; consequently the methanogenesis (a mechanism responsible for CH_4 production in flooded soils) is not supposed to occur frequently in the oil palm cultivation at Amazon region. So, CH_4 emissions are therefore low even in the experiment of nursery.

4.3.3 Soil GHGs fluxes in the frond piles

The results of soil GHGs emissions achieved in frond piles are shown in Figure 5. To assess the magnitude of GHG emissions from the crop residue decomposition we compared the results with those obtained in MN1, control treatment installed in the inter-row at site 2 without fertilizer application or frond deposition after harvesting operation.

The Soil N_2O fluxes in frond piles ranged from 7.56 µg m^{-2} h^{-1} to 43.13 µg m^{-2} h^{-1} during the evaluated period. The mean for 10 consecutive days of measurement was 22.12±13.06 µg m^{-2} h^{-1}. This mean value were higher ($p<0.01$) than mean value for the same period in MN1 (6.92±3.91 µg m^{-2} h^{-1}). These results are agreeing with results obtained by Escobar et al. (2010) in study determining the N_2O emissions from soybean crop residues in no-tillage system. Other authors have reported similar effects of crop residues on soil emissions under field conditions (GOMES et al., 2009; GREGORICH et al., 2005; ROCHETE et al., 2004). The addition of fresh residues promotes the more intense and short-lived increases in N_2O emissions. In addition, the deposition and maintenance of crop residues on the soil surface lead to conditions suitable for denitrification due to the enhancement of water storage and C supply (GOMES et al., 2009).

We found CO_2 fluxes ranging from 46.17 mg m^{-2} h^{-1} to 109.88 mg m^{-2} h^{-1} and the mean for the evaluated period was 83.46±21.35 mg m^{-2} h^{-1}. In MN1, the mean value for the evaluated period was 38.23±15.34 mg m^{-2} h^{-1}. The higher soil CO_2 emissions in frond piles suggest an increase in microbial metabolism acting on easily decomposable organic substrates, such as a death microbial biomass (GARCIA-MONTIEL, 2003). According to Potter et al. (1998) the soil heterotrophic respiration is controlled by several factors as temperature, soil moisture, litter substrate quality (N and lignin content) and soil texture. The soil and climate conditions observed in the study site promote the rapid decomposition of crop residue added on soil and consequently the release of CO_2 into the atmosphere.

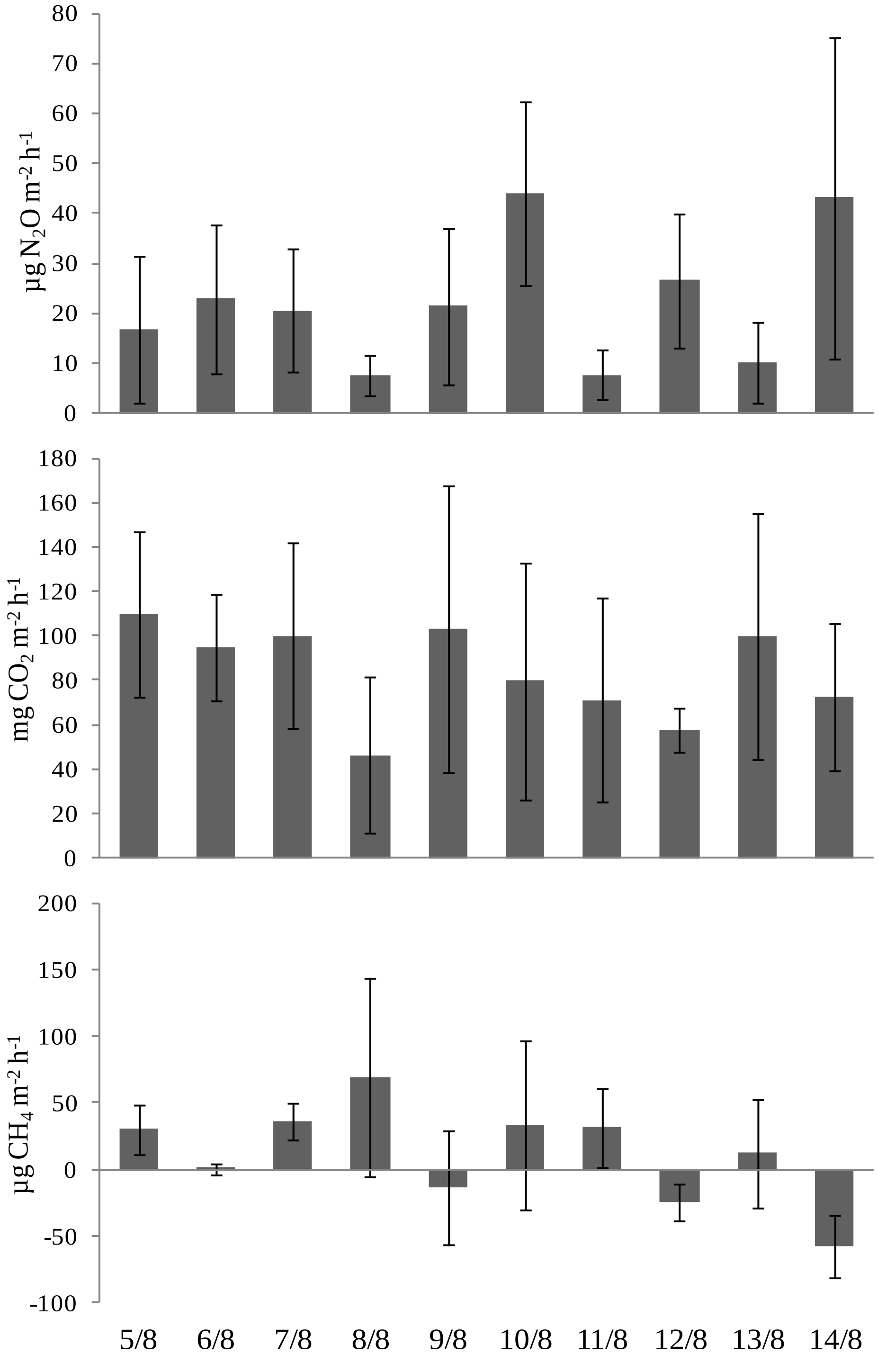

Figure 5 - Nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4) fluxes from the frond piles in the oil palm plantations in Agropalma farm, Pará State, Brazil. The values represent the mean (n=5) ± standard deviation during the studied period.

The CH_4 fluxes ranged from -24.51 to 68.77 µg m^{-2} h^{-1} and were positive for the most part of the studied period (Figure 7c). The mean value was 11.55±35.45 µg m^{-2} h^{-1} and showed no statistical difference between MN1 (27.44±17.69 µg m^{-2} h^{-1}) for the same period evaluated. According to Metay (2007), the first stages of cover residue decomposition are favorable to soil CH_4 emissions. The positive CH_4 fluxes is due to constant input of crop residue, since the harvesting operations in oil palm stands occur every 22 days and the cut leaves for bunches harvest are deposited on frond piles.

5 Conclusions

The seedlings production is the stage of oil palm cultivation that produces the greater GHGs emissions into the atmosphere due to use of nutshell and fiber in the substrate for production system.

The emission factor from fertilizer was higher in the nursery stage than in the juvenile and mature stands due the highest emissions of N_2O from interaction between substrate, N fertilizer applied and high humidity. However, considering the plant life cycle (26 years), the seedlings
production represent 3.8 % of the total, and the emission factor founded in this study was low than value proposed by IPCC.

Decomposition of frond piles contributed to GHGs emissions from soil to the atmosphere and our results suggest that this is an important compartment to be considered in oil palm plantations. The results founded here may be used to evaluate the total GHG emissions in the total life cycle of oil palm in the Amazon region.

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5 CARBON FOOTPRINT OF CRUDE PALM OIL: A BRAZILIAN AMAZON CASE STUDY

Abstract

As the oil palm has cited as a main raw material for biodiesel in Brazil it is important to measure the carbon footprint associated to crude oil palm (CPO) production in the Amazon region. So, the aim of this study was to determinate the GHG emissions in the agricultural phase, extraction and transportation of CPO to the refinery. The study was carried out at Agropalma farm, located at Para State (Amazon region). We considered the cropping stages (nursery, juvenile and mature phases), the extraction of CPO in a palm oil mill and the transportation of CPO to refinery allocated out-of-gate from the farm. Inventory data were collected through questionnaires applied in the farm. On-site visits were carried out for data verification. Resource exploitation and production of input materials were obtained through available background data. Specific data from nursery, plantations, palm oil mill and transportation were obtained on the farm. Using a yield of 21.2 t of fresh fruit bunches (FBB)/ ha and a production area of 39,000 ha, the results showed that the carbon (C) footprint to produce 1 kg of CPO is approximately 0.7 kg CO_2 eq. The main source of greenhouse (GHG) emissions was the management of palm oil mill effluent (POME), followed by the fuels combustion and use of fertilizers, pesticides and electricity. Considering the GHG emissions in the extraction process of CPO were 79,590 t CO_2 eq (75% of total emissions). The agricultural phase of CPO production resulted in emissions of 25,820 t CO_2 eq (24% of total emissions) and the fuel consumption during transport of CPO to the refinery represented only 1% of total emissions. Considering the entire production process of CPO we found the highest emissions associated to the management of effluent in the anaerobic lagoons, emitting a large amount of CH_4 to the atmosphere and representing a significant share of crude oil palm C footprint. The correct effluent management, the burning of CH_4 generated during anaerobic decomposition, and the use of effluent as electric energy are cited as alternatives for reduction of GHG emissions associated to palm oil production.

Keywords: Crude oil palm; Fresh fruit bunches; GHG; Oil palm plantations; Oil palm seedlings; Transportation of palm oil

5.1 Introduction

The palm oil and palm kernel oil represent 36% of the vegetable oil production in the world. Malaysia and Indonesia are responsible for 86% of the world's production (USDA, 2009). The largest producer in the American continent is Colombia with 62% of the continental production. In Brazil, more than 80% of the palm oil production is located in Pará State, in the Amazonian region (ISTA, 2009). It has about 70 million hectares of potential area for cultivation of oil palm in Brazilian Amazon (BARCELOS; SANTOS; RODRIGUES, 2002).

Brazil is described as a future leader in biodiesel production, due to its excellent soil and climate conditions, and vast land area. Diverse oilseed crops can be cultivated in Brazilian territory without promoting competition with food crops, and furthermore, without increasing deforestation (FRAZÃO et al., 2010). Palm oil is expected to contribute to the Green Biodiesel Programme and the biodiesel may be considered as an input in cleaner energy production (REIJINDERS; HUIJBREGTS, 2008).

The cultivation system based on bioenergy varies according to the length of plant life cycle, productivity, efficiency of energy conversion, demand for nutrients, inputs of carbon in the soil, losses of nitrogen, and other characteristics, all of them resultant from management operations. Such factors affect the magnitude of the components that contribute to the net fluxes of greenhouse gases (GHG) and losses of N (ADLER; DEL GROSSO, PARTON, 2007).

The urgent need for the reduction of GHG emissions to the atmosphere favors the acceptance of biofuels due to its low CO_2 emissions. An accurate assessment of the productive chain of raw material for biodiesel should be conducted under an environmental approach. So, the aim of this study was to quantify the carbon footprint in the Brazilian crude palm oil production. The GHG emissions derived from agricultural production (nursery and plantation), extraction (palm oil mill) and transportation of palm oil were quantified in a company located at Pará State, Amazon Region, Brazil.

5.2 Material and methods

5.2.1 Study area

The study was carried out at Agropalma (48°46’W, 2°27’S), a conventional commercial farm located in Para State, Brazil. The native vegetation in the region is classified as tropical rainforest. According to Köppen classification the climate is Afi (tropical monsoonal). The rainfall for 2009 was 2,705 mm year^{-1} and the mean temperature was 26.5^{o} C. The temperature ranged from22.6 ^{o} C to 33.4 ^{o} C and mean annual relative humidity was high throughout the year. The mean altitude of the region is 49 m and the soil was well drained with medium clay content (18-29%).

5.2.2 System description

The agricultural step to produce palm oil consists in the seedlings cultivation (nursery phase) and cultivation system for fresh fruit bunches (FFB) production (field crop phase). The industrial step consists in the extraction of crude palm oil (CPO). After that, the CPO is transported to refinery.

5.2.2.1 Agricultural phase

The first stage in the agricultural phase is the seedlings production. In prenursery, seeds sown in small polyethylene bags (0.5 L) are kept under the shade to protect them from direct sunlight until they are 3 months old. In the subsequent main nursery stage, the seedlings are planted in larger polyethylene bags (13 L) and grown without a protective shade until they are 15 months old and ready for planting in the plantation. Sprinkler systems are used to provide sufficient water in prenursery and nursery. The seedlings are supplied with nutrients fertilizer applications.

Oil palms from nursery are transferred to oil palm plantations when they are 15 months old. The palms are planted at a density of 143 palms/ ha on low and medium clay content soils. Before the palms are planted the soil is covered with a legume (*Pueraria phaseoloides*). The cover crop prevents erosion and fixes nitrogen from the atmosphere in their root nodules, especially during the stage when the palms are young. A circle with no vegetation is established around each oil palm, preventing against dispersion of weeds. The circle allows the herbicide application and easy access for harvesting and picking of loose fruits.

The fertilizers applied in the oil palm plantations are potassium chloride, ammonium sulphate, kieserite and rock phosphate. The herbicide glyphosate is used mainly to doing the circles around the plant. The insecticide acephate is used in a small quantity due to use of integrated pest management, where natural predators are used instead of pesticides.

The harvest operations are from 3 years old until 25 years old in oil palm plantations. Harvesting of ripe FFB is manually carried out every 21 days using a sickle mounted on an aluminum pole. Normally, two fronds beneath the fruit bunch are pruned before harvesting. The pruned fronds are placed in the field between the palm rows for mulching. Detached FFB are placed by the roadside, collected and disposed in dumpsters, and later taken by truck to a palm oil mill.

Replanting of oil palm is carried out when palms are 25 years old due to difficulty in harvesting tall palms and to low FFB yield. The palms are felled and left in the plantation as a nutrient source for replants.

5.2.2.2 Extraction of crude palm oil

In the palm oil mill, the FFB are transferred into the sterilizer. The fruits are sterilized (135 ^{o}C) under a pressure of 3 kg cm^{-2} for 60 min. This sterilization step loosens the individual fruits from the bunch and also deactivates the enzyme which causes the breakdown of the oil into free fatty acids (FFA).

The sterilized FFBs are sent to a thresher where the fruits are separated from the bunch. The empty fruit bunches (EFB) are sent back to the organic plantations for mulching as fertilizer substitute.

The fruits from the thresher are then sent to a digester where they are converted into a homogeneous oily mash by means of a mechanical stirring process. The digested mash is then pressed using a screw press to remove the major portion of the CPO. At this point, the CPO comprises a mixture of oil, water and fruit solids which are screened through a vibrating screen to remove as much solids as possible. The oil is then clarified in a continuous settling tank which decanted CPO is then passed through a centrifugal purifier to remove remaining solids and then sent to the vacuum dryer to remove moisture. The CPO is then pumped to storage tanks before it is sent off to the refining process.

The nuts with the pressed mesocarp fibers are separated at the fiber cyclone and then cracked to produce kernels and shells. The kernels are shipped to kernel crushing plants to be processed into crude palm kernel oil (CPKO), while the shell and pressed mesocarp fiber are used as boiler fuel.

The main solid waste from the milling process is EFB, pressed mesocarp fiber, shell and boiler ash, while the liquid waste is palm oil mill effluent (POME). The gaseous emissions are from the boiler stack and the effluent treatment ponds. All the waste from the palm oil extraction process is reused in the oil palm production (EFB, ashes, and POME) or palm oil mill (fiber and shell).

5.2.2.3 Transportation of CPO from palm oil mill to refinery

The CPO stored in tanks is sent by pipelines to the ferry boat docks and then is taken by ferry to the refinery located 200 km from the farm. Each ferry boat carries 1100 tons of CPO and travels for about 20 hours on the river course. Ferry boat transportation has economic advantages and operational security. Besides being cheaper due to geographical conditions of the palm oil mill, the CPO transportation by the waterway is easier than by road in the region of study.

5.2.3 Scope

This study evaluated the carbon footprint of palm oil production at Agropalma farm. Inventory data included the main steps in the palm oil supply chain: agricultural production of

FBB, extraction of CPO and transportation of CPO to a refinery. The period considered in this study was year of 2009 (January 1 to December 31). Details of the inventory are described below.

5.2.3.1 Agricultural production of FBB

Here we evaluated the GHG emissions related to seedlings production, planting and cultivation of juvenile and mature oil palm plantations. The study measured direct and indirect emissions derived from use of fossil, fertilizers (i.e. nitrogen, phosphorous and potassium) and pesticides in the production system.

5.2.3.2 Extraction of CPO

There was the preparation of GHG emissions inventories in the palm oil mill. The raw material (FBB) came from production systems under the operational control of Agropalma. In addition to direct and indirect GHG emissions from industrial processes, emissions related to transportation of FBB from the field to the palm oil mill were calculated.

5.2.3.3 CPO transportation

We calculated the direct and indirect GHG emissions from transportation of CPO by pipelines to the ferry boat docks and then until the refinery.

5.2.4 Sources of GHG included in the carbon footprint calculation

The GHG sources associated with the palm oil production, extraction and transportation are the use of fossil fuel, electricity, fertilizers, pesticides, organic and industrial residues, and treatment and disposal of POME.

5.2.5 Normative basis

This study was performed based on the main GHG protocols used in LCA studies listed below:

- Guidelines for National Greenhouse Gas Inventories (IPCC, 2006);
- Environmental management - Life cycle assessment: Principles and framework (ISO, 2006a);
- Environmental management - Life cycle assessment - Requirements and guidelines (ISO, 2006b);

- Publicly Available Specification (PAS) 2050. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services (PAS, 2008);
- Greenhouse gases – Part 1: Specification with guidance at the organization level for the quantification and reporting of greenhouse gas emissions and removals (ISO, 2006c);
- The Greenhouse Gas Protocol - A Corporate Accounting and Reporting Standard (WRI;WBCSD, 2004);
- Greenhouse Gas Protocol - Product Life Cycle Accounting & Reporting Standard (WRI; WBCSD 2010);
- Carbon Footprint of products - Part 1: Quantification (draft) (ISO, 2010).

5.2.6 GHG emissions

The company had a total area of 107,000 hectares occupied with native vegetation (59.8 %), with oil palm plantation (36.4 %) and with infrastructure (3.8 %). The input data used to calculate the GHG emissions are listed on Table 1. We grouped the data into the following production stages: agricultural, industry and transportation.

Table 1 – Fertilizers, pesticides, fossil fuel and energy inputs and waste generated in the palm oil production (2009) by Agropalma farm, Pará State, Brazil

GHG Source	Production stage		
	Agricultural	Industrial	Transportation
Fertilizers (t)			
Nitrogen (N)	362	-	-
Phosphate (P)	256	-	-
Potassium (K)	3,634	-	-
Pesticides (L)			
Gliphosate	52,745	-	-
Acephate	6,678	-	-
Fossil fuel (L)[a]			
Diesel	3,708,216	854,458	365,909
Gasoline	124,834	64,476	-
Energy			
Electricity energy (kw/h)	-	1,685,636	-
Fibers (t)	-	80,064	-
Residue			
POME (m^3)	-	693,193	-

[a] It was computed the quantities of biodiesel and ethanol mixed in diesel and gasoline, respectively.

5.2.7 Emission factors

Table 2 presents the emission factors (EF) used in this study. Indirect emissions are related to production and transportation of the products used in the farm (out of the gate). Direct emissions occur directly on the farm (within the gate). The EF measured in this study (Chapter 4) was used to calculate the direct emissions derived from fertilizer application.

Table 2 – Emission factors used to calculate the carbon footprint in the oil palm production (2009) by Agropalma farm, Pará State, Brazil

Emission factor	Type of emission	Unit	Value	Reference
Fuel				
Diesel	Indirect	kg CO_2/ L diesel	0.43	ECOINVENT, 2010
	Direct		2.68	IPCC, 2006
Gasoline	Indirect	kg CO_2/ L gasoline	0.52	MACEDO et al., 2008
	Direct		2.33	IPCC, 2006
Ethanol	Indirect	kg CO_2/ L ethanol	0.48	MACEDO et al., 2008
	Direct		0.01	IPCC, 2006
Biodiesel	Indirect	kg CO_2/ L biodiesel	0.39	ALMEIDA et al., 2008
	Direct		0.01	IPCC, 2006
Fertilizers				
Nitrogen	Direct	kg N_2O/ kg N	0.0058	Measured[a]
Nitrogen	Indirect	kg CO_2/ kg N	3.14	WEST; MARLAND, 2002
Phosphate	Indirect	kg CO_2/ kg P	0.61	WEST; MARLAND, 2002
Potassium	Indirect	kg CO_2/ kg K	0.44	WEST; MARLAND, 2002
Electricity				
2009 (medium value)	Indirect	ton CO_2/ Megawatt/h	0.0245	MCT, 2010
Herbicide				
Glyphosate	Indirect	kg CO_2 eq/kg A.I.[b]	15.95	ECOINVENT, 2010
Insecticide				
Organophosphate	Indirect	kg CO_2 eq/kg A.I.	7.68	ECOINVENT, 2010
Effluent (POME)				
Anaerobic ponds (> 2 m deep)	Direct	kg CO_2 eq/kg DQO	5.00	ECOINVENT, 2010

[a] Calculated EF in the present study

[b] A.I. = active ingredient

5.2.8 Methodology to calculating the GHG emissions

2.8.1 Fossil fuel

We considered the production and transportation of the fossil fuels to calculate the indirect emissions, and the combustion to calculated direct emissions. The percentage of biodiesel and ethanol added to diesel and gasoline were considered to obtain the total of GHG emissions. The equations 1 and 2 were used to obtain the indirect and direct emissions, respectively.

$$F_{FUEL1} = Tot \times EF \qquad (1)$$

Where,

F_{FUEL1} = emission (CO_2 eq) from production and transportation of fuel;

Tot = quantity of fuel used (L);

EF = emission factor to each fuel from indirect emission (Table 2).

$$F_{FUEL2} = Tot \times EF \qquad (2)$$

Where,

F_{FUEL2} = emission (CO_2 eq) from combustion of fuel;

Tot = quantity of fuel used (L);

EF = emission factor to each fuel from direct emission (Table 2).

5.2.8.2 Fertilizers

The GHG emissions due to N fertilizers application on the soil were calculated considering the N_2O emissions per kg of N used. Also the indirect emissions of the main nutrients present in the formulations of synthetic fertilizer used (N, P and K) were accounted. The equation 3 was used to obtain the indirect emissions of synthetic fertilizer.

$$F_{SN1} = A_{TOT} \times Tot \times \%_{EL} \times EF \qquad (3)$$

Where,

F_{SN1} = emission (CO_2 eq) from production of synthetic fertilizer;

A_{TOT} = total oil palm area (ha);

Tot = Quantity of fertilizer applied (kg fertilizer/ ha);

$\%_{EL}$ = % of the chemical element in the fertilizer formulation (N, P and K);
EF = emission factor from indirect emissions of synthetic fertilizer (Table 2).

The equation 4 was used to obtain the direct emissions from soil due to N fertilizer application.

$$F_{SN2} = A_{TOT} \text{ x } N_{FERT} \text{ x } EF \quad (4)$$

Where,
F_{SN1} = emission (CO_2 eq) from N fertilizer application;
A_{TOT} = total oil palm area (ha);
N_{FERT} = Quantity of N applied as N fertilizer (kg N/ ha);
EF = emission factor from direct emissions of N fertilizer (Table 2).

5.2.8.3 Pesticides

Emissions from pesticides were calculated using specific emission factors to each pesticide applied (Ecoinvent, 2010). The equation 5 was used to obtain de indirect GHG emissions from pesticides.

$$F_{PEST} = A_{TOT} \text{ x } Tot \text{ x } \%_{IA} \text{ x } EF \quad (5)$$

Where,
F_{PEST} = emission (CO_2 eq) from production and transportation of pesticides;
A_{TOT} = total oil palm area (ha);
Tot = Quantity of pesticide applied (kg/ ha);
$\%_{AI}$ = % active ingredient (A.I.) on each pesticide used (kg A.I./ L pesticide);
EF = emission factor from each pesticide (table 2).

5.2.8.4 Electricity

The emission from electricity use were calculated based on the total of energy (MW/ h) used during 2009. The equation 6 was applied to obtain the emission from electricity use.

$$F_{ENE} = Tot \text{ x } EF \quad (6)$$

Where,

F_{ENE} = emission (CO_2 eq) from electricity use;

Tot = total electrical energy (MW/ h) input during the year of 2009;

EF = mean emission factor for 2009 (Table 2).

5.2.8.5 Effluent

The GHG emissions from palm oil mill effluents (POME) were calculated using equations and EF recommended by IPCC (2006). The equation 7 and 8 were applied to obtain the emissions from effluent management.

$$F_{EFLU} = ((TOW - S) \times EF_{EFL} - R) \quad (7)$$

Where,

F_{EFLU} = CH_4 emissions from effluent management (kg CH_4/ year);

TOW = total degradable C in the effluent (kg COD/ year);

S = quantity of C removed as sludge (kg COD/ year);

EF_{EFL} = emission factor from effluent (kg CH_4/ kg COD);

R = quantity of CH_4 recovered (kg CH_4/ year).

$$EF_{EFL} = B \times MCF \quad (8)$$

Where,

B = maximum production capacity of CH_4 (kg CH_4/ kg de COD);

MCF = Correction factor to CH_4

5.2.9 Conversion of N_2O and CH_4 emissions into CO_2 equivalent

Conversion of N_2O and CH_4 to equivalent CO_2 is necessary since each GHG has a different global warming potential (GWP). N_2O fluxes have a GWP 298 times larger than CO_2, while CH_4 fluxes have a GWP 25 times larger than CO_2 (IPCC, 2006). So, the conversion of N_2O and CH_4 fluxes into equivalent CO_2 is presented in equations 9 and 10.

$$CO_2 \text{ eq } (N_2O) = N_2O \text{ emission} * 298 \quad (9)$$

$$CO_2 \text{ eq } (CH_4) = CH_4 \text{ emission} * 25 \quad (10)$$

Where,

298 = global warming potential of N_2O in relation to CO_2;

25 = global warming potential of CH_4 in relation to CO_2.

5.2.10 Emissions allocation

Based on the guidelines of ISO 14044, the approach to allocating emissions followed the criteria below:

- When possible, the allocation of emissions was avoided by analyzing separately the production systems of the products from the same area;
- When was not possible to analyze separately the inputs used to produce CPO and CPKO we used the allocation criteria based on the produced oil weight and also for the generated revenue in the marketing of these products.

5.3 Results and discussion

5.3.1 Total GHG emissions

The total GHG emissions resulting from the production, extraction and transportation of CPO was 106,515 t CO_2 eq (Figure 1). The main source of GHG was the management of POME, followed by the fuel combustion, fertilizer application, pesticides and electricity. Choo et al (2011) founded similar results in a study carried out in Malaysia where the highest emissions were associated to POME without biogas capture.

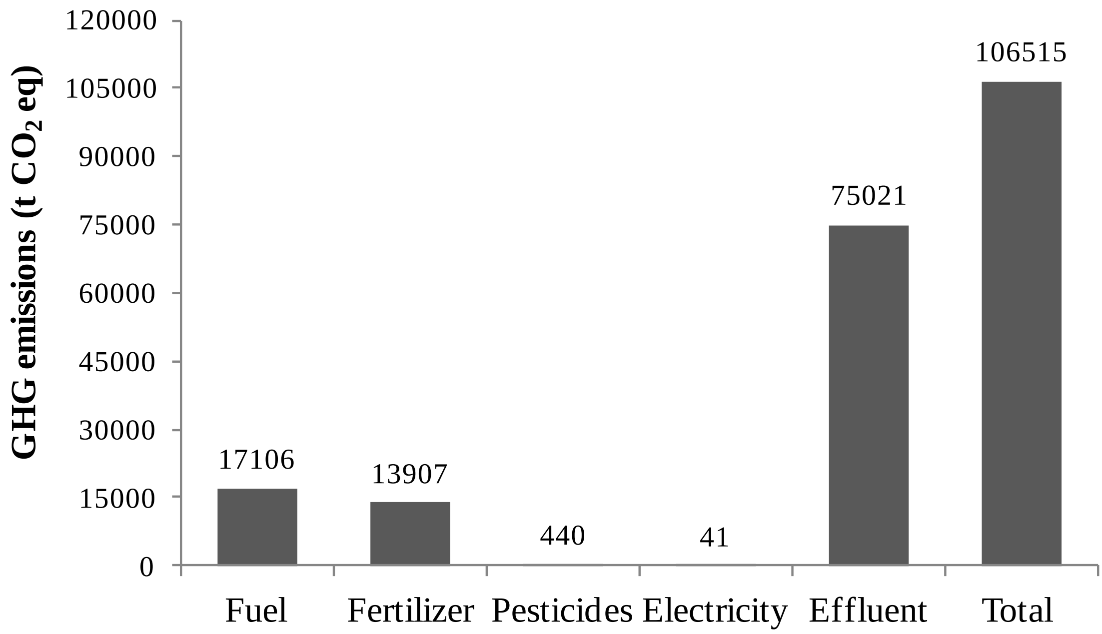

Figure 1 - Total GHG emissions (t CO_2 eq) in 2009 from crude oil palm production in Agropalma, Pará State, Brazil

The highest GHG amount emitted from POME is related to CH_4 emissions in anaerobic ponds. The anaerobic ponds located in Agropalma farm have more than two meters of depth and the POME has a large amount of C available and, consequently, high COD (chemical oxygen demand). In this study, the COD had an average of 21.64 kg m^{-3} which is considered a high value by the standards of the Intergovernmental Panel on Climate Change (IPCC, 2006) for effluents generated in the vegetable oil industry.

The fuel combustion, the second largest source of GHG emissions, is related to agricultural operations, FBB transportation, extraction and transportation of CPO to a refinery. According to results previously reported (REIJINDERS; HUJIBREGTS, 2008; WICKE et al., 2008), GHG emissions associated to use of diesel in plantations, internal transport and machinery varies from 180 until 404 kg CO_2 eq ha^{-1} yr^{-1}. If the FBB yield is set at 21.2 t ha^{-1}, the total emissions would be between 8.5 and 19.1 kg CO_2 eq/ t FBB wich is lower than the 24.68 kg CO_2 eq/ t FBB founded in this study. The higher value reported here can be attributed to the inclusion of also transport of CPO to the refinery.

The fertilizers applied in the seedlings production and oil palm plantations resulted in the emission of 13,907 t CO_2 eq. The oil palm cultivation in Agropalma farm uses small amount of pesticides, resulting in low GHG emissions due to use of these products (Figure 1). In 2009, the pesticides glyphosate (herbicide) and organophosphate (insecticide) were used.

We reported GHG emissions derived from fertilizer and pesticides application lower than results previously found in Malaysia (CHOO et al., 2011; WICKE et al., 2008) and Brazil (SOUZA et al., 2010).

The electricity is derived from hydroelectric which is considered a clean energy source. So, the GHG emissions were low (41 t CO_2 eq), in agreement with the results founded by Souza et al (2010). The use of biomass in the boilers (shell and pressed mesocarp) also contributed to the reduced use of electricity.

Figure 2 shows the percentage of GHG emissions in the agricultural production, extraction and transportation of CPO produced by Agropalma Group in 2009. The high CH_4 emissions in anaerobic ponds, when converted into CO_2 eq represented 70.4% of the total emissions. The fuel combustion, especially fossil fuels, contributed with 16.1% of the total emissions. The use of fertilizers contributed with 13.1%, while pesticides and electricity use represented less than 1% of the total GHG emissions.

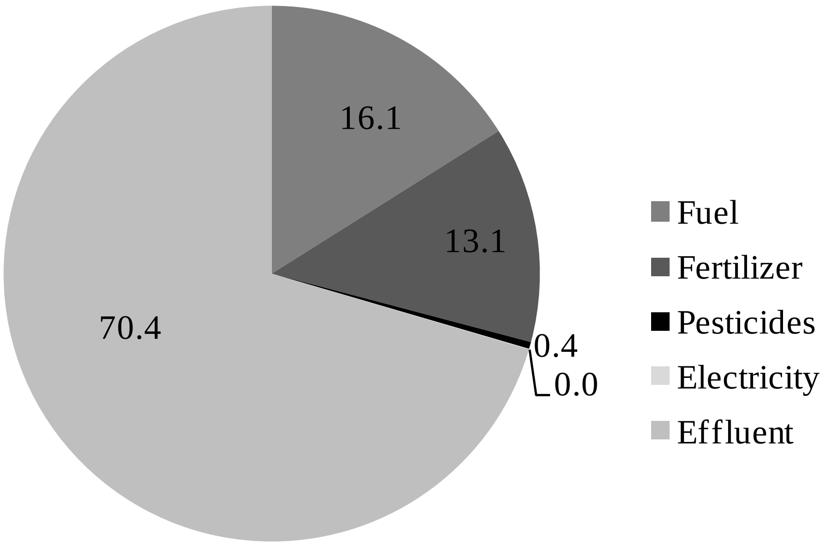

Figure 2 - Proportion of the total GHG emissions in 2009 from crude oil palm production in Agropalma, Pará State, Brazil

5.3.2 GHG emissions in the different steps of CPO production

When GHG emissions were subdivided into different phases of CPO production, we observed that the extraction process was the largest source of GHG, emitting 79,590 t CO_2 eq (75% of total emissions) (Figure 3). The management of POME in anaerobic ponds represented 94.2% of the GHG emissions on CPO production, while the fuel combustion and electricity use accounted 5.7 and 0.1%, respectively. Other studies carried out in Malaysia also reported the highest emissions associated to POME production (CHOO et al., 2011), and their results showed reduction of GHG emissions from oil palm mill when the biogas (CH_4) was captured from POME. According to Reijinders and Huijibregts (2008), when a control efficiency of 95% is assumed, for the treatment of POME this would correspond to an emission reduction of about 0.15 ton CO2 eq/ t CPO produced.

The agricultural phase (seedling production, juvenile and mature plantations) resulted in 24% of total GHG emissions (25,820 t CO_2 eq). The fuel use of fertilizers was the largest source of GHG emissions (54%), followed by the fuel combustion (44%) and pesticide use (2%). The fuel combustion during the CPO transportation from the palm oil mill to the refinery represented 1% of the total GHG emissions.

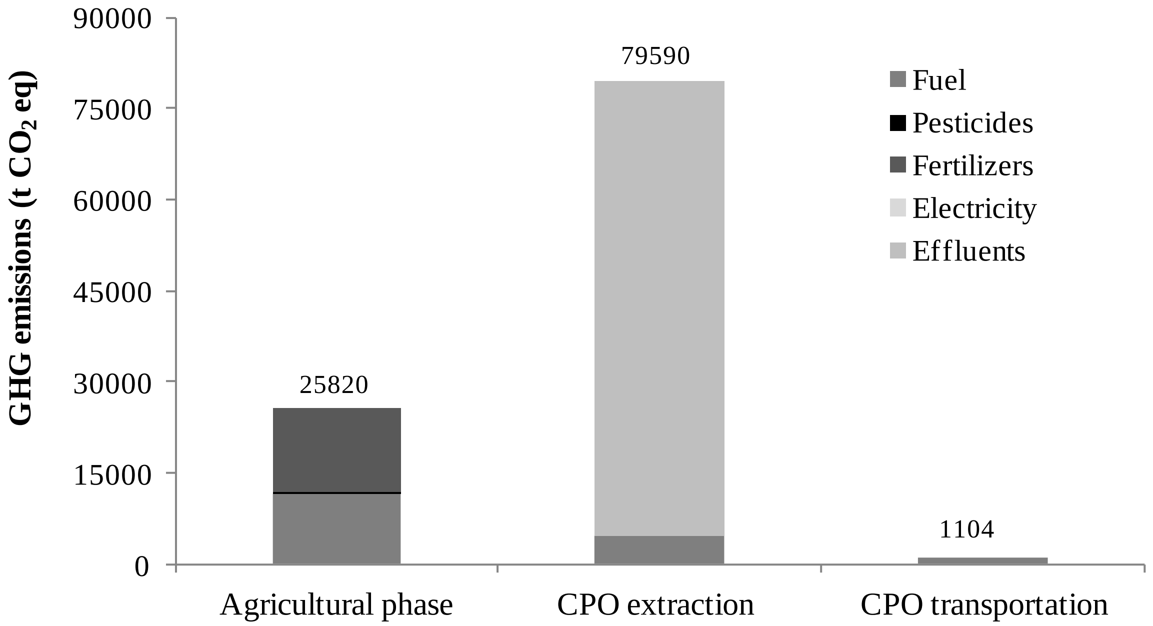

Figure 3 - GHG emissions (t CO_2 eq) in the agricultural step, extraction and transportation of CPO produced in Agropalma (2009), Pará State, Brazil

5.3.3 GHG emissions in the agricultural phase of FBB production

The agricultural step contributed to emissions of 25,820 t CO_2 eq in 2009. We observed that 88% of emissions are related to mature crop stage (Figure 4). The step of seedlings production in the nursery and juvenile stands of oil palm represented 1 and 11%, respectively.

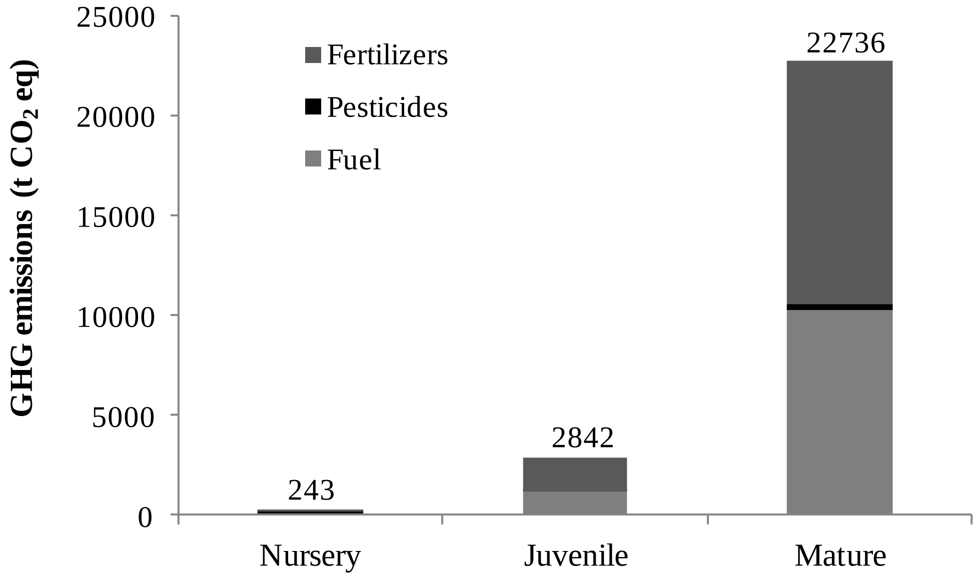

Figure 4 - GHG emissions (t CO_2 eq) in the agricultural phase of CPO produced in Agropalma (2009), Pará State, Brazil

The main GHG emissions in juvenile and mature stands of oil palm were associated to use of fuels, followed by fertilizer and pesticide application. The results founded here are in agreement with other studies analyzing the sources of GHG in agricultural phase of crop production (HARDTER; CHOW; HOCK, 1997; REIJINDERS; HUJIBREGTS, 2008).

5.3.4 Carbon footprint of CPO

Although the total GHG emissions derived from corporate inventories are used as environmental indicators, there are other ways to evaluating the emissions of a particular production process. Several studies have reported the farm GHG considering the production area or the quantity produced (CHOO et al, 2011; REIJINDERS; HUJIBREGTS, 2008; SOUZA et al., 2010).

When considering the production area, it is possible to have a magnitude of GHG emissions from an agricultural area. However, when performing this type of approach, the results are related to fluctuations in productivity which can result from many factors such as climatic variations and pests. So, the best way to expressing GHG emissions in the CPO production are based on the oil palm production in their respective agricultural year. The evaluation of GHG emitted per kg of CPO produced is known as carbon footprint.

As cited above, the palm oil mill extraction provides two final products, CPO and CKPO. Thus, it is necessary to allocate the GHG emissions between both types of oil. In this study we performed the allocation of GHG emissions considering the mass of CPO and

CKPO produced and the economic value in the international market. Table 3 presents some indicators used to allocate the GHG emissions.

Table 3 – Production (t), average price per t (R$) economic value (R$) of CPO and CKPO from Agropalma (2009), Pará State, Brazil

Product	Production (t)	Average price/ t (R$)	Economic value (R$)
CPO	130,210.84	644.07	83,864,790.14
CKPO	11,205.51	700.00	7,875,358.44

The carbon footprint calculated was 0.756 and 0.675 kg CO_2 eq/ kg CPO to the allocation performed by mass produced and economic value, respectively. The two values were similar due to similarity in the price of the two oils in 2009. So, the allocation system for economic value is less recommended, since prices can vary significantly in time.

As cited above, 70% of the total GHG emissions are associated to management of POME in anaerobic ponds. So, the C footprint of CPO may be decreased through the capture of CH_4 from POME (CHOO et al, 2011).

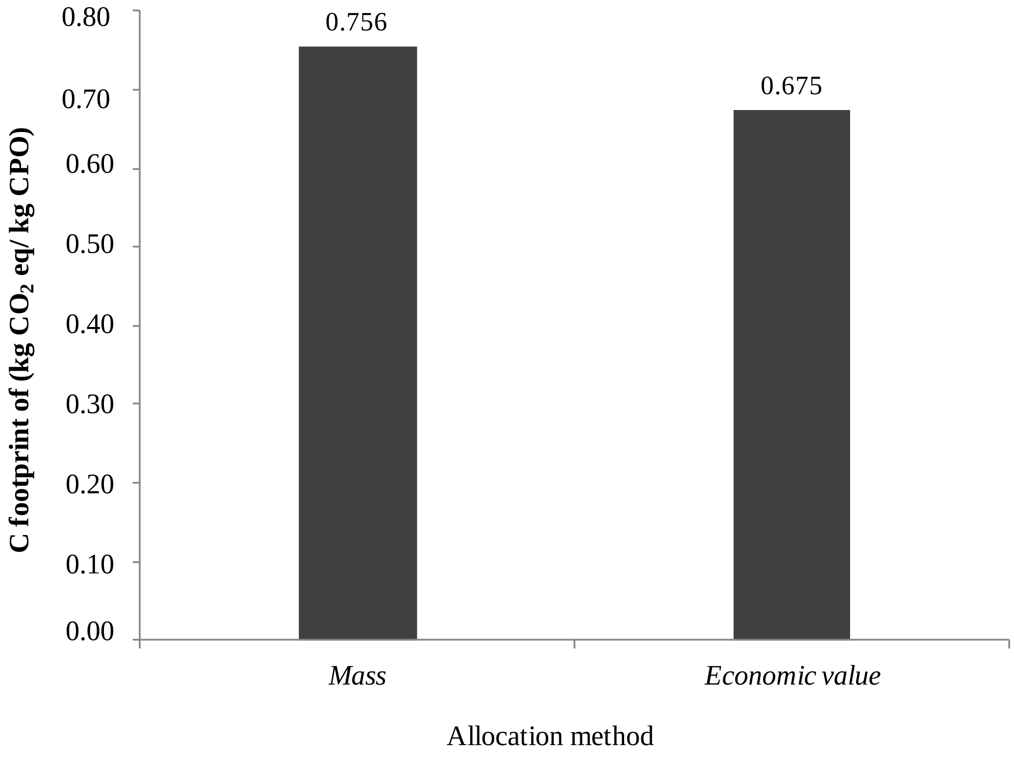

Figure 5 - Carbon footprint of CPO produced in Agropalma (2009), Pará State, Brazil

As presented in previous sections, CPO supply chain results in GHG emissions into the atmosphere. However, the oil palm plantations and the native vegetation capture CO_2 through photosynthesis and keep stored in plant tissues. The quantification of the CO_2 stored on vegetation is important since deforestation is not allowed to introduce oil palm plantations in the Brazilian Amazon region (LOPES; STEIDLER NETO, 2011). So, during the measurements of GHG emissions we considered that commercial farms have a constant CO_2 stored on their native vegetation.

Several published studies have estimated the amount of CO_2 or carbon (C) stored in the oil palm plantations in Brazil (MRD, 2007; RAO et al. 2001; SILVA et al.; 2000) and other countries (MURDIYARSO et al., 2002; PALM et al., 2000; REIJNDERS; HUIJBREGTS, 2008; YUSOFF; HANSEN, 2007).

The C stored in the oil palm production areas at Agropalma farm was calculated using the estimates performed by Silva et al. (2000) in the same study region. According to these authors, the oil palm stands stock an average of 41.43 t C ha^{-1} when it reaches 12 years old (mean age of the oil palm plant). Considering a cultivated area of 39,000 hectares, we obtained a CO_2 accumulation of 5,924 t CO_2 (Table 4). As palm trees have a mean life of 25 years, the Agropalma stocks 237,000 t CO_2 in oil palm plantations. The annual CO_2 accumulated is twice the total GHG emissions (CO_2 eq) from Agropalma in 2009. A large part of CO_2 stored in the palm plantations cannot be considered as immobilized because it will be emitted to the atmosphere through the decomposition of organic material. The plant material that remains on site after the renewal of stands is exposed to decomposition, releasing CO_2 to the atmosphere (GREGORICH et al., 2005)

Approximately 60% of the Agropalma farm area (64,000 hectares) is maintained with native vegetation classified as Tropical rain forest and characterized by legal reserve and permanent preservation areas. According to estimates made by the Project RADAMBRASIL (Vol. 5) and cited in the National Communication (2004), each hectare of Tropical rain forest in the study region stocks from 102.32 to 140.86 t C per hectare. So, it is estimated that the Agropalma farm maintains stored from 24 to 33 Mt CO_2 in the native area (Table 4).

Table 4 - C and CO_2 stored in oil palm stands and native vegetation in Agropalma farm (2009), Pará State, Brazil

Land use	C stocks ha^{-1}	Area	Total C stocks	Total CO_2 stocks
	T	ha	Mt	Mt
Oil palm	41.43[a]	39,000	1.6	5.9
Native vegetation	102.32 -140.86[b]	64,000	6.5 - 9.0	24.0 - 33.01

[a,b] Source: Silva et al. (2004) and National Communication (2004)

As oil palm plantations are increasing in the Amazon region, it has been suggested the use of degraded pasture areas and lands that have been previously deforested (DA COSTA, 2004). According to Reijinders and Huijibregts (2008), the oil palm cultivation in degraded lands can reduce the GHG emissions up to 7 t CO_2 eq/ t CPO produced. So, the maintenance of native vegetation can provide environmental benefits to oil palm commercial farms.

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5.4 Final considerations

The production of palm oil requires amounts of fertilizers and pesticides similar to other crop systems in Brazil. The N application is reduced due to legume nitrogen fixing cultivated in the inter-row of oil palm plantation. However, during the agricultural phase the largest source of GHG emissions is due to use of fertilizers. When the entire production process is considered, including transportation and residues, effluent management in anaerobic ponds is the main source of CH_4 emissions to the atmosphere, representing a significant portion of the C footprint of CPO.

The C footprint associated to CPO production was about 0.7 kg CO_2/ kg CPO and 70% of the GHG emissions are associated to management of POME in anaerobic ponds. So, the effluent treatment in the anaerobic ponds and the combustion of CH_4 during anaerobic decomposition are cited as the main strategies to reduce the GHG emissions. During the burning of CH_4, CO_2 is generated, which is 25 times less potent in warming the atmosphere and therefore reduces the total emissions in the process. Futhermore, the CH4 burning may generate energy to be used in the process, reducing even more the environmental impact of oil palm production.

The maintenance of native vegetation and the use of degraded areas to introduce new oil palm plantations can promote environmental benefits to commercial farms in the Amazon region.

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6 FINAL CONSIDERATIONS

Different regions and cultivation systems of oil palm were selected in Brazil to perform this study. The first area is located at Pará State (Amazon region) where the climate is characterized by well distributed rainfall and constant mean temperatures throughout the year. The second area is located at Atlantic Forest region (Bahia State) where the dry season is well defined between May and August and temperatures fluctuate throughout the year. Soil C stocks, GHG emissions and C footprint in oil palm areas were evaluated.

The variability of soil C dynamics can be explained in several aspects listed below:

1) Temporal variations: as oil palm is a perennial plant with continuous growth, the litter and root material inputs contribute to the increase in soil C stocks over time;
2) Spatial variations: during the economic life of the plantation (about 25 years) the palm inter-rows receive less organic matter inputs than the region near the stem and the frond piles and, therefore, there is a different equilibrium of soil organic C contents over time;
3) Land use prior to the establishment of oil palm plantations: when the area derives from pasture, usually a decrease of soil organic C is seen; when it derives from forest, an increase of soil organic C over time can occur; when the agroforestry system derives from forest the soil organic C decreases over time.

This study also reported that GHG emissions are variable over time due to decomposition of plant material in frond piles and due to different doses of N fertilizers applied according to the stages of oil palm growth. The seedlings production phase contributed with most of the GHG emissions, although this step represents only 3.8% of the plant life cycle. In general, the GHG emission rates at different stages of oil palm production are not larger than by other agricultural crops.

Finally, the C footprint associated to oil palm production was determined as approximately 0.7 kg CO_2 per kg CPO produced and 70% of this value is associated to the effluent management in the anaerobic lagoons, which emit a large amount of CH_4 to the atmosphere. The correct treatment of the effluent can result in reductions of GHG emissions, and consequently, decrease the C footprint associated to oil palm production in the Amazon region.

The results of this study may be used to improve the analysis of GHG emission associated to the agricultural step of palm oil production in Brazil, introducing the evaluation of the derived biodiesel life cycle assessment.