Environment and Natural Resources Research; Vol. 8, No. 4; 2018
ISSN 1927-0488 E-ISSN 1927-0496
Published by Canadian Center of Science and Education

Carbon and Nitrogen Dynamics of Soil Organic Matter Fractions in Thickets and Intergrowth Areas of Sudanian Savannah Grasslands, Bondoukuy, Western Burkina Faso

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Received: November 10, 2018 Accepted: November 19, 2018 Online Published: November 30, 2018

doi:10.5539/enrr.v8n4p16 URL: https://doi.org/10.5539/enrr.v8n4p16

Abstract

Soil organic carbon (SOC) and total nitrogen (TN) play a central role in physico-chemical fertility of a soil, and thus promoting agricultural productivity. Yet little is known about SOC and TN dynamics in tropical ferruginous soils of Sub-Saharan Africa. In this study, thicket and intergrowth soil samples, under both cultivation and perennial grass fallow (*Andropogon gayanus*), were collected in Bondoukuy, western Burkina Faso. The samples were fractionated and their SOC and TN contents in six organo-mineral fractions were analyzed. Because of the high labile organic matter pools in coarse sand fractions, SOC (~630 µg C g^{-1} soil) associated with these fractions appeared to be more accessible to soil microbes than recalcitrant and occluded pools (~440 µg C g^{-1} soil) within the fine fractions of the fallow soils. The results also indicated that clay fractions are likely to represent a source of the available nitrogen to crop following long fallow periods (~20 years). In contrast, the differences in TN contents were not significant ($p>0.05$) between ploughed plots and young fallow lands (~10 years). The substantial decrease in C/N ratios from coarse particulate organic matter pools (C/N=68) to fine pools (C/N=10) suggested an increase in the SOC decomposition rate in the fine fractions. This indicates a substantial decrease in microbial activities following a reduction in particulate organic matter sizes. The SOC contents were relatively high in coarse (~930 µg C g^{-1} soil) fractions of the thicket soils compared to those of the adjacent intergrowth soils (~620 µg C g^{-1} soil). A similar SOC distribution pattern was also observed in fine fractions of the thicket and the intergrowth soils. Total nitrogen also exhibited a high distribution pattern in fine sand and very fine sand fractions. The findings of this study demonstrated that SOC and TN restoration in semi-arid tropical savannah soils is a function of particulate organic matter sizes, vegetation type and soil management practices.

Keywords: *Andropogon gayanus*, fallow lands, particulate organic matter fractions, soil organic carbon, total nitrogen

1. Introduction

Although a sharp increase in planted land areas in the past 200 years has led to sequestration of large amounts of carbon by vegetation around the globe, in Sudanian tropical climatic zones (i.e., semi-arid) of Africa, removal of vegetation through ploughing, grassing, browsing and burning not only have impacted the local physical environment (e.g., soil degradation and nutrient loss), but have also dramatically reduced soil organic matter (soil organic carbon and total nitrogen) contents as well as carbon sequestration levels in soils (Mann, 1986; Schlesinger, 1986). A decline in the carbon sequestration levels has negative feedback mechanism for atmospheric CO_2 and N_2O contents (Wilson, 1978; Sellers, 1997). Destruction of biomass has also adversely impacted nitrogen fixation rates, which, in turn, has affected soil fertility and agricultural production (Pimentel et al., 1995; Tiessen et al., 1984).

To increase soil organic carbon (SOC) and total nitrogen (TN) storage capacity so that the soil structure and fertility can be restored, farmers in Burkina Faso use organic fertilizers. However, in some areas, localized use of manure has very little effects on the soil fertility (Serpantié, 2003). Furthermore, the limited availability of long term fallow lands and inherent intensive agricultural practices across the country indicate that the soil fertility is rarely maintained (Floret & Serpantié, 1993). In contrast, in moist soils, the presence of plants tends to have a conservatory effect on SOC and TN contents which can also have positive impacts on microbial activities and soil nutrient cycling (Doormar, 1990). Studies have also shown that fallows following perennial grass species such as *Andropogon gayanus* (*A. gayanus*), can restore the soil fertility (De Blic & Somé, 1997; Fournier et al., 2000; Serpantié, 2003).

The perennial grass *A. gayanus* is a common plant species encountered in fallow lands of the Sudanian tropical climatic zone of Bondoukuy, western Burkina Faso. This grass is closely involved in carbon and nitrogen cycles, and thereby influencing physico-chemical properties of the fallow lands (Yoni, 1995; 1997; Fournier et al., 2000). Before starting a new farming session, the farmers in Bondoukuy determine if vegetation has been properly restored using density and height of *A. gayanus* of the fallow lands as indicators of improvement of the soil fertility (Yoni, 1997; Fournier et al., 2001). Several studies have demonstrated a strong negative relationship between the presence of *A. gayanus* and soil particle sizes (Campbell & Souster, 1982). Thus, a negative relationship has been also found between SOC and TN turnover and organo-mineral particle sizes (Coote & Ramsey, 1983; Somé, 1996). Moreover, the stable organic matter pools are thought to be associated with fine soil particles, whereas the labile pools are generally found in fresh plant residues (Zhang et al., 1988). To identify quantitative variations in SOC and TN contents within different organo-mineral particles (i.e., particulate organic matter), the SOC and the TN contents were extracted through physical fractionation of soil samples under fallow and cultivated field conditions. We expect a substantial increase of labile SOC compounds in coarse fractions and more stable recalcitrant SOC in the fine fractions. This suggests that:

i. soil organic matter would be more accessible at the end of vegetation stage (fallow periods) compared to the end of crop stage

ii. and (ii) the alternation between vegetation and crop growth status would not only affect the labile soil organic matter pools (i.e., more dynamic), but also those associated with fine fractions (i.e., less dynamic) that cannot sustain rapid changes of vegetation cover.

The objectives of this study were therefore twofold: 1) to investigate the grain size effects on SOC and TN accumulation in fallow lands around Bondoukuy and 2) to determine the differences in SOC and TN contents in vegetation tickets (clusters) and sparsely vegetated intergrowth areas. The findings of this comprehensive study are likely to shed some light on the SOC and TN dynamics in arable lands under a semi-arid tropical climatic setting and provide the decision makers a robust management plan for efficient land use and soil conservation.

2. Environmental and Geological Context

Soil samples were collected in Bondoukuy, situated in the northern border of the South Sudanian climatic zone, known as cotton farming zone (Figure 1). Bondoukuy lies between 11°51'N and 3°45'W with an elevation above sea level of 360 m. The average annual rainfall of the study area is 850 mm with the maximum rainfall occurring in August. The daily maximum temperature ranges between 31 and 39°C with an average annual potential evapotranspiration of about 1900 mm. The natural vegetation cover in the area is predominantly composed of open woody savannah, where as the dominant grass biome is *A. gayanus*, *Pennisetum pedicellatum* and *Loudetia togoensis* (Fournier et al., 2001).

The geology of the study area is composed of sedimentary rocks made of sandstones and schist of Palaeozoic and Infra cambrian ages (Ouédraogo, 1998). The sandstone bedrock in the plateau is composed of quartz, whereas in the glacis (iron duricrust) it is of schist-dolomite (Ladmirant and Legrand, 1969). Different soil types are encountered along the local pedotoposequence unit. At the plateau, pedological cover is predominantly composed of sandy loam (i.e., ferric lixisols), whilst at the glacis, soils are loamy (i.e., luvisols; Kissou, 1994; Ouattara et al., 2006).

For centuries, human presence in Bondoukuy has markedly affected the local ecosystem. Subsistence (cereals) and cash crop (cotton) farming are the main activities practiced in the area. Although the most fertile soils are regularly ploughed, less fertile ones are increasing subjected to short period fallowing (~5 years). The annual ploughing, based on cotton–maize rotations, usually leads to the collapse of soil structure, erosion and reduction of soil organic matter content. The second most common activity in the study area is extensive animal husbandry. As a result, the area is over–grazed and exposed to high demands for aerial biomass (tree bark, firewood and perennials stems) by the local rural communities.

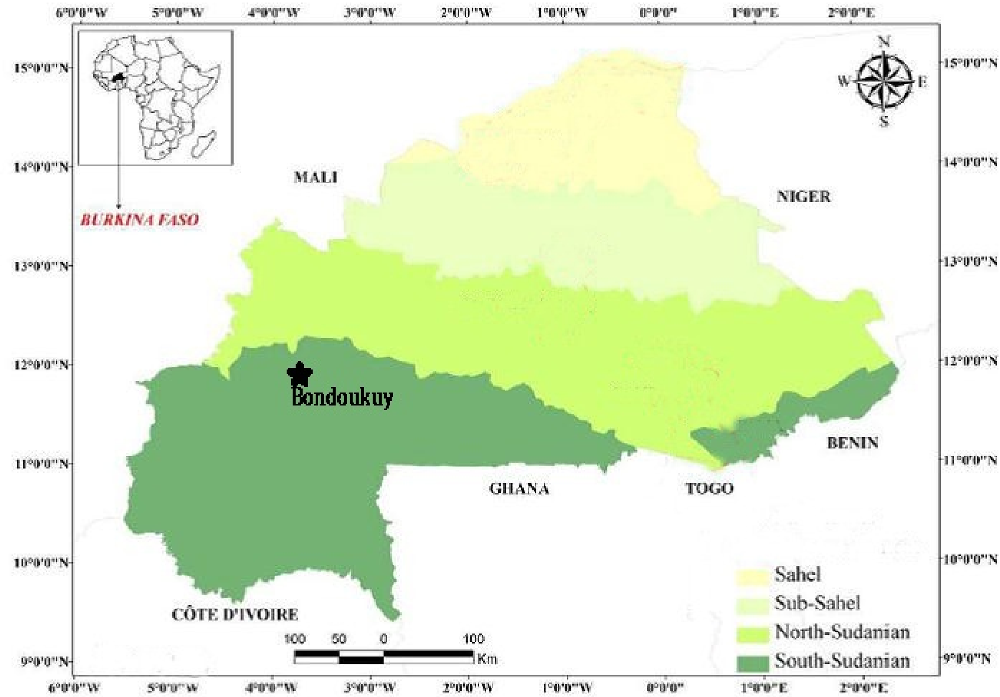


Figure 1. Phytogeographical map of Burkina Faso, showing the study area (Modified from Guinko, 1984)

3. Materials and Methods

According to the spatial variability of the vegetation cover due to environmental heterogeneity, pedological cover and human activities (Yoni et al., 2005), the main criterion in selecting plots was the presence of *A. gayanus* with a representative density. The plots were on the same soil type (i.e., ferruginous tropical soil) and had the same cropping history, but with different ages. Nine plots of 2500 m^2 and 500 m apart were used: 3 cultivated plots (CP), 3 ten year fallow lands (F10) and 3 twenty year fallow lands (F20). The CP (Figure 2a) are considered as control plots, whereas, the F10 (Figure 2b) corresponded to *A. gayanus* set up time and the F20 (Figure 2c) corresponded to *A. gayanus* colonization time. Six topsoil (0–10 cm) samples were randomly collected on cultivated fields, the thickets and the intergrowth (Figure 2d) areas of the fallow lands, using an auger. The sampling approach was based on 0–10 cm in this study because variations in SOC and TN content are likely to be greatest near the soil surface (Mills et al., 2005). The soil samples were air dried, sieved through a 2 mm sieve and stored for subsequent analyses.

Organo-mineral fractions (defined here as all organic and mineral particles of the same size) were separated into different size classes without organic matter destruction (Nacro, 1997). Particle size separation into six particle size fractions (0.05–2000 µm) were isolated (Baize, 1988). The separated organo-mineral fractions were dried in an oven at 50 °C and then weighed. Each fraction was subsequently ground in a ceramic mortar into very fine powder for chemical analysis at the ENS-Paris Ecological Laboratory (France). The results were expressed as percent (%) of sums of the fractions and used for calculation of SOC and TN contents of each fraction.

Soil organic carbon and TN contents in subsamples of individual fractions were analysed using a Carlo-Erba CHN analyser, and they were expressed as µg C g^{-1} fraction and µg N g^{-1} fraction. Soil organic carbon and TN contents (µg g^{-1} soil) within each fraction were calculated from the soil textural composition and SOC and TN concentrations of the corresponding fractions (µg g^{-1} fraction). In order to better estimate SOC and TN contents in each fractions during the crop-fallow rotation, we calculated the following variables (Eq. 1–2):

$$DC = HC-LC \quad (1)$$

Where DC = difference between high and small organic carbon contents; HC = high carbon content and LC = low carbon content

$$DN = HN-LN \quad (2)$$

Where DN = difference between high and small total nitrogen contents; HN =high nitrogen content and LN = low nitrogen content.

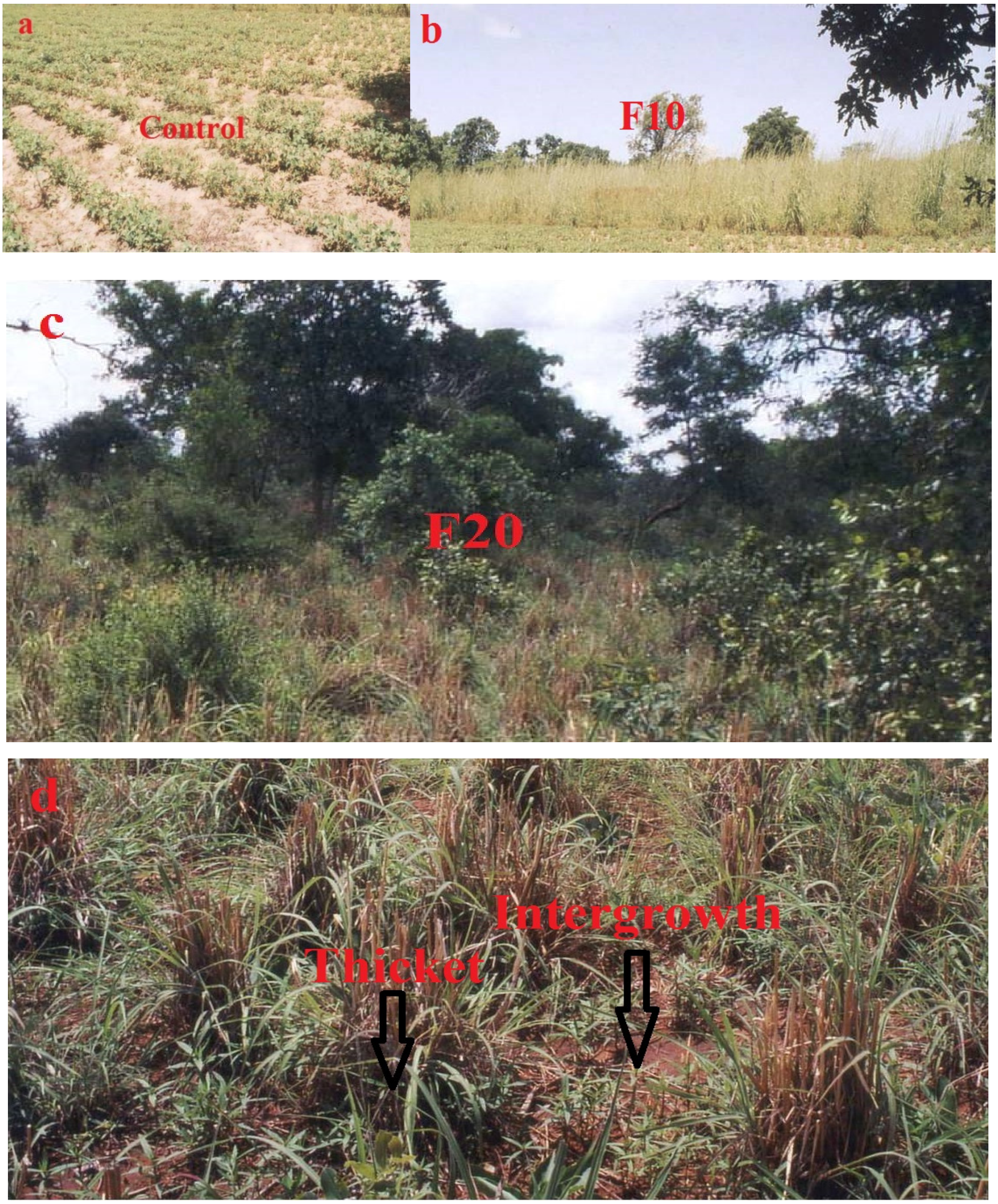


Figure 2. Crop and vegetation stages in Bondoukuy grasslands: a) cultivated field (control); b) young fallow land; c) old fallow land; d) vegetation cluster (thicket) and surrounding intergrowth area

3.1 Statistical Analysis

The experimentation design was based on randomized plots in which the main treatment was the plot stage and the sub-treatment was the granulometric size fraction. All statistical analyses were conducted using the StatView 6.0 software (SAS Institute, 1996). ANOVA (Scheffe's test, 1959) was performed to test the differences in SOC and TN across fallow periods for individual fractions. Differences were considered as statistically significant at $p < 0.05$.

4. Results

4.1 Soil Organic Carbon and TN Dynamics in different Fractions

ANOVA conducted on the data showed a significant effect of the plot stage on SOC and TN contents within the different granulometric fractions (Scheffe's test, $p<0.05$). Scheffe'S test also indicated a net increase in SOC contents within the coarse fractions over time (Scheffe'S test, $p< 0.05$; Table1). In overall, the SOC contents in old fallow lands were higher in all fractions (except clay).

Furthermore, the mean TN concentrations were significantly higher (Scheffe'S test, $p<0.05$) in old fallow lands compared to young fallow lands and cultivated plots (Table 1). As expected, there were particle size effects on C/N ratios of soil organic matter (Table 2), resulting in higher ratios in coarse fractions (>20 µm) compared to the fine ones (<20 µm). In addition, the C/N in fractions greater than 20 µm were significantly ($p<0.05$) lower in cultivated fields compared to the two fallow lands, but they remained constant in fine silt (C/N=10) and clay (C/N=8) fractions (Table 2).

Significant ($p<0.05$) variations in SOC contents were observed in coarse sand and fine silt fractions (Figure 3). However, the silt fraction accumulated more SOC than the clay fraction during the crop-fallow rotations (Table 1). Likewise, fine fractions showed higher variations ($p<0.05$) in TN during the crop-fallow rotations, whereas the highest TN concentrations were found in the fine silt fractions (Figure 4).

Table 1. Soil organic carbon (SOC) (µg C g^{-1} soil) and total nitrogen (TN) (µg N g^{-1} soil) contents in different fractions in the samples collected in the intergrowth soils. The standard error is in parenthesis, n = 18. Numbers with the same letters by column are not significantly different at the 5 % level (Sheffé's S test)

	SOC (µg g^{-1} soil)						TN (µg g^{-1} soil)					
	Granulometric fractions (µm)											
Land use	0.05-2	2-20	20-50	50-100	100-250	250-2000	0.05-2	2-20	20-50	50-100	100-250	250-2000
CP	860.52 ^{a}	651.04 ^{b}	173.08 ^{c}	101.22 ^{b}	186.62 ^{b}	305.68 ^{c}	103.03 ^{b}	54.95 ^{b}	4.64 ^{b}	8.83 ^{b}	7.34 ^{b}	13.03 ^{b}
	(496.82)	(375.87)	(90.92)	(58.43)	(107.74)	(176.48)	(29.46)	(31.72)	(2.67)	(5.09)	(4.24)	(7.52)
F10	763.09 ^{b}	708.48 ^{b}	276.46 ^{b}	143.73 ^{b}	220.10 ^{b}	588.92 ^{b}	99.70 ^{b}	58.07 ^{b}	5.00 ^{b}	12.75 ^{b}	5.65 ^{b}	13.20 ^{b}
	(240.57)	(309.61)	(159.61)	(82.98)	(127.07)	(340.01)	(27.56)	(33.52)	(2.88)	(7.35)	(3.26)	(7.62)
F20	855.33 ^{a}	995.49 ^{a}	426.29 ^{a}	265.72 ^{a}	510.77 ^{a}	732.88 ^{a}	120.99 ^{a}	101.45 ^{a}	11.46 ^{a}	23.66 ^{a}	17.84 ^{a}	25.52 ^{a}
	(493.83)	(574.74)	(246.12)	(153.41)	(294.89)	(423.12)	(69.85)	(88.57)	(16.61)	(13.66)	(12.29)	(14.52)

Table 2. C/N ratios analysed in the thickets and in the intergrowth areas in the different soil fractions. The standard error is in parenthesis, n = 18. Numbers with the same letter by column are not statistically significant different at 5 % level (Scheffé's S test)

	Intergrowth soils						thicket soils					
	Granulometric fractions (µm)											
Land use	0.05-2	2-20	20-50	50-100	100-250	250-2000	0.05-2	2-20	20-50	50-100	100-250	250-2000
CP	8 ^{a}	12 ^{a}	20 $^{a, b}$	43 ^{b}	37 ^{b}	70 ^{b}	-	-	-	-	-	-
	(4)	(7)	(12)	(25)	(21)	(40)						
F10	8 ^{a}	12 ^{a}	24 ^{a}	50 ^{b}	166 ^{a}	174 ^{a}	7 ^{a}	11 ^{a}	19 ^{a}	16 ^{a}	17 ^{b}	44 ^{b}
	(4)	(7)	(14)	(29)	(96)	(93)	(4.2)	(6.5)	(9.1)	(9.4)	(9.8)	(25.4)
F20	6 ^{a}	10 ^{a}	18 ^{b}	164 ^{a}	45 ^{b}	175 ^{a}	8 ^{a}	12 ^{a}	17 ^{a}	18 ^{a}	38 ^{a}	68 ^{a}
	(4)	(6)	(5)	(94)	(26)	(89)	(4.6)	(7.1)	(9.8)	(10.2)	(21.9)	(59.1)

CP: cultivated plots; F10: Ten years old fallow lands; F20: Twenty years old fallow lands.

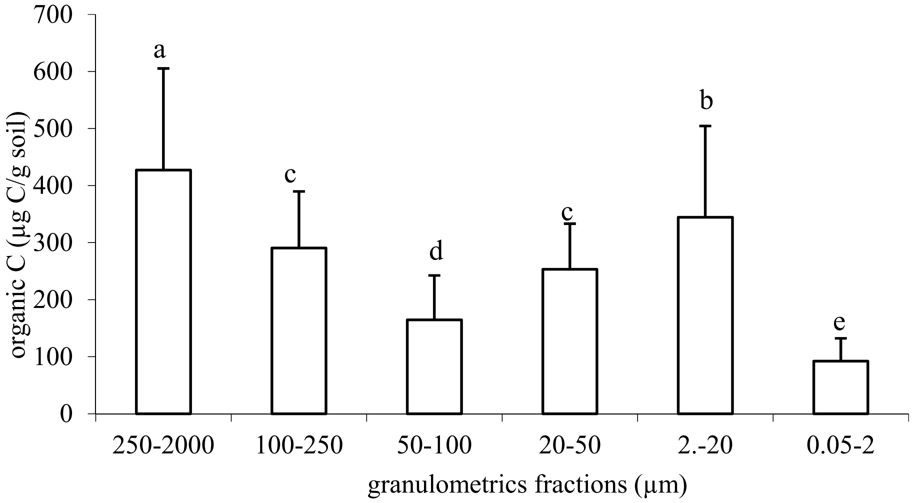


Figure 3. Variations in soil organic carbon (DC) distribution in different fractions from cropping to fallowing. Means with the same letters are not statistically significant at 5% level (Scheffé's S test). Results expressed as µg C g^{-1} of soil

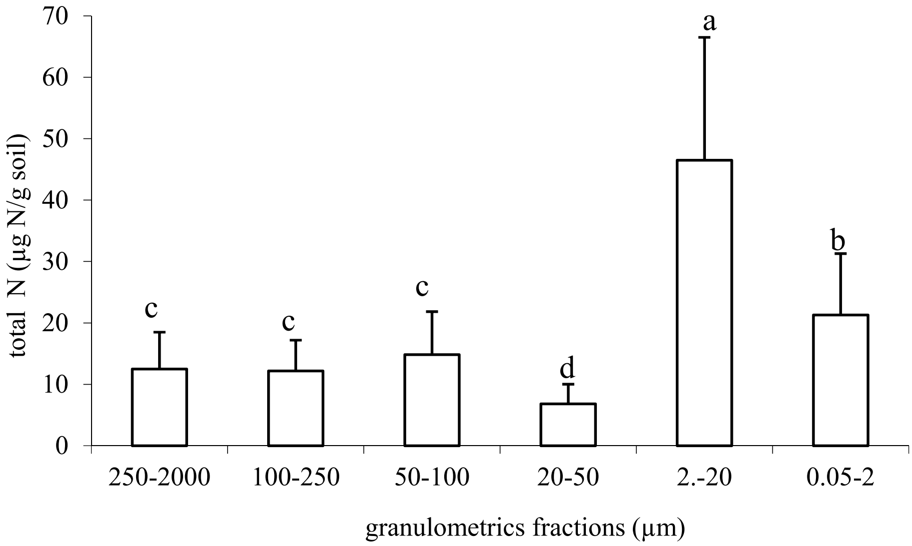


Figure 4. Total nitrogen variations (DN) in different soil fractions during the transition from cropping to fallow lands. Means with the same letters are not statistically significant at 5% level (Scheffé's S test). Results expressed as µg N g^{-1} of soil

4.2 Recovery of SOC and TN in Intergrowth and in Thicket Soils

The effects of fractionation on SOC and TN concentrations were quantified by comparing the concentrations of individual fractions to those obtained in non-fractionated bulk soil samples (Table 3). The results indicated that the fractionation and chemical analysis only caused small losses of SOC contents in the samples collected in the intergrowth areas. However, the sum of TN of individual fractions in the intergrowth soil samples was higher than those found in the bulk soil samples. Thus, at the end of the fractionation and chemical analysis, the sums of SOC were 0.22, 0.27 and 0.37 % in cultivated fields, young and old fallow lands respectively, as opposed to total concentrations of 0.25, 0.31 and 0.38 % in the bulk soil samples.

The fractionation did not cause any losses of organic compounds in the thicket samples (Table 3). In contrast, the fractionation balance of the samples from the sparsely vegetated intergrowth soils was positive as the sum of organic compound contents in different fractions was lower than to those found in bulk soil samples. The sums of SOC in the different fractions were also lower in young and old fallow lands (0.27 and 0.33%, respectively) than its total concentrations in the bulk soils collected from the same plots (0.36 and 0.44%, respectively). Similarly, the sums of TN in the individual fractions were relatively lower in young and old fallow lands (0.17 and 0.25 %) than the total TN in the bulk soils (0.23 and 0.30 %, respectively).

Table 3. Qualitative balance of carbon and total nitrogen contents in different fractionation of thickets and intergrowth soils under different land uses. Standard error is in parenthesis, n = 18. Numbers with the same letters by line are not statistically significant at 5 % level (Scheffé's test). Results express as µg g^{-1} soil

	Balance of the fractionation							
	Intergrowth soils				Thicket soils			
	Total Nitrogen (µg g^{-1} soil)		Organic carbon (µg g^{-1} soil)		Total Nitrogen (µg g^{-1} soil)		Organic carbon (µg g^{-1} soil)	
Land use	Bulk soil	Amount	Bulk soil	Amount	Bulk soil	Amount	Bulk soil	Amount
CP	136.67 ^{d}	191.82 ^{c}	2516.67 ^{a}	2278.16 ^{b}	-	-	-	-
	(68.9)	(105.27)	(1452.99)	(804.04)				
F10	183.33 ^{d}	194.37 ^{c}	3100.00 ^{a}	2710.78 ^{b}	230.00 ^{c}	172.13 ^{d}	3636.72 ^{a}	2706.15 ^{b}
	(75.84)	(111.81)	(1768.62)	(994.99)	(114.41)	(88.20)	(2099.66)	(1562.36)
F20	223.33 ^{c}	300.92 ^{b}	3873.67 ^{a}	3786.48 ^{a}	307.33 ^{c}	253.74 ^{d}	4430.00 ^{a}	3386.33 ^{b}
	(80.94)	(173.58)	(2236.46)	(2186.13)	(97.44)	(146.49)	(2554.66)	(1952.71)

CP: cultivated plots; F10: Ten years old fallow lands; F20: Twenty years old fallow lands.

4.3 Distribution of SOC and TN in Organo-Mineral Fractions in the Intergrowth Soils

Organic carbon and TN contents were mainly high in fine and coarse fractions, with pronounced lower concentrations in intermediate size fractions (fine sand, coarse sand, very fine sand and fine silt; Tables 1 and 2). Thus, the results showed that fine fractions (clay + fine silt) had about 67 % of SOC in cultivated fields and 54 % and 49% in young and old fallow lands, respectively. With 83%, the fine fractions in cultivated fields had the highest TN content compared to young (81%) and old (74%) fallow lands. The soil organic carbon contents in the coarse fractions (coarse sand + fine sand) varied between 3 and 8 %, whereas those of TN ranged from 4 to 22 %.

4.4 Soil Organic Carbon and TN Dynamics in Thicket Soils

The study of temporal variations in the vegetation tickets showed that SOC and TN contents varied in different fractions with SOC in coarse sand (F10 = 562 µg C g^{-1} soil and F20 = 939 µg C g^{-1} soil) and TN in fine silt (F10 = 15 µg N g^{-1} soil and F20 = 10 µg N g^{-1} soil) being the most dynamic layers as turnover time seems to be higher in these layers. ANOVA performed on the data demonstrated a significant ($p<0.05$) fallow age effect on SOC and TN distribution patterns in the various fractions (Table 3). According to the Scheffé S test, there is a net variation ($p<0.05$) in SOC distribution over time within clay (0.05–2 µm) and coarse sand fractions (>250 µm) in which SOC contents increase from young to old fallow lands (Table 4). However, in the intermediates fractions there were no significant ($p>0.05$) variations in SOC contents.

Table 4. Organic carbon (µg C g^{-1} soil) and total nitrogen (µg N g^{-1} soil) contents in different fractions of soils collected in thickets. The standard error is in parenthesis, n = 18. Numbers with the same letters by **column** are not statistically significant at 5 % level (Sheffé's S test)

	C (µg g^{-1} soil)						N (µg g^{-1} soil)					
	Granulometric fractions											
Land use	0.05-2	2-20	20-50	50-100	100-250	250-2000	0.05-2	2-20	20-50	50-100	100-250	250-2000
F10	578.27 ^{b}	867.68 ^{a}	276.7 ^{a}	144.8 ^{a}	276.53 ^{a}	562.17 ^{b}	78.86 ^{b}	37.22 ^{b}	15.22 ^{b}	8.77 ^{a}	15.64 ^{a}	16.42 ^{b}
	(323.2)	(500.6)	(158.15)	(83.03)	(150.53)	(304.23)	(25.06)	(21.49)	(6.26)	(4.72)	(15.05)	(8.64)
F20	911.2 ^{a}	841.06 ^{a}	290.62 ^{a}	155.17 ^{a}	249.07 ^{a}	939.21 ^{a}	113.09 ^{a}	69.47 ^{a}	24.87 ^{a}	9.15 ^{a}	10.21 ^{b}	26.95 ^{a}
	(500.58)	(485.58)	(118.4)	(89.5)	(141.21)	(542.25)	(57.17)	(40.01)	(20.62)	(4.97)	(5.13)	(20.36)

CP: cultivated plots; F10: Ten years old fallow lands; F20: Twenty years old fallow lands.

The mean comparison test showed that TN contents were higher ($p<0.05$) in old fallow lands than in young ones for all fractions except for fine sand fractions (Table 4). The C/N ratios were also higher in coarse fractions (i.e., coarse sand and fine sand) than in fine fractions (i.e., clay, fine silt, coarse silt and very fine sand). Likewise, the C/N ratios of fine sand and coarse sand fractions were higher in old fallow lands than in young ones. In other fractions, the C/N ratios did not vary between old fallow and young fallow lands (C/N~24).

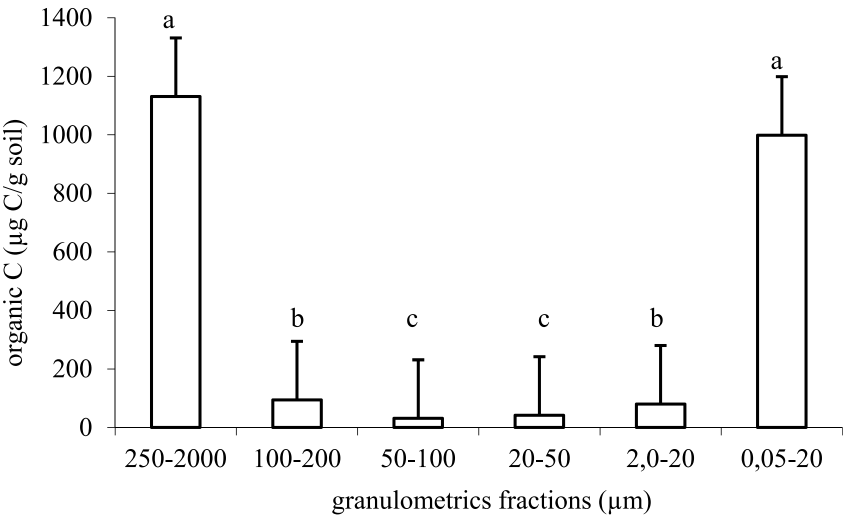


Figure 5. Variations in soil organic carbon (DC) contents in different fractions during transition from young to old fallow lands. Means with the same letters are not statistically significant at 5% level (Scheffé's S test). Results expressed as µg C g^{-1} of soil

The variables DN and DC showed that:

- for SOC contents, DC was higher in coarse sand and clay fractions than in other fractions (Figure 5). These fractions were therefore the most dynamic ones in sequestrating SOC during the natural succession of fallow lands;

- for TN contents, DN was more pronounced in fine fractions (i.e., clay and fine silt fractions) than in coarse fractions (>20 µm) (Figure 6). Coarse sand fractions accumulated the lower proportion of TN relative to fine sand, very fine sand and coarse silt fractions during the transition from young to old fallow lands.

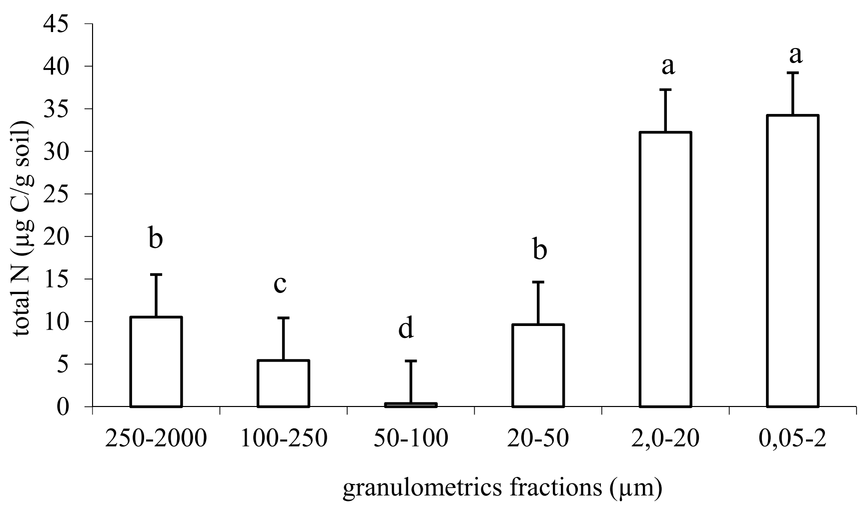
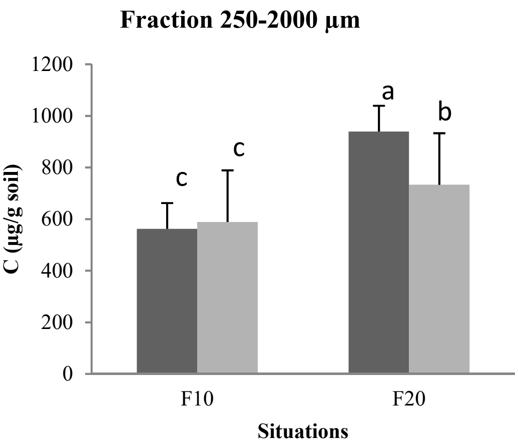


Figure 6. Total nitrogen variations (DN) in different soil fractions during the transition from young to old fallow land. Means with the same letters are not statistically significant at 5% level (Scheffé's S test). Results expressed as

μg N g^{-1} soil



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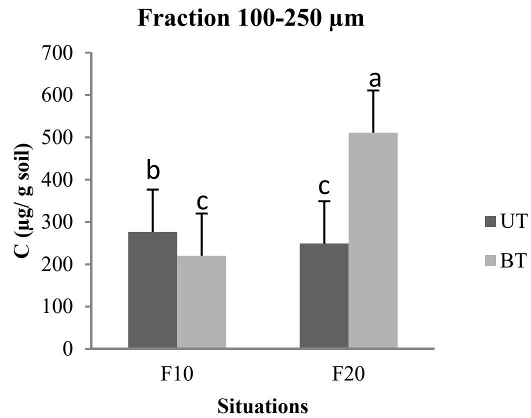

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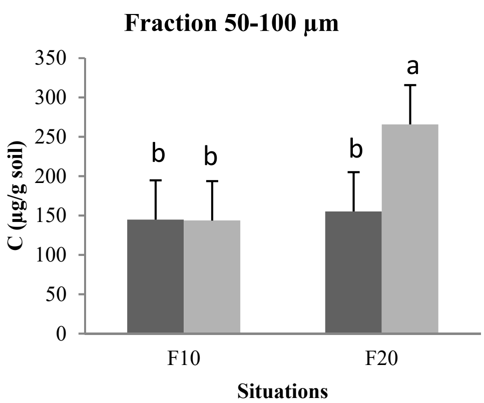

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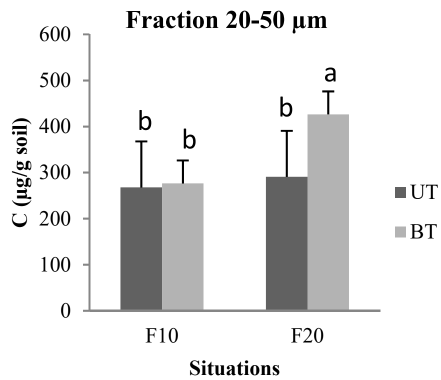

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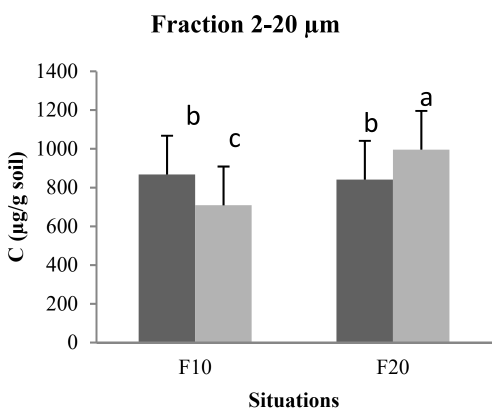

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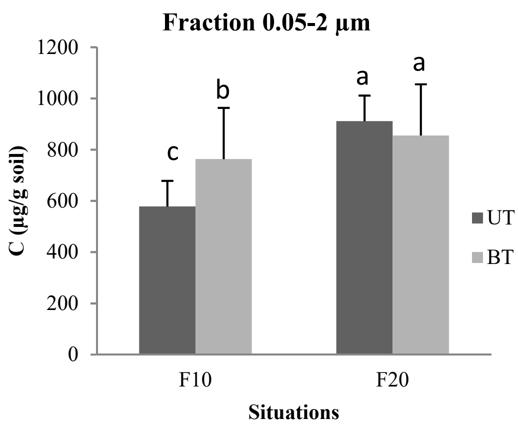
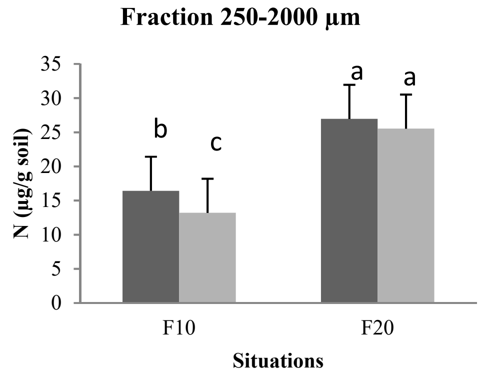
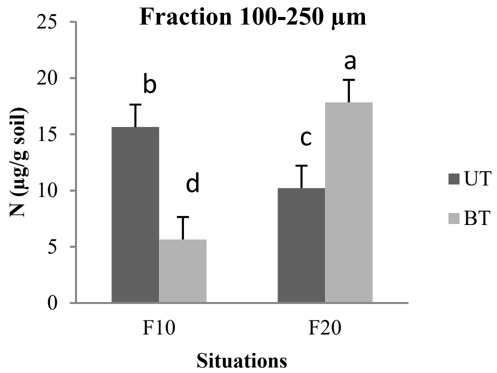


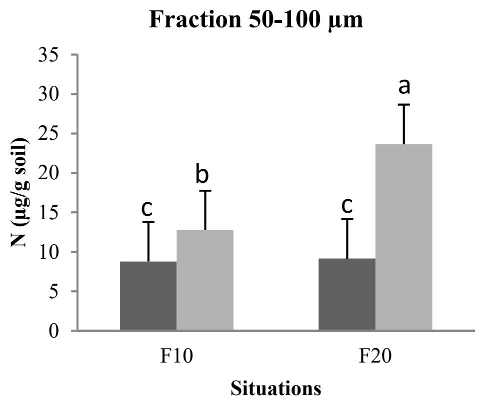
f

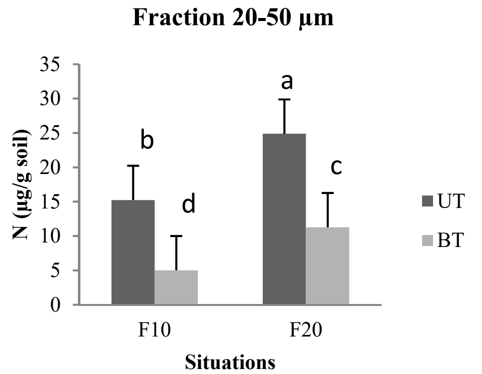
Figure 7.a, b, c, d, e and f**.** comparison of organic carbon contents in soil fractions during fallow transition. Means with the same letters are not statistically significant at 5% level (Scheffé's S test). Results expressed as µg C g^{-1} soil. Where F10: Ten years old fallow land; F20: Twenty years old Fallow land. UT = thicket soils and BT = intergrowth soils





a b





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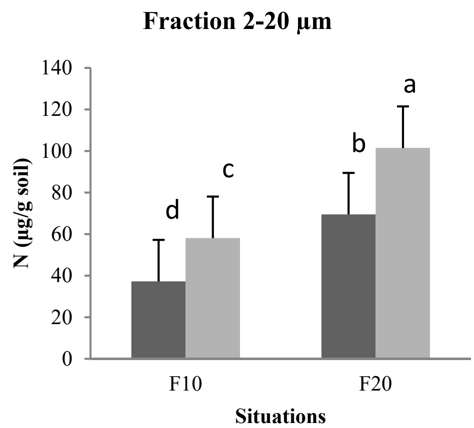

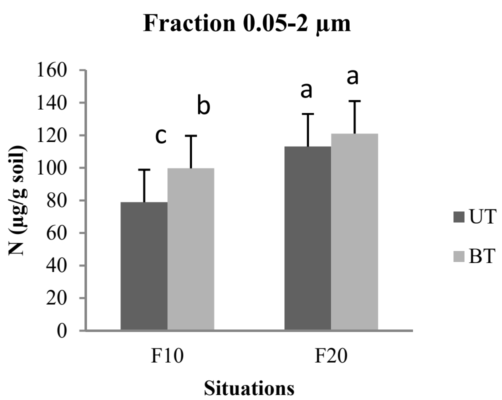

e f

Figure 8.a, b, c, d, e and f: comparison of total nitrogen contents in soil fractions during fallow transition. Means with the same letters are not statistically significant at 5% level (Scheffé's S test). F10: Ten years old fallow land; F20: Twenty years old Fallow land. UT: thickets; BT: intergrowth areas

4.5 Soil Organic Carbon and TN Distribution in Organo-Mineral Fractions in the Thicket Soils

Most of SOC was found in clay and coarse sand fractions, whereas TN was mainly found in fine fractions (Table 4). Coarse fractions contribution to SOC contents varied from 44 to 52 % in young fallow lands and about 49 % in old ones, but those of fine fractions were high (48–56 % and 51 % for young fallow lands and old fallow lands, respectively). Fine fractions contributed up to 70 % of TN contents in both young and old fallow lands as compared to the low contribution of coarse fractions (22–32 % and 18–34 % for young fallow lands and old fallow lands, respectively).

4.6 Spatial Abundance of SOC and TN in the Ticket and Intergrowth Soils

Transition from young to old fallow lands showed relatively high SOC in all fractions in the intergrowth areas, whereas only the coarse fractions exhibited a relative increase of SOC in the thickets (Figure 7). The same transitional pattern was observed in TN contents with high contents in all fractions in the intergrowth areas and two distinct distribution patterns in the thickets (Figure 8):

i. TN contents decreases in fine sand fractions (100–250 µm) and remains constant in very fine sand fractions (50–100 µm) and

ii. TN contents increased in coarse sand (250–2000 µm), coarse silt (20–50 µm), fine silt (2–20 µm) and clay fractions (0.05–2 µm).

5. Discussion

5.1 Soil Organic Carbon and TN Contents in Different Fractions

Soil physical fractionation is a complex process, which sometimes results in loss of soil organic compounds. Furthermore, analysis of SOC and TN may be affected by the mineral matrices which vary within fractions and between fractions and bulk soil. Thus, many authors have observed organic compounds loss during soil physical fractionation (Feller, 1994; Nacro, 1997; Lehmann et al., 1998; Stemmer et al., 1999; Manlay et al., 2002 a, b; Balesdent et al., 2000). This loss is expected in water-soluble compound exportation (about 5–10% of SOC contents) during successive wet sieving and centrifugations. As a result, organic compounds could be transferred from coarse to fine fractions. In fact, soil shaking can lead to coarse organic compound division (sand abrasive effect) which may transfer small quantities of organic compounds to small fractions (Feller, 1994).The importance of this transfer depends on coarse organic matter concentrations, which are particularly small in the present study. Balesdent et al. (1991) have shown that organic matter transfer from coarser to finer fractions is possible, and it can be even significant when bulk soil is exposed to sonication. However, when ultrasonic sounds are applied on less than 50 µm fractions, as in the present study, the amounts of organic matter transferred are negligible.

5.2 Temporal Variations in SOC and TN Contents

Because of the labile condition of coarse fractions, particularly coarse sand, the organic matter pools are more prone to decomposition. This finding is consistent with several studies carried out on tropical soils (e.g., Feller, 1994; Nacro, 1997; Six et al., 1999; Six et al., 2000; Six, Paustian et al., 2000; Manlay et al., 2002 a; Devine et al., 2014; Peter, 2018). It can be therefore suggested that, despite their low organic matter content, the coarse fractions are likely to contribute more to the soil organic matter mineralization in cultivated fields. Although the fine fractions are quantitatively far more important than the coarse fractions, the turnover time of soil organic matter in these fractions is lower during fallowing. This suggests that fallowing may have reduced the stability of the fine fraction layers in the present study area. In contrast, several studies have demonstrated that although organic matter turnover time is low in the fine fractions, these fractions are more stable than coarser fraction (Feller, 1994; Puget et al. 2000; Mills et al., 2005). The low stability found in this study is likely due to bioturbation of the *A. gayanus* root systems.

By contrast, the processes that control SOC abundance in the clay layer are more difficult to explain because of the low SOC contents in young fallow lands relative to ploughed fields and old fallow lands. The recent change in the vegetation cover under young fallow lands may have resulted in rapid organic matter decomposition and its stabilization in the clay fractions. A negative transitory effect of fallow lands on SOC contents, the so-called “priming effect”, in the clay fractions may also exist. In the priming effect, a stimulation of soil organic matter mineralization is carried out through continuous fresh organic matter inputs (Fontaine, 2002).

The high DN variations in TN contents observed in the fine silt fractions could be ascribed to the uncertainties produced during the physical fractionation. As far as nitrogen availability for upcoming crops is concerned, the results showed that fine silt, clay and coarse fraction layers are likely to play a crucial role in soil TN replenishment. In overall, fallow lands had a positive effect on soil TN contents, but this effect is only noticeable in the long term fallowing since the differences in contents were not significant between ploughed plots and young fallow lands.

The decrease in C/N ratios from coarser to finer fractions suggests an increase in soil organic matter decomposition levels and, thus a decrease in soil organic matter biodegradability following particle size reduction (Goma-Tchimbakala, 2009; Subhrajit et al., 2010; Plaza-Bonilla et al., 2014). The high C/N ratios found in coarse fractions indicate the recent origin of soil organic matter which is a characteristic of fresh organic matter inputs rich in cellulose (Feller, 1994; Nacro, 1997). During decomposition, soil organic matter particle sizes are reduced progressively, and part of this organic matter ends up being associated with fine fractions with low C/N ratio (Liang et al., 2014). The fact that the high C/N ratios is found within coarse fractions of young and old fallow lands rather than in ploughed plots can be explained by an important quantity of dead roots in the soil and often by the incorporation of unburned aboveground plant materials.

5.3 Soil Organic Carbon and TN Distribution in Soil Organo-Mineral Fractions

Regardless of land-use practices, the relative SOC and TN contents tend to increase from coarse to fine fractions despite the low content of fine mineral particles. Comparing the relative SOC and TN contents, it can be noticed that for fractions greater than 20 µm (i.e., sands and coarse silt fractions), old fallow lands present more significant SOC and TN contents than young fallow lands and cultivated fields. In fractions smaller than 20 µm (i.e., clay and fine silt fractions), the differences between SOC and TN contents are less significant between ploughed plots and fallow lands. Fallow lands affect positively and significantly coarse fractions' contribution to soil organic matter restoration as corroborated by many studies (Liang et al., 2014; Sheng et al., 2015; Yu et al., 2017).

Climatic conditions such as humidity and high temperatures can also explain the small contribution of coarse fractions to the soil organic matter contents in the present study. It is possible that, at the beginning of the rainy season, the mineralization rate of plant litters within coarse fractions is high. This will strongly limit the organic matter accumulation in layers having particle sizes greater than 20 µm. This hypothesis is reinforced by many authors (Balesdent et al. 2000; Voncir et al., 2006; Feyssa et al., 2011; Ratnayake et al., 2011; Guimares et al., 2013; Udom et al., 2015) who have demonstrated that organic matter renewal rate in coarse fractions is higher than in the fine fractions. The high mineralization rate of fresh soil organic matter observed in the present study, with high sand contents, is due to the fact that the bulk soil organic matter contents are always associated with fine particles which can physically protect them against microbial attacks (Feller, 1994). Because SOC constitutes a large reservoir and supplier for nutrients, it can be concluded that the soil is characterised by essential nutrient paucity.

5.4 Soil Organic Matter Dynamics in the Different Fallow Stages

Comparison of SOC and TN contents in thicket soils and in the surrounding intergrowth soils highlights an unexpected mechanism. In fact, SOC contents are higher in the thickets than in the intergrowth areas in coarse sand fractions. Likewise, nitrogen contents tend to be higher in coarse silt fractions in the thicket soils than in the intergrowth soils. This can be attributed to high percentage of roots in the thickets compared to the intergrowth areas. In general, coarse fractions contain organic particles (e.g., root litters) whose sizes are greater than 250 µm. High SOC contents found in the thickets may be ascribed to an active contribution of *A. gayanus* to the soil organic matter restoration. It can be suggested that organic particles transfer from *A. gayanus* roots has already been taken place from coarse fractions in the thickets to fine fractions in the intergrowth areas. Consequently, organic matter incorporation during the fallow period occurred rapidly in coarse fractions with grain size less than 250 µm. The organic matter incorporation was also accompanied by a transfer of organic matter from the thickets to the intergrowth areas.

Soil organic carbon contents in fine silt fractions (< 20 µm) and coarse factions (< 250 µm) followed a similar distribution patterns, characterised by high contents in the intergrowth areas compared to those in the thickets, suggesting a progressive incorporation of SOC through fraction overtime. In contrast, in the clay fraction, SOC contents found in the thickets are higher than those found in the intergrowth areas.

The organic matter contents observed in young and old fallow lands suggested that organic matter contents increase with decreasing soil textural sizes, and they were always high in old fallow lands than in young ones. However, the high organic matter restoration dynamics in coarse fractions of the thicket soils is an indication of a possible contribution of *A. gayanus* biomass to SOC contents. However, organic matter contents in the thicket soils are not always higher than those in intergrowth soils, as organic matter distribution is a function of fractions. The presence of *A. gayanus* alone cannot justify organic matter restoration, but the fallow process appears to play a crucial role in the soil organic matter restoration. It can also be noticed that irrespective of SOC and TN distribution patterns through different fractions, the inflow of fresh organic matter seems to occur in coarse sand fractions, whereas its long term storage takes place in clay fractions.

6. Conclusion

This study showed that fallowing of intensively ploughed soils in a tropical climatic setting can restore SOC and TN contents. The study also identified the various processes through which the soil organic matter restoration takes place. Hence, the results showed that although fallowing leads to organic matter accumulation within the soil coarser fractions, which can significantly make essential nutrient available to crops during cultivation phases, the finer fractions constitute the sites of the organic matter restoration and improvement of physical properties. An extended fallowing (10–20 years) can produce two important effects:

i. accumulation of organic compounds in coarser fractions and restoration of SOC in the short term so that crop needs in essential nutrients during cultivation can be satisfied and

ii. accumulation of organic compounds in finer fraction and restoration of SOC in the long term to make nutrients available to crops during cultivation.

The optimal fallowing period remains an open question as far as the investigated system is concerned. In other words, in a sandy soil, organic matter sources are mainly based on spatially heterogeneous perennial grasses with an aggregated shallow root system. The obtained results on granulometric fractions of the soils in thickets and intergrowth areas suggested that a long fallowing period is not always necessary.

Acknowledgements

We are grateful to Benest D. and Verdier B. from the Laboratoire d'Ecologie at ENS Paris, for the carbon and nitrogen analyses and for the granulometric characterization. This study was financed through an inter-state co-operative research programme set up by the French Institut de Recherche pour le Développement.

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