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Seasonal variation of soil attributes in oil palm plantations in the Eastern Amazon

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ABSTRACT: Brazil stands out worldwide in the production of oil palm; however, there is a need to understand the interaction between the plantations and the environment. The objective was to evaluate the microbiological and chemical attributes of the soil in plantations of different ages of oil palm and of a secondary forest in two seasonal conditions. The microbiological variables analyzed were the carbon of the microbial biomass (C_{BMS}), total carbon (C_{TOTAL}), total nitrogen (N_{TOTAL}), basal respiration (RB), metabolic quotient (qCO_2), carbon / nitrogen ratio (C/N) and gravimetric humidity (Ug); (P), potassium (K), calcium (Ca), magnesium (Mg), aluminum (Al), effective cation exchange capacity (CTC) and aluminum saturation (% m) . The chemical attributes of soil fertility and soil microbial biomass presented stronger and larger correlations in the rainy season. The most sensitive microbiological attributes to age of oil palm were C_{BMS}, qCO_2 and C/N ratio, while the chemical variables were P, Ca, Al, CTC, and pH in water.

Key words: *Elaeis guineenses*; soil fertility; rainfall

Variação sazonal dos atributos do solo em plantios de palma de óleo na Amazônia Oriental

RESUMO: O Brasil se destaca mundialmente na produção de palma de óleo, no entanto há necessidade da compreensão da interação entre os plantios e o meio ambiente. Objetivou-se avaliar os atributos microbiológicos e químicos do solo em plantios de diferentes idades de palma de óleo e de uma floresta secundária, em duas condições sazonais. As variáveis microbiológicas analisadas foram o carbono da biomassa microbiana (C_{BMS}), carbono total (C_{TOTAL}), nitrogênio total (N_{TOTAL}), respiração basal (RB), quociente metabólico (qCO_2), relação carbono da biomassa microbiana/carbono total (C_{BMS}:C_{TOTAL}), relação carbono/nitrogênio (C/N) e umidade gravimétrica (Ug); e para a análise química foram avaliados o fósforo (P), potássio (K), cálcio (Ca), magnésio (Mg), alumínio (Al), capacidade de troca efetiva de cátions (CTC) e saturação por alumínio (%m). Os atributos químicos de fertilidade do solo e a biomassa microbiana do solo apresentaram correlações significativas mais fortes e em maior número no período mais chuvoso. Os atributos microbiológicos mais sensíveis à idade de palma de óleo foram o C_{BMS}, o qCO_2 e a relação C/N enquanto as variáveis químicas foram o P, o Ca, o Al, a CTC efetiva e o pH em água.

Palavras-chave: *Elaeis guineenses*; fertilidade do solo; precipitação

Introduction

Oil palm (*Elaeis guineensis* Jacq.) is one of the main oleaginous crops cultivated in Brazil and an important source of vegetable oil, widely used in the cosmetic and biodiesel industries (Carvalho et al., 2014). There is a growing demand for products derived from this palm in national and international markets, resulting in the need to increase its production. Brazil is among the largest oil palm producers in the world (FAO, 2012) and among the countries with the greatest potential for expansion of agricultural areas with this crop due to favorable climate and soil conditions (Carvalho et al., 2014). In this context, the state of Pará in the eastern Amazon stands out as the main state responsible for approximately 90% of the national production (Santiago et al., 2013).

Increasing agricultural production in the Amazon, where soils have low natural fertility (Junqueira et al., 2016), involves increasing the availability of nutrients to plants through soil organic matter management, especially for producers with restricted access to industrialized products (Santiago et al., 2013). When the vegetation does not receive fertilization, such as in the Amazon, it is generally sustained by nutrient cycling from litter decomposition by soil microorganisms, according to biotic and abiotic factors of the ecosystems (Mishra & Kumar et al. 2016).

The different compositions of organic material that reaches the soil influence the density and diversity of microorganisms, as well as the time required for total decomposition (Gougoulias et al., 2014). In this sense, Vasconcellos et al. (2013) observed microbiological indicators of soil quality in the process of forest recovery in the Brazilian biome and found that the community structure of the microbial biomass was closely linked to soil recovery time, which means that the longer the recovery time, the greater are the chances of recovery of the microbial community of the soil.

In addition, there are some chemical attributes that can serve as quality indicators such as nitrogen, phosphorus and potassium slowly made available in the soil from soil organic matter (Li et al., 2013).

In general, the substitution of natural vegetation for agricultural crops causes an imbalance in the ecosystem. The adopted management influences the physical-chemical and biological processes of the soil, being able to modify its characteristics and often causing its degradation (Mojiri et al., 2012). However, oil palm has been indicated as a crop for the Amazon because it helps in the recovery of deforested areas (Vijay et al., 2016) and promotes the generation of employment and income, contributing to regional development (Austin et al., 2017).

This study sought to help the understanding of the relationship between seasonality and age of palm crops and soil quality. The hypothesis tested was that agro-ecological systems with oil palm cultivation result in increased microbial activity and chemical availability of the soil in function of the time of planting. Thus, the objective was to evaluate soil microbiological and chemical factors in oil palm crops of different ages and to make comparisons with a successional forest area in two seasonal conditions of rain intensity.

Material and Methods

The study area covers commercial plantations of the Dendê do Pará SA-DENPASA company (1º08’2.13’’ S and 48º00’15.23’’ W), located in the municipality of Castanhal, Pará. The weather is tropical hot and humid (Ami type) according to Köppen’s classification. The pluviometric precipitation of the experimental area was monitored daily during the period from 2011 to 2012 by means of a rain gauge with a collection area of 78.5 cm^2. The mean rainfall was 2,428 mm distributed between the rainy season, from January to June 2012 (cumulative rainfall of 1,698 mm), and the less rainy season, from July to December 2011 (cumulative precipitation of 739 mm).

The experiment consisted of 6 treatments in a 4 x 2 factorial scheme, with four different plantations: three oil palm plantations aged 5 (P05), 8 (P08) and 11 (P11) years, and a secondary forest (SECFOR), and two seasonal conditions: less rainy (September 2011) and rainiest (March 2012) season.

Oil palms were planted with the BRS Manicoré cultivar spaced 9 m between plants and 7.5 m between rows, resulting in a density of 143 plants ha^{-1} within an area of 4 ha. In turn, the secondary forest was approximately 15 years old and characterized by an average density of 480 trees (trees with diameter at breast height above 10 cm), average height of the canopy of 15 m, and predominance of the species *Tapirira guianensis* Aubl., *Vismia guianensis* Aubl. Prers., *Inga alba* Willd. and *Apeiba burchelli* Sprague.

Each study area was fertilized12 months before soil sampling and depended on the age of the crop; the areas P05 and P08 were fertilized with crop residues and 5 kg of NPK 7-2-19 per plant, containing 8.2% calcium; 10.9% of sulfur and 2% of magnesium, while the area P11 received as chemical fertilizer 8 kg of NPK 9-4-23 per plant; 8.8% calcium; 5.4% sulfur; and 0.4% boron, and as organic fertilizer, crop residues and poultry manure mixed with sawdust powder.

Soil samples were collected in 0 - 0.10; 0.10 - 0.20 and 0.20 - 0.30 m deep layers and in four 20 x 20 m sub-areas randomly chosen for soil analysis. Results of the physical and chemical analysis of the studied areas are presented in Table 1.

To determine microbiological attributes of the soil, twelve soil samples were collected per treatment in each sampling campaign. In each sub-area, 3 samples, each composed of two simple sub-samples were collected at 0-10 cm depth. Considering the management of vegetal residues in the area, a simple sample was collected in the planting line and another between planting lines.

Total organic carbon and total nitrogen in the soil were determined by means of an elemental analyzer (CNS-2000, LECO Corporation, Michigan, USA, model “CHNS TruSpec”)

Table 1. Average values of the physical-chemical characteristics of the soil where oil palms were planted with 5 (P05), 8 (P08), and 11 (P11) years of age and secondary forest (SECFOR) in the municipality of Castanhal, PA, Brazil.

Treatment	Depth	Sand	Thin sand	Silte	Clay	Ds	pH_{water}
				($g\ kg^{-1}$)		($g\ cm^{-3}$)	
P05	0-10	520.5	321	49	110	1.43	4.65
	10-20	470	313	97	120	1.49	4.45
	20-30	368	377	215	40	1.51	4.47
P08	0-10	511.5	326.5	62.5	100	1.36	4.48
	10-20	480	277	103	140	1.48	4.53
	20-30	494	256	51	200	1.42	4.57
P11	0-10	179.5	629.5	72	120	1.45	4.66
	10-20	356	442	122	80	1.52	4.65
	20-30	267	488	85	160	1.54	4.65
SECFOR	0-10	414	398	58.5	130	1.32	4.38
	10-20	469	317	34	180	1.52	3.88
	20-30	412	286	23	280	1.41	4
		P	K	Na	Ca	Ca + Mg	Al
			($mg\ dm^{-3}$)			($cmol\ dm^{-3}$)	
P05	0-10	3.12	29	15.12	1.05	1.437	0.6
	10-20	2.12	23.87	15.37	0.57	0.987	0.925
	20-30	2.12	23.62	14.12	0.512	0.912	0.937
P08	0-10	2.37	22.37	16.87	0.65	1.062	1
	10-20	8.12	19.5	17.87	0.637	0.912	0.937
	20-30	2.62	17.62	17	0.525	0.837	0.962
P11	0-10	30.62	27.5	20.12	1.425	1.962	0.625
	10-20	5.5	48.75	26.12	0.637	0.962	0.862
	20-30	8.62	47.37	27.12	0.537	0.837	0.887
SECFOR	0-10	1.5	19.37	18.5	0.762	1.212	0.975
	10-20	1.12	22.87	21.62	0.475	0.787	1.15
	20-30	1.12	21.5	17.25	0.475	0.937	1.037

and the results were expressed as g kg^{-1}. Soil microbial biomass carbon was determined by the fumigation-extraction method (Vance et al., 1987). Data were expressed as mg C kg^{-1} dry soil.

Basal soil respiration (microbial respiration) was determined according to the incubation method described by Jenkinson & Powlson (1976). In addition, the metabolic quotient (qCO_2), also called the specific respiration rate of microbial biomass, was calculated by the ratio between basal respiration (BR) and soil microbial biomass carbon (C_{SMB}) (Anderson & Domsch, 1993). Based on the C_{TOTAL}, N_{TOTAL}, and C_{SMB} values, the microbial biomass carbon/ total carbon ratio (C_{SMB}/C_{TOTAL}) and C/N ratio were estimated. The determination of soil gravimetric moisture followed the methodology of Embrapa (2007) and was expressed in percentage and obtained according to the formula: Ug = ((Wet weight - Dry weight) / Dry weight) x 100.

To determine soil chemical attributes, four soil samples per treatment were collected in each sampling campaign. A sample composed of six simple sub-samples was collected at 0-10 cm depth in each sub-area. The chemical attributes of soil fertility measured were pH in water, phosphorus (P), potassium (K), sodium (Na), calcium (Ca), magnesium (Mg) and exchangeable aluminum (Al) according to “the Manual of methods of soil analysis” of the National Center for Soil Research (Embrapa, 2007).

The normality of data was evaluated by the Kolmogorov-Smirnov test ($p \leq 0.05$). When the assumptions of normality and/or homoscedasticity were not met, simple logarithmic transformation of the data was made (log10). Data on biological and chemical attributes of the soil were submitted to analysis of variance and Tukey’s test ($p \leq 0.05$) and the Pearson correlation analysis ($p \leq 0.05$) in the statistical software Sigmaplot 11.0. A multivariate principal component analysis was also made using the Statistica 7.0 software.

Results and Discussion

The seasonal variation of precipitation induced changes in 12 of the 17 evaluated attributes. Mean C_{TOTAL} did not differ statistically between three of the four areas; however, a higher mean C_{TOTAL} was observed in P11 in the less rainy season, and in the SECFOR in the rainiest season, both systems with older vegetation. As for $N_{TOTAL,}$ there was no interaction between treatments, being the highest value statistically obtained in the SECFOR (Table 2). C_{TOTAL} and N_{TOTAL} were described in the study by Parton et al. (1989) as a less active fraction of soil organic matter, thus with a slower cycling and less able to explain short-term temporal variations.

In this study, it was verified that the C_{TOTAL} of the soil in the rainiest season did not differ statistically between the 5-, 8- and 11-year-old planting areas, suggesting that the C of the soil reached the steady state reported by Smith et al. (2012) as soon as at five years from the age of 11 years of oil palm planting.

Table 2. Microbiological analysis of soil, total organic carbon (C_{TOTAL}), total nitrogen (N_{TOTAL}), soil microbial biomass carbon (C_{SMB}), basal respiration (BR), soil metabolic quotient (qCO_2), microbial biomass carbon/total carbon ratio (C_{SMB}/C_{TOTAL}); carbon/nitrogen ratio (C/N); and gravimetric soil moisture (Moisture) from oil palm plantations with 5 (P05), 8 (P08) and 11 (P11) years and a secondary forest (SECFOR) in two rainfall regimes, less rainy and rainiest season, in the municipality of Castanhal, PA, Brazil.

	C_{TOTAL} (g kg^{-1})			
	P11	**P08**	**P05**	**SECFOR**
Less rainy	9.38 Ba	7.90 Bab	7.35 Bb	6.80 Bb
More rainy	10.99 Ab	9.39Ab	10.30 Ab	13.74 Aa
	N_{TOTAL} (g kg^{-1})			
	P11	**P08**	**P05**	**SECFOR**
	0.4 b	0.39 b	0.38 b	0.52 a
	C_{BMS} (mg C kg^{-1} solo)			
	P11	**P08**	**P05**	**SECFOR**
Less rainy	1499 Ba	1047 Bb	1196 Bab	1391 Aa
More rainy	2513 Aa	1933 Ab	1711 Ab	1320 Ac
	RB (mg C-CO_2 kg^{-1} solo h^{-1})			
	P11	**P08**	**P05**	**SECFOR**
Less rainy	3.94 Ab	3.79 Ab	5.17 Aa	5.20 Aa
More rainy	2.71 Bbc	4.39 Aa	3.59 Bab	2.09 Bc
	qCO_2 (mg C-CO_2 g^{-1} C_{BMS} h^{-1})			
	P11	**P08**	**P05**	**SECFOR**
	2.81 c	3.74 ab	4.43 a	3.78 b
	Less rainy		**More rainy**	
	3.69 a		1.83 b	
	C_{BMS} : C_{TOTAL} (%)			
	P11	**P08**	**P05**	**SECFOR**
Less rainy	16.24 Bb	13.99 Bb	16.31 Ab	20.88 Aa
More rainy	23.35 Aa	20.85 Aab	17.38 Ab	9.75 Bc
	C/N ratio			
	P11	**P08**	**P05**	**SECFOR**
	26.74 a	22.06 b	23.74 ab	19.79 b
	Less rainy		**More rainy**	
	18.85 b		27.32 a	
	Humidity (%)			
	Less rainy		**More rainy**	
	13.25 a		15.27 a	

* Means followed by the same letters, upper case letters in the columns and lower case letters in the lines, do not differ significantly according to the Tukey test ($p \geq 0.05$).

The rainiest season caused a rise in C_{SMB} in all planting areas (Table 2). Aragão et al. (2012) and Silva et al. (2016) also found increases in C content in biomass during the rainiest season. This may be associated with an increase in nutrient availability with increasing precipitation as well as a decrease in aluminum saturation.

The close relationship between the nutritional quality of the environment and microbial activity was indicated by direct significant correlations between C_{SMB} and chemical attributes of soil fertility mainly during the rainiest season. Azcón-Aguilar & Barea (2015) affirmed that variations in the microbial population can occur due to the nutrient input of the soil. According to Smith et al. (2012), the nutritional status of the soil may be of equal or greater relevance to the availability of organic substrate for microbial activity. In general, C_{SMB} showed to be a more sensitive attribute to planting time.

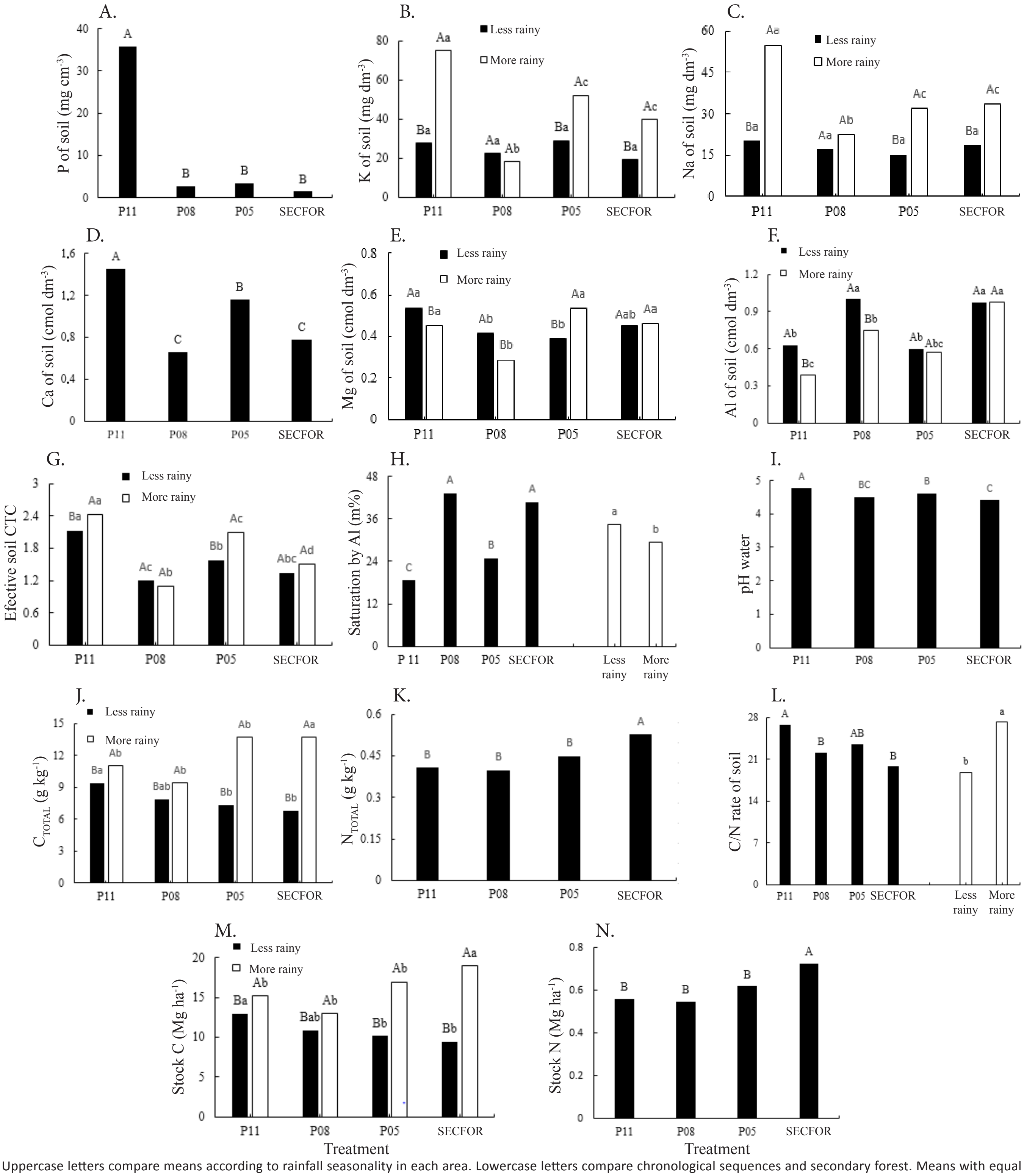
There was interaction between the age of the oil palm crop and seasonality (rainiest and less rainy periods) for C_{SMB} and BR (Table 2). The higher the crop age (P11) under the influence of the rainiest season, the higher was the mean C_{SMB}, indicating that in these areas there were changes in the soil properties reflecting in the microbial population. BR presented higher means in the less rainy period in the areas P05 and SECFOR, what can be explained by changes in the behavior of the soil microbial population (Nascimento et al., 2009).

The attribute qCO_2 showed a significant statistical difference in isolated comparisons of the effect of crop age and season (Table 2). Regarding the age of the vegetation, P11 had the lowest mean. As for the effect of the season, the increase in precipitation induced a decrease in mean qCO_2; this result can be linked to microbial biomass, because when microbial biomass becomes more efficient in the use of ecosystem resources, less CO_2 is lost by respiration and greater proportion of carbon is incorporated into microbial tissues (Silva et al., 2007). Therefore, the area P11 in the rainy season had a higher mean of C_{SMB} and a lower mean of qCO_2 and BR, in line with the results of Simões et al. (2010) who affirm that plantations can promote an increase of carbon of the soil microbial biomass and a decrease of the metabolic quotient, indicating the possibility of organic carbon accumulation in the soil in the long term.

In the case of the attribute C_{SMB}/C_{TOTAL}, there was an interaction effect between the crop age and rainfall seasonality. In the rainy season, the area P11 presented the highest percentage of total carbon contained in the soil microbial biomass while SECFOR obtained the lowest percentage in the same period (Table 2). This, together with low BR values caused the P11 to be one of the closest to a state of equilibrium among the studied areas, since P11 also held the lowest qCO_2 values.

Overall, the percentage of C_{TOTAL} immobilized in microbial biomass, represented by the C_{SMB}/C_{TOTAL} ratio, exceeded the results found by Santiago et al. (2013) during the study of conservationist systems in the Amazon. This suggests that even in conventional palm oil crops, management may provide conditions for microbial biomass to be more efficient than in natural or agroforestry environments. This was seen in the joint evaluation of the planting areas, because the soil quality indicators C_{TOTAL}, C_{SMB}, BR, qCO_2 and C_{SMB}/C_{TOTAL} were not far from the results of the SECFOR, i.e. the natural system.

P, K, Na, Mg, Ca and Al levels were estimated in the chemical evaluation of the soil. Only P and Ca did not present seasonal changes (Figure 1). The variable pH in soil water did not present a significant seasonal difference between the studied areas and did not have major variations. Nevertheless, the area P11 had a higher mean than the other areas.



* Uppercase letters compare means according to rainfall seasonality in each area. Lowercase letters compare chronological sequences and secondary forest. Means with equal letters do not differ significantly according to the Tukey test ($p \geq 0.05$).

Figure 1. Chemical soil fertility attributes of oil palm crop areas, with 11 (P11), 8 (P08) and 5 (P05) years of age, and of secondary forest in the municipality of Castanhal, PA, in the less rainy and rainiest periods. A- P (phosphorus) in the soil; B- K (potassium) in the soil; C- NA (sodium) in the soil; D- Ca (carbon) in the soil; Mg (magnesium) in the soil; F-aluminum in the soil; G- cation exchange capacity (CEC) in the soil; H- saturation by Al (aluminum); I- pH of the soil; J- C total (total carbon) in the soil; Total K- N (total nitrogen) in the soil; L- C/N (carbon and nitrogen) ratio in the soil; M- stock of C (carbon) and N- stock of N (nitrogen) in the soil.

Aluminum saturation of the soil was higher in the areas P08 and SECFOR compared to the areas P11 and P05 (Figure 1). It was observed that in the rainiest period, there was a decrease in the mean level of Al in the soil. The highest levels of K, Na and effective CEC of the soil were found in the rainiest season. Probably, this occurred due to the deposition of residues from oil palm, which normally return to the plantations and are rich mainly in K and N, containing still considerable amounts of other nutrients (Furlan Júnior, 2006).

Significant differences were observed in the C/N ratio, in the isolated comparisons between crop ages and seasonal periods. The rainy season presented higher means (Figure 1). Among the crop ages, it was observed that the mean of the area P11 was significantly higher than those of P08 and also SECFOR. Oil palm is a rustic plant and produces vegetable residues rich in fibers and organic material sometimes difficult to decompose, such as the remains of a bunch or stalk that has a C/N ratio around 50 (Furlan Júnior, 2006). This may explain why the area P11 had the highest means of C/N ratio. In the study areas, the deposition of leaves, chaff residues and by-products from the oil palm industry may have contributed to the high C/N ratios found. Santiago et al. (2013) found lower C/N ratios. However, in the area studied by them, oil palm plantation areas were enriched with fertilizer species that improve the quality of the organic substrate deposited in the soil.

The high concentrations of C and N in the soil of SECFOR may be related to a more balanced system for the input and output of organic components, being also favored by a more diverse microbiota associated to a greater plant diversity typical of natural systems (Carney & Matson, 2005).

As for the correlation analysis, soil moisture did not cause major variations in the measured attributes, but was significantly and positively related to total nitrogen and nitrogen stocks, and negatively associated to C/N ratio. Thus, the higher the soil moisture, the higher is N_{TOTAL} and the higher is N stock, and the lower is the C/N ratio (Table 3).

The multivariate principal component (PC) analysis showed that, in the less rainy season, PC 1 explained 51.67% of the data set variation, of which C_{SMB} had the highest discriminatory capacity in the formation of clusters. K, Mg, C_{TOTAL} and N_{TOTAL} were also identified as the complementary variables that most correlated with PC1 variations in the dry period (Table 4). PC 2 was able to explain 41.31% of the variation of the less rainy season, and BR associated mainly to C_{TOTAL} and Mg presented the greatest discriminatory capacity in the formation of clusters. This result is similar to those found by Loss et al. (2009) who evaluated the influence of agro-ecological management systems on the attributes and chemicals of a Red-Yellow Argisol and observed the lowest cumulative variance of 72.97% and values of 49.54 % and 23.43% for the F1 and F2 axes, respectively.

In the rainiest season, the components 1 and 2 were able to explain 96.63% of the variation (Table 4). PC 1 explained 55.21%, with a highlight to C_{SMB} that was mainly related to P and Al, corroborating the results of the Pearson correlation. This relationship of C_{SMB} with aluminum was also found to be an important component in the study by Cenciani et al. (2009), according to whom Al is associated to soils with low pH resulting in lower diversity and richness of microorganisms. In this sense, Ferreira (2008) stated that despite the fact that the microbiota has an organic material supply, this can be inhibited by the reduction of pH. During his study, this author also found P, K and Mg as important components to explain variations in treatments under different uses and management.

In general, the principal component analysis allowed a clearer visualization of the strengthening of the correlations between chemical attributes of the soil fertility and microbial

Table 3. Pearson correlation coefficient between microbiological and chemical variables analyzed in the two seasonal periods, less rainy and rainiest.

Variables	C_{BMS}	RBS	qCO_2	C_{TOTAL}	N_{TOTAL}	Stock C	Stock N	C/N	C_{BMS} : C_{TOTAL}	pH	P	K	Na	Ca	Mg	Al	$CTC_{EFECTIVE}$	(m%)
Humidity	ns	ns	ns	ns	0.449	ns	0.449	-0.561	ns	ns	ns	ns	ns	ns	ns	ns	ns	Ns
C_{BMS}	1	ns	-0.528	-0.343	-0.43	-0.343	-0.43	ns	-0.884	0.451	0.641	0.535	0.507	0.406	ns	-0.639	0.362	-0.505
RBS		1	0.762	-0.434	-0.345	-0.434	-0.345	ns	ns	ns	ns	-0.346	ns	ns	-0.301	ns	ns	ns
qCO_2			1	ns	ns	ns	ns	ns	-0.319	-0.292	-0.438	-0.552	-0.471	-0.359	ns	ns	-0.383	0.354
C_{TOTAL}				1	0.58	1	0.58	ns	-0.714	ns	ns	ns	ns	ns	0.417	0.349	ns	ns
N_{TOTAL}					1	0.58	1	-0.649	-0.597	ns	ns	ns	ns	ns	0.347	ns	ns	ns
Stock C						1	0.58	ns	-0.714	ns	ns	ns	ns	ns	0.417	0.349	ns	ns
Stock N							1	-0.649	-0.597	ns	ns	ns	ns	ns	0.347	ns	ns	ns
C/N								1	ns	ns	ns	ns	ns	ns	ns	ns	ns	Ns
C_{BMS} : C_{TOTAL}									1	0.324	0.399	ns	ns	ns	-0.294	-0.583	ns	-0.363
pH										1	0.659	0.548	0.487	0.787	ns	-0.834	0.701	-0.781
P											1	0.752	0.823	0.622	Ns	-0.605	0.633	-0.64
K												1	0.772	0.813	0.598	-0.654	0.869	-0.843
Na													1	0.653	0.408	-0.42	0.722	-0.62
Ca														1	0.672	-0.786	0.979	-0.93
Mg															1	-0.304	0.776	-0.61
Al																1	-0.713	0.91
$CTC_{EFECTIVE}$																	1	-0.917

*ns - not significant; C_{TOTAL} - total soil organic carbon; N_{TOTAL} - total soil nitrogen; C/N - carbon ratio: soil nitrogen; C_{SMB} - soil microbial biomass carbon; Stock C - carbon stock in the soil; Stock N - nitrogen stock in the soil; C_{SMB}: C_{TOTAL} - microbial carbon ratio: total carbon in the soil; BR - basal respiration; qCO_2 - metabolic quotient; MS - gravimetric soil moisture; $CEC_{EFECTIVE}$ - effective cation exchange capacity of the soil; (m%) - percentage of saturation by aluminum; pH in water - soil hydrogenation potential; P - phosphorus; K - potassium; Na - sodium; Ca - calcium; Mg - magnesium; Al - aluminum.

Table 4. Basis of correlation of the active and supplementary variables of the principal component analysis for the less rainy and rainiest periods in the study areas.

Period	Variable type	Factor 1			Factor 2			Cumulative variance (%) F1 + F2
		Associated variable	Correlation	Variance (%)	Associated variable	Correlation	Variance (%)	
Less rainy	Active	C_{BMS}	0.95	51.67	RB	0.96	41.31	92.99
		C_{BMS}:C_{TOTAL}	0.82	-	qCO_2	0.74	-	-
	Additional	K	0.44	-	C_{TOTAL}	0.60	-	-
		N_{TOTAL}	0.28	-	Mg	0.53	-	-
More rainy	Active	C_{BMS}	0.92	55.21	RB	0.96	41.41	96.63
		C_{BMS}:C_{TOTAL}	0.83	-	qCO_2	0.62	-	-
	Additional	P	0.58	-	C_{TOTAL}	0.60	-	-
		Al	0.57	-	N_{TOTAL}	0.49	-	-

* C_{TOTAL} - total organic carbon in the soil; N_{TOTAL} - total nitrogen in the soil; C_{SMB} - soil microbial biomass carbon; C_{SMB}: C_{TOTAL} - microbial carbon/total soil carbon ratio; BR - soil basal respiration; qCO_2 - soil metabolic quotient; P - phosphorus in the soil; K - potassium in the soil; Mg - magnesium in the soil; Al - aluminum in the soil.

biomass during the rainiest season, probably due to the greater availability of nutrients in this period.

The comparisons established with the SECFOR suggest that monoculture of oil palm, if well managed, can provide conditions for the microbial biomass to be able to work as in the natural ecosystem studied, in relation to the evaluated attributes. The results obtained for qCO_2 in the areas cultivated with oil palm suggest lower stress levels than SECFOR. However, complementary studies are necessary to allow a qualitative and quantitative evaluation of the soil microbiota in commercial plantations.

Conclusion

The microbiological attributes C_{SMB}, qCO_2 and C/N ratio, as well as the chemical components P, Ca, Al, effective CEC and pH in water varied with oil palm crop age. Moreover, the rainiest season strengthened the correlations between chemical soil fertility attributes and soil microbial biomass activity.

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