GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2012), doi: 10.1111/j.1757-1707.2012.01196.x

Soil carbon stocks and changes after oil palm introduction in the Brazilian Amazon

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Abstract

As oil palm has been considered one of the most favorable oilseeds for biodiesel production in Brazil, it is important to understand how cultivation of this perennial crop will affect the dynamics of soil organic carbon (SOC) in the long term. The aim of this study was to evaluate the changes in soil C stocks after the conversion of forest and pasture into oil palm production in the Amazon Region. Soil samples were collected in March 2008 and September 2009 in five areas: native forest (NARF), pasture cultivated for 55 years (PAST), and oil palm cultivated for 4 (OP-4), 8 (OP-8) and 25 years (OP-25), respectively. Soils were sampled in March 2008 to evaluate the spatial variability of SOC and nitrogen (N) contents in relation to the spacing between trees. In September 2009, soils were sampled to evaluate the soil C stocks in the avenues (inter rows) and frond piles, and to compare the total C stocks with natural forest and pasture system. Soil C contents were 22–38% higher in the area nearest the oil palm base (0.6 m) than the average across the inter row (0–4.5 m from the tree), indicating that the increment in soil organic matter (SOM) must have been largely derived from root material. The soil C stocks under palm frond piles were 9–26% higher than in the inter rows, due to inputs of SOM by pruned palm fronds. The soil carbon stocks in oil palm areas, after adjustments for differences in bulk density and clay content across treatments, were 35–46% lower than pasture soil C stocks, but were 0–18% higher than 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, residue inputs on soil, soil organic C

Received 28 November 2011 and accepted 22 May 2012

Introduction

As biodiesel production expands in Brazil, with oil palm being targeted as the main feedstock, it is critical to understand the environmental consequences of the oil palm cultivation system. Oil palm (*Elaeis guineensis* Jacq.) is a perennial plant of African origin which came to Brazil in the sixteenth century and was originally established along the southern coast of Bahia. In addition to this state, other states in northern Brazil have favorable climate conditions for the cultivation of oil palm (Lopes & Steidle Neto, 2011). The state of Pará is now the largest producer of oil palm in Brazil, representing 80% of the cultivation area in the country, with an area of 60 000 hectares in 2008 (ISTA, 2009). Brazil is a smaller 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, including degraded and deforested land in the Brazilian Amazon region (Barcelos *et al.*, 2002; Nogueira, 2011).

One potential impact of biofuel cultivation is on stocks of soil organic carbon (SOC). Losses of SOC represent a net CO_2 emission to the atmosphere from the soil, whereas increases in SOC represent a removal of CO_2 and C sequestration. Since land use change and land management can greatly modify 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 *et al.*, 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

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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).

Soil organic carbon is more variable in space and time in oil palm plantations than in most other crops (Haron *et al*., 1998). Following planting, growth of legumes for ground cover 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 (Jourdan & Rey, 1997). The ground cover is suppressed by canopy closure at about 6–8 years. During the crop phase (from about 8–25 years), above-ground inputs are highly heterogeneous because fronds, which are frequently pruned to facilitate harvesting of fruit bunches, are piled between palm rows. Fruit bunches are generally removed using small tractors which can cause soil compaction in the inter rows (Brito, 2006). In this study, the areas comprising the inter rows and frond piles constitute about 80% and 20%, respectively, of the ground surface.

During the economic life of the plantation (about 25 years) the palm inter rows receive much lower organic matter inputs than the region near the plant and the frond piles; thus soil C stocks should develop distinct patterns of spatial variability over time. Given the difficulty of determining the SOC dynamics in the short term for such heterogeneous systems, we used a chronosequence approach to measure the soil C stocks in different ages of oil palm plantations, to infer possible SOC changes following oil palm establishment on land derived from pasture and forest.

Materials and methods

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, located in the city of Tailândia, Para State, Brazil (Fig. 1).

The native vegetation of the region is tropical rainforest. According to Koppen (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. Mean annual rainfall is 2,500 mm year^{-1} and mean temperature is 26.6 °C (Fig. 2). Mean temperature for the warmest and coolest months varies by less than 3 °C and mean annual relative humidity is 89%.

The mean altitude of the region is 49 m and the soil is well drained with medium clay content (18–29%) and classified as 'Latossolo Amarelo distrofico tipico' in the Brazilian System of Soil Classification, and an Oxisol (Xanthic Hapludox) in the USDA classification.

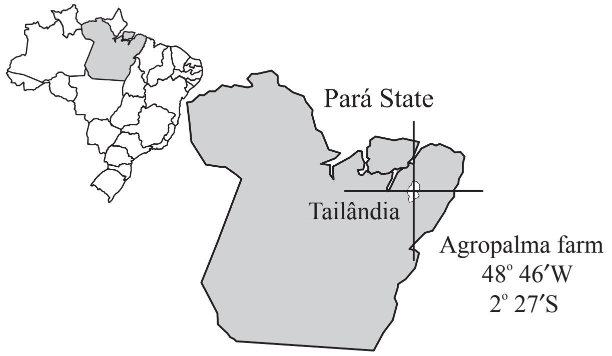

Fig. 1 Location map of the study area in the Agropalma Farm, Para State, Amazon region, Brazil.

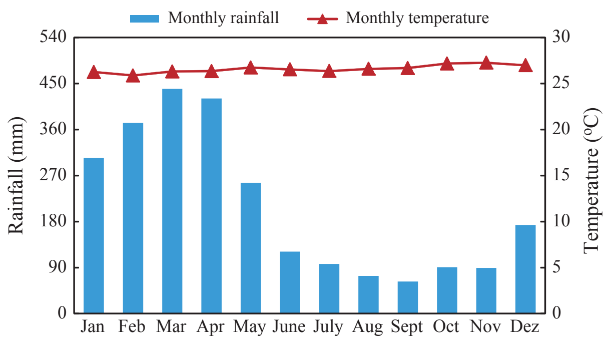

Fig. 2 Monthly rainfall and temperature distribution for the 25-year (1984–2009) in the Agropalma farm, Pará State, Amazon region, Brazil.

Conversion of native vegetation and pasture into oil palm cultivation

Before 1999, native forest areas on the farm were cleared annually for oil palm cultivation. However, for environmental reasons, the company decided to stop with deforestation and subsequently planted new areas on land previously occupied by pasture. According to Sommer *et al*. (2000), the land use change from forest to pasture in north-eastern Para began in the 1950s, so we consider that the pasture area was occupied for ca. 55 years with *Brachiaria humidicola*.

Five different sites (treatments) were considered in this study: native Amazon rainforest (NARF), permanent *Brachiaria* pasture (PAST), oil palm plantations derived from pasture cultivated for 4 (OP-4) and 8 years (OP-8), and oil palm derived from native rainforest, 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.

Soil sampling and analysis

Soils were sampled in March 2008 (wet season) and September 2009 (dry season). We picked 1 ha (100 × 100 m) area for each treatment and then selected five different sampling sites within

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

Area	Plantation age (y)	BD ($g\ cm^{-3}$)	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.

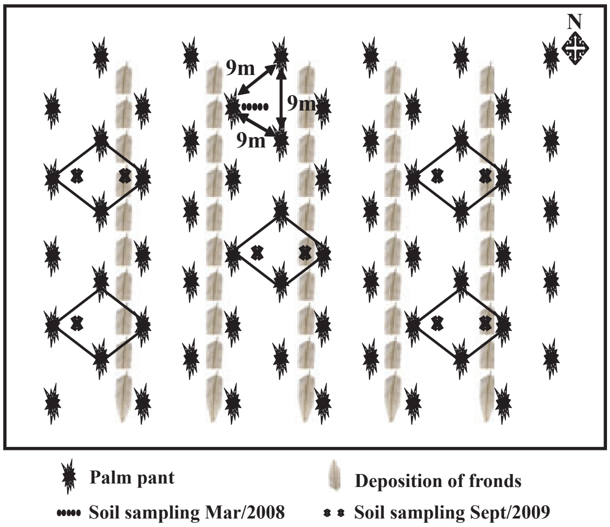

Fig. 3 Experimental design to soil sampling in oil palm plantations at Agropalma farm located in Para State, Amazon region, Brazil.

that, based on a completely randomized sampling (Fig. 3). We consider those as pseudo replicates, since they came from the same evaluated areas.

Palms on our study site were 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. To determine the spatial variability of soil carbon relative to the tree location, samples were collected in March 2008 from five profiles located at 0.6, 1.2, 2.5, 3.5, and 4.5 m away from the oil palm base. For each profile, samples were taken at 0–5, 5–10, 10–20, and 20–30 cm depth increments (Fig. 3).

The second soil sampling (September 2009) was to compare inter row and palm frond areas. For each treatment five profiles were sampled 3.5 m away from the oil palm base, defined as in the inter row location, and five profiles were taken under frond piles, for 0–5, 5–10, 10–20, and 20–30 cm depths increments (Fig. 3). In addition, soil samples were collected from five profiles, using the same depth increments, in both the NARF and PAST systems.

Samples were air-dried and sieved (2 mm) to remove stones and root fragments before analysis. Sub-samples were ground to a fine powder to pass through a 0.150 mm 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 bulk density (BD), samples of undisturbed areas were collected using a steel cylinder (5 × 5 cm). Samples from the 10–20 and 20–30 cm soil layers were taken from the middle part of the corresponding layer.

Soil C stock calculation and density and clay adjustments

For each soil layer, carbon stocks were calculated by multiplying the concentration of C ($g\ g^{-1}$) by BD ($kg\ m^{-3}$) and layer thickness (m). To account for the effect of differing BD (as a function of land use change and management) on soil C stock comparisons, the results were adjusted to an equivalent soil mass basis (Ellert & Bettany, 1996; Goidts *et al*., 2009). To calculate C stocks in an equivalent soil mass, the proportion of the deepest (20–30 cm) depth increment included in the SOC total was adjusted to yield the same soil mass in each treatment as the corresponding mass (0–30 cm) in native forest reference soil.

Although the sites included in our chronosequence approach were chosen to be as similar as possible in all attributes except for land use history, there were some differences in soil characteristics that influence SOC dynamics. Previous work with chronosequences in Brazil have shown that clay content is a key variable and that independent of land use, variability in SOC within a specific soil type tends to be linearly related to clay content (Feller *et al*., 1991; Moraes *et al*., 1996). Thus, for comparisons across treatments, we included a normalization factor for soil C stocks to account for differences in clay content between the treatment areas relative to the native reference condition (Eq. 1), as proposed by Moraes *et al*. (1996), i.e.,

$$C_{norm} = C_{mea} \times (clay_{ref}/clay_{mea}) \qquad (1)$$

where C_{norm} is the normalized SOC stock, $clay_{ref}$ is the mean clay content for each soil layer of the forest reference site, and C_{mea} and $clay_{mea}$ are the measured values, by soil layer, for the pasture or oil palm treatments.

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 compared using ANOVA to assess 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.

Results

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

Lateral gradients were found in the SOC levels across oil palm inter rows for all oil palm sites (OP-4, OP-8 and OP-25) (Table 2). In general, C and N contents were highest near the trunk, decreasing with increasing distance from the base of the plant.

At 0.6 m from the trunk, SOC contents were 17%, 30%, and 37% higher than average levels in OP-4, OP-8 and OP-25, respectively. Conversely, at the farthest distance from the trunk (3.5 m), SOC contents in OP-4, OP-8 and OP-25 were lower than average levels in the same areas about 3%, 6%, and 17%, respectively. Similar patterns as a function of distance from the tree base were observed for all soil depths.

The C/N ratio in the top soil (0–5 cm) ranged from 10.8 to 15.8 (Table 2). Mean values were 12.0, 13.5, and 13.3 in OP-4, OP-8 and OP-25, respectively.

Figure 4 shows that the difference in C and N levels was more pronounced in the region near the trunk, which has the highest concentration of roots and is constantly shaded.

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

In addition to quantifying the SOC gradient across the inter row, to estimate overall soil C stocks, we need to

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

		0–5 cm			5–10 cm			10–20 cm			20–30 cm		
		C	N	C/N	C	N	C/N	C	N	C/N	C	N	C/N
Areas	Dist. (m)	—% —			—% —			—% —			—% —		
OP-4[a]	0.6	1.17	0.10	12.0	1.11	0.09	12.2	1.05	0.09	11.7	0.72	0.07	10.1
	1.2	0.96	0.09	10.8	0.88	0.08	10.8	0.79	0.07	11.3	0.60	0.06	10.8
	2.5	1.03	0.09	11.5	0.92	0.08	10.9	0.70	0.06	11.7	0.55	0.05	10.9
	3.5	1.05	0.09	11.8	1.03	0.09	10.8	0.67	0.06	11.2	0.57	0.06	10.3
	4.5	1.05	0.08	13.7	0.98	0.10	10.0	0.67	0.05	13.4	0.64	0.06	10.8
	Mean	1.05	0.09	12.0	0.98	0.09	10.9	0.78	0.07	11.8	0.62	0.06	10.3
	SD	0.07	0.01	1.1	0.09	0.01	0.8	0.16	0.02	0.9	0.07	0.01	0.6
	CV	7.0	8.7	9.2	8.8	7.8	7.3	20.7	23.0	7.6	10.9	11.8	5.7
OP-8[a]	0.6	1.57	0.10	15.8	1.16	0.08	14.3	1.01	0.07	14.4	0.63	0.04	11.5
	1.2	1.13	0.08	14.4	1.02	0.08	13.4	0.55	0.04	13.8	0.49	0.04	13.3
	2.5	1.00	0.08	11.8	1.02	0.08	12.4	0.53	0.04	13.3	0.46	0.04	11.0
	3.5	1.14	0.08	13.7	0.89	0.07	12.9	0.66	0.05	13.2	0.48	0.04	12.4
	4.5	0.95	0.08	12.0	0.85	0.07	12.3	0.67	0.05	13.4	0.50	0.05	13.0
	Mean	1.16	0.09	13.5	0.99	0.08	13.0	0.68	0.05	13.6	0.51	0.04	12.3
	SD	0.24	0.01	1.7	0.13	0.01	0.8	0.19	0.01	0.5	0.07	0.00	2.1
	CV	21.0	9.9	12.3	12.7	8.5	6.3	28.2	24.5	3.7	13.2	10.6	17.2
OP-25[b]	0.6	1.87	0.14	13.4	1.37	0.10	13.7	1.16	0.09	12.9	0.81	0.06	13.5
	1.2	1.34	0.11	12.2	1.16	0.08	14.5	0.98	0.07	14.0	0.72	0.06	12.0
	2.5	1.09	0.08	13.6	0.92	0.08	11.5	0.78	0.06	13.0	0.70	0.05	14.0
	3.5	1.00	0.07	14.3	0.85	0.07	12.1	0.68	0.05	13.6	0.65	0.05	13.0
	4.5	0.93	0.07	13.3	0.80	0.06	13.3	0.57	0.04	14.3	0.52	0.04	13.0
	Mean	1.25	0.09	13.3	1.02	0.08	13.0	0.83	0.06	13.5	0.68	0.05	13.1
	SD	0.38	0.03	0.8	0.24	0.01	1.2	0.24	0.02	0.6	0.11	0.01	0.7
	CV	30.6	32.4	5.7	23.5	19.0	9.3	28.4	31.0	4.4	15.7	16.1	5.7

SD (standard deviation) and CV (coefficient of variation).

[a]Areas derived from pasture.

[b]Area derived from native Amazon rain forest.

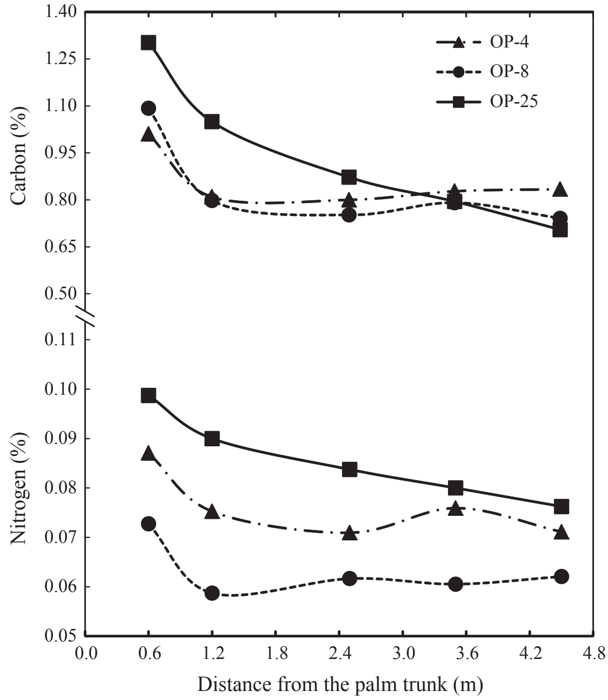

Fig. 4 Soil C and N contents considering different distances from the palm trunk in Agropalma farm, Para State. Amazon region, Brazil.

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. Due to time and spatial variability in SOM in the inter rows we chose a fixed distance from the tree and sampled at 3.5 m away from the oil palm base in inter rows and under frond piles.

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

Comparison of normalized soil carbon stocks under forest, pasture, and oil palm areas

To compare soil C stocks across management treatments, average C contents and bulk densities in inter rows and under frond piles were combined on an area-weighted basis, where 80% of the area is comprised of the inter row and 20% under frond piles.

The mean bulk density (0–30 cm) was 1.29 g cm^{-3} in OP-4 and OP-8, and 1.34 g cm^{-3} in OP-25 (Table 1). Oil

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

	Inter rows		
Soil depth (cm)	OP-4[a]	OP-8[a]	OP-25[b]
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 ± 0.3Ab	27.0 ± 2.0Ba	25.4 ± 1.1Cb
	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 ± 1.4Aa	27.4 ± 2.6Ba	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.

palm areas derived from pasture (OP-4 and OP-8) had slightly higher bulk density than oil palm area derived from forest (OP-25) in all soil layers evaluated. The bulk density of forest soils in the 0–5 cm surface layer was 1.1 g cm^{-3} and soils under pasture and oil palm had greater soil BD in the surface and deeper layers compared to forest.

Average soil C stocks, computed on a mass equivalent basis, suggest a decline over time, from 33.2 Mg ha^{-1} in the 4 year old plantation to 22.7 Mg ha^{-1} in the oldest (25-year) plantation (Table 4). However, due to variability among the site locations, soil clay contents varied for the different aged plantations, with the highest clay content in the youngest plantation and the lowest clay content in the oldest plantation (Table 1). When normalized for differences in soil clay content (Table 4), soil C stocks remained relatively unchanged as a function of plantation age. Soil C stocks under oil palm were similar to or slightly higher (0–18%) than under native forest but substantially lower (35–46%) than those under pasture (Table 4).

Table 4 Total soil carbon stocks (Mg ha^{-1}) for 0–30 cm, with and without normalization for soil clay content, for native rainforest (NARF), pasture (PAST) and oil palm plantations (OP-4, OP-8 and OP-25) in Agropalma farm, Para State, Amazon region, Brazil

	Soil C stock Adjustments (0–30 cm)	
Area	Mass equivalent basis	Normalized for soil 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.

Discussion

The highest soil C and N contents in oil palm were in the area near the plant which is likely due the input of organic matter derived from roots, agreeing with the results found by Haron *et al.* (1998) in western Malaysia. Decreased SOC content with distance from the trunk can be attributed to lower plant C inputs and possibly 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), because the oil palm has an adventitious root system, the use of machines during harvesting and other management operations could contribute to the gradual deterioration of soil physical conditions, which restrict the growth and function of roots.

Our results suggest that following establishment, average SOC under oil palm were largely maintained over time, but with increasing spatial heterogeneity over time, with SOC accumulation near the tree bases and decreases in SOC in the inter row (Fig. 4). In Malaysia, Haron *et al.* (1998) reported SOC contents under oil palm increasing over time, but different results were found by Sommer *et al.* (2000), where oil palm plantations reduced the soil C throughout the profile. In the Sommer *et al.* study, the considerably lower SOC content in the top soil was probably caused by repeated removal of the ground cover.

In inter rows there is no deposition of the oil palm fronds and soil C inputs are derived from some root material and from residues of the nitrogen-fixing legumes (*Pueraria phaseoloides* (Roxb.) Benth.) spread out in the inter row of the oil palm plantation. However, with canopy closure, the surface ground cover declines and this may explain the small decreases in SOC levels in the inter row over time.

In frond piles, the aboveground 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 and a relatively small fraction of this above-ground C input contributes to the SOC pool.

The pasture system showed the highest carbon stocks, as has been observed in numerous other studies in the Amazon region (Fearnside & Barbosa, 1998; Cerri *et al.*, 2003; Zinn *et al.*, 2005; Garcia-Oliva *et al.*, 2006). 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 *et al.*, 1995, 1996; Trumbore *et al.*, 1995; Neill *et al.*, 1997; Bernoux *et al.*, 1998). This is typical when pasture is not subjected to extreme regimes of burning or overgrazing.

Pasture grass 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). In contrast, the frond residues added to soil in oil palm plantations promote an input of SOM much less than the residue input and root decomposition of pasture (Lamade *et al.*, 1996).

According to Maia *et al.* (2010), perennial crops had a minimal impact on soil C stocks, suggesting these systems can maintain about 98% of the SOC found under native vegetation. Our results, i.e., that oil palm can maintain similar soil C stocks as under native forest, can be attributed to management practices that minimize soil tillage, maximize residue return, and where there is an absence of water stress because precipitation occurs throughout the year. These management conditions have been suggested to increase the soil C stocks (West & Marland, 2002; Ogle *et al.*, 2005; Zinn *et al.*, 2005).

In summary, our results suggest that SOC can be maintained over time with proper management of oil palm in northern Brazil. However, land use conversion to oil palm may involve significant 'C debts'. For conversion from native rain forest, losses of SOC appear to be insignificant (or there may be a small gain) but there is a large loss of above-ground biomass, on the order of 136 Mg C ha^{-1} during the first 50 years of this process of land conversion to biodiesel production (Fargione *et al.*, 2008). In contrast, conversion to oil palm from pasture can result in significant losses of SOC, although this may be largely offset by the increased aboveground biomass C stocks in oil palm, on the order of

41.4 Mg ha^{-1} during the first 12 years of planting (Silva *et al*., 2001), compared to pasture. These insights about soil carbon stocks under oil palm production in the Amazon region, Brazil, provide valuable information to be used in life cycle assessments of biodiesel production using oil palm as the feedstock.

Acknowledgements

This work was supported by Petroleo Brasileiro S.A. We thank Conselho Nacional de Desenvolvimento Cientifico e Tecnologico (CNPq) for financial support and the graduate scholarship provided to L.A. Frazao. We also thank the Corporate Social and Environmental Responsibility Manager of Agropalma Farm, Tulio Dias, for all the support given during this study.

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