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Chapter *in* Nutrient Cycling in Agroecosystems · October 2007

DOI: 10.1007/978-1-4020-5760-1_70

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Nutr Cycl Agroecosyst (2006) 76:331–339
DOI 10.1007/s10705-006-9023-0

Intensity cultivation induced effects on soil organic carbon dynamic in the western cotton area of Burkina Faso

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Received: 1 September 2004 / Accepted: 26 April 2006 /

Abstract The soil organic carbon (SOC) dynamic is a key element of soil fertility in savannah ecosystems that form the key agricultural lands in sub-Saharan Africa. In the western part of Burkina Faso, the land use is mostly linked to cotton-based cropping systems. Use of mechanization, pesticides, and herbicides has induced modifications of the traditional shifting cultivation and increased the need for sustainable soil fertility management. The SOC dynamic was assessed based on a large typology of land cultivation intensity at Bondoukui. Thus, 102 farm plots were sampled at a soil depth of 0–15 cm, considering field–fallow successions, the cultivation phase duration, tillage intensity, and soil texture. Physical fractionation of SOC was carried out by separating the following particle size classes: 2,000–200, 200–50, 50–20, and 0–20 μm. The results exhibited an increase in SOC stock, and a lower depletion rate with increase in clay content. After a long-term fallow period, the land cultivation led to an annual loss of 31.5 g m^{-2} (2%) of its organic carbon during the first 20 years. The different fractions of SOC content were affected by this depletion depending on cultivation intensity. The coarse SOC fraction (2,000–200 μm) was the most depleted. The ploughing-in of organic matter (manure, crop residues) and the low frequency of the tillage system produced low soil carbon loss compared with annual ploughing. Human-induced disturbances (wildfire, overgrazing, fuel wood collection, decreasing fallow duration, increasing crop duration) in savannah land did not permit the SOC levels to reach those of the shifting cultivation system.

Keywords Cultivation intensity · Fallow · Savannah · Soil fractions · Soil organic carbon

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Introduction

Soil organic matter (SOM) content is considered to be a key element determining the fertility of tropical savannah soils (Piéri 1989; Sédogo 1993; Feller 1995; Six et al. 2002). Many studies have shown that organic matter dynamics in tropical areas involve several parameters determining SOM stock level. It includes the soil tillage system during the cropping period, the rainfall pattern, organic and mineral fertilizer inputs, and soil texture (Feller 1995; Chan et al. 2002; Lal 2000; Olaoye 2002).

Long-term agricultural experiments carried out both in Europe and the USA indicate that SOM is lost during intensive cultivation, typically showing an exponential decline after the first cultivation of virgin soils, but with continuing steady loss over many years (Arrouays and Pélissier 1994; Reicosky et al. 1995, 1997; Pretty and Ball 2001). The ability of soils to retain carbon and nutrients is related to soil texture and many biogeochemical processes in the ecosystem (Whendee et al. 2000). Generally, SOM increases linearly with clay content on regional and global scales (Feller et al. 1991; Parton et al. 1993; Schimel et al. 1994). However, the interactions between soil texture and biogeochemical cycling are complex. Clay soils can facilitate the formation of passive carbon pools with slow turnover times due to the physicochemical protection of SOM by clay minerals (Christensen 1992; Balesdent et al. 2000). Sandy soils are often associated with high fine root biomass in tropical forests due to greater carbon allocation to roots for nutrient and water uptake (Cuevas and Medina 1988). Evaluating the size of carbon pools and the carbon sequestration potential is presently one of the most serious and complex areas of research in environmental science (Trofimow et al. 1997). Thus, several studies dealt with the effects of tillage and cropping systems on soil organic carbon (SOC) pools and carbon sequestration (Benny et al. 2002; West and Post 2002; Gonzalez and Laird 2003; Fabrizzi et al. 2003; Mikha and Rice 2004). The chemical structure of SOM may not adequately characterize carbon turnover (Duxbury et al. 1989); thus, physical fractionation techniques, which are less destructive than chemical extractions, are commonly used. Particle size fractionation is based on the observation that carbon in the sand fraction is generally more labile than carbon in clay and silt size fractions (Tiessen and Stewart 1983). SOM monitoring in tropical agricultural areas led to sparse results and few results exist on SOM dynamics in line with cropping systems at the farm/field level. The present study deals with land use intensity-induced effects on SOC dynamics, and size distribution in the western cotton area of Burkina Faso. It covers two contrasting landscapes, different fallow lengths, and various tillage systems. We propose to analyze, using a synchronic approach, where the SOM dynamic in different particle size fractions is related to the land use intensity.

Material and methods

The study was carried out at Bondoukui (11°51′ N lat., 3°46′ W long., 360 m altitude), located in the western cotton zone in Burkina Faso. Mean average annual rainfall is between 900 and 1,000 mm, and is monomodally distributed over May to October. The maximal temperatures vary between 31 and 39°C. The average potential evapotranspiration reaches 1,900 mm per year. The main vegetation types in the Bondoukui area according to Devineau et al. (1997) are related to the hydrographic network (gallery forests, grassland often subjected to flooding and the savannah system). Vegetation type prior to cropping was an open woody savannah and the main species *Vittelaria paradoxa* and *Parkia biglobosa* constitute parklands in the cultivated areas. The soil type is ferric lixisols on the highland position (plateau) and ferric luvisols on the lowland position (low glacis). The soil characteristics in the study area are shown in Table 1. The soils of the lowland area appear to be chemically richer than those of the plateau.

Preliminary studies carried out by Ouattara et al. (1999) were used to establish the typology of the fields according to the intensity of cultivation (IC) as defined by Ruthenberg (1971). Thus, three major cropping systems (MCS) were identified:

- The shifting cultivation system, characterized by short cultivation periods (<10 years) and long fallow periods (>30 years). These old fallow lands are locally called ‘‘diuré‘‘

Table 1 Physical and chemical characteristics of Bondoukui soils (depth 0–15 cm)

Characteristics	Ferric lixisols (plateau)	Ferric luvisols (lowland)
Clay + fine silt (%)	13±8	29±10
Total sands (%)	74±11	50±13
Bulk density	1.53±0.06	1.44±0.09
Total base cations (cmol kg^{-1})	3.1±0.8	4.2±1.3
CEC (cmol kg^{-1})	3.3±1.0	4.9±1.7
Organic carbon (g kg^{-1})	3.9±1.4	6.3±2.0
Nitrogen (g kg^{-1})	0.27±0.10	0.5±0.10
pH water	5.9±0.3	6.1±0.4

CEC cation exchange capacity

- The fallow cultivation system or cyclical cultivation system with about the same duration of cultivation and fallow phases (<10 years)
- The continuous cultivation system, interrupted by very short fallow periods (1–3 years).

These MCS were split into the length of cultivation–fallow phases, and soil tillage types (Table 2).

Ploughing was done in most cases with cattle-drawn equipment. Some farmers had tractors, but in all cases, tillage did not exceed a depth of 15 cm.

Farm plots were sampled in each soil type (the sandy plateau and the silt to silt-clay lowland). The gravel content was <5% of the sampled soils. A total of 102 farms, including 33 natural fallow lands were sampled during the dry season at a depth of 15 cm corresponding to the soil layer that was much more influenced by tillage and organic matter input. Soil was sampled in consecutive bulk density measurements using a rubber balloon densitometer in three replications. These replicates were gathered to constitute composite samples for laboratory analysis.

Finely sieved soil (sieve opening 2 mm) was used to determine soil particle size distribution using the Robinson pipette method (Mathieu and Pieltain 1998). SOM fractionation was done following a procedure based on particle-size distribution with soil dispersion (Vanlauwe 1996; Fabrizzi et al. 2003). One-hundred grams of fine air-dried soil were dispersed in 100 ml of a sodium hexametaphosphate-bicarbonate solution (20 vol concentration) mixed with 500 ml of distilled water. After dispersion, the soil slurry was wet-sieved on a wet-sieve shaker to separate the 2,000–200, 200–50, 50–20 and 0–20 μm organo-mineral fractions. The different organo-mineral particle size fractions obtained were oven-dried at 60°C and weighed.

The SOC content was measured using the Walkley and Black method adapted to Burkina soils by Gnankambary et al. (1999). The organic carbon recovery rate was between 95 and 100%. Soil effective cation exchangeable capacity (CEC) and exchangeable base cations were determined using cobaltihexamine chloride according to the method described by USDA (1996). Soil pH was measured at a soil–solution ratio of 1:2.5. Statistical analyses, ANOVA, were carried out using the software Genstat, version 6.

Results

Texture effect on soil carbon stock

Soil organic carbon stock was different for the MCS in the two types of soils in the Bondoukui agricultural landscape. The amount of carbon in the 0–15 cm layer was higher on the silty-clay texture ferric luvisols than in the sandy ferric lixisols (Fig. 1).

Table 2 Number of plots in the cropping system typology according to major cropping systems (MCS) and the tillage types

	Shifting system		System with fallow periods			Continuous system			
	F30	C10	F20	F10	C10	Plough./2 years	Plough./year	Manure	Total
Plateau	2	2	10	7	14	7	12	5	59
Low glacis	9	7	3	2	9	9	3	1	43
Total *n*	11	9	13	9	23	16	15	6	102

F30 30–40 years fallow; *F10* 1–10 years fallow; *F20* 11–20 years fallow; *C10* 1–10 years cultivation; *Plough./2 years* biennial ploughing; *Plough./year* annual ploughing; *Manure* manure ploughing-in

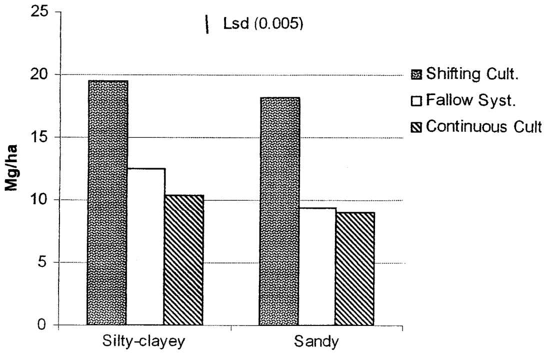

Fig. 1 Soil carbon stock in the major cropping systems (MCS) on the two types of soil

Soil clay content was the main parameter of texture that affected SOC stock. A comparative regression of SOC stock in fields and fallows according to soil clay content showed a linear regression in fallows ($y = 0.18$, $x + 3.3$, $r^2 = 0.39$), while it was better with a logarithmic adjustment in cultivated fields ($y = 2.6$, $\log x - 1.1$, $r^2 = 0.42$; Fig. 2).

Previous studies in the Bondoukui area conducted by Ouattara et al. (1999) showed two equilibrium levels of SOC contents according to the ecological conditions of the forest and the savannah. A comparative analysis of SOC stocks with these equilibrium values showed that almost all soils of the continuous cultivation system (C) are below the "savannah" line (Fig. 3). The annual ploughed plots occupied the lower limits. For soils with clay content below 10% (sandy soils), young fields of cyclical cultivation systems, cleared forest, and some organic fertilized fields displayed SOC stocks larger than savannah SOC, proving an increase in SOC stock after cultivation.

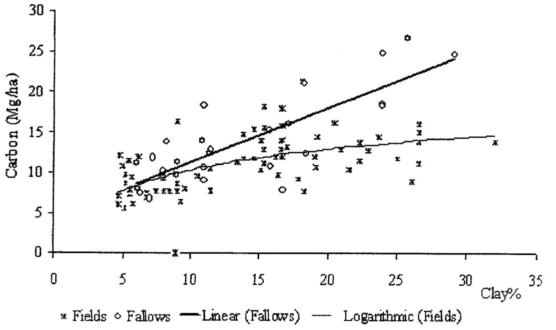

Fig. 2 Field and fallow soils carbon stocks related to soil clay content in the whole cropping systems

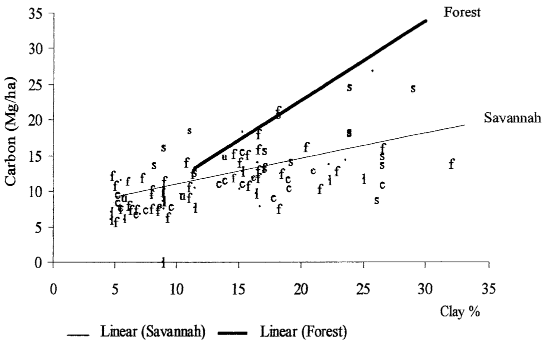

Fig. 3 The MCS soil carbon stocks related to soil clay content. *f* fallow system, *c* continuous cropping, *s* shifting cultivation

Soil carbon stock and carbon to nitrogen ratio in the different systems

The statistical analyses of SOC stocks in the two soil types showed significant differences between the shifting cultivation system and the two other MCS that were not statistically different. The average carbon stock in the shifting cultivation system was 16.90 Mg ha^{-1}, while it was 10.68 and 10.05 Mg ha^{-1} for the fallow cultivation system and the continuous cultivation system respectively (LSD = 2.43). In the shifting cultivation system the old fallows had the higher carbon stock compared with the fields on the two landscapes (Fig. 4). In the fallow system on the sandy plateau, the lower carbon stock was found in the cropped farms (Fig. 4a), while on the clay lowland the lower carbon stock was found on the short fallows, F10 (Fig. 4b). In the continuous cultivation system for the two soil types annual ploughing had the lower SOC stock compared with biennial ploughing and manure application, which were not statistically different (Fig. 4). There was a progressive decline in SOC stocks from the shifting system plots to the cyclical system then to the continuous cultivation system.

Cultivated field SOC stocks were lower than those of the natural fallows. Indeed, in natural fallows, SOC stocks increased with fallow age: 10.33, 12.64 and 19.66 Mg ha^{-1} respectively for F10, F20, and F30, but no significant difference was found between young fallows (F10) and intermediate age fallows (F20).

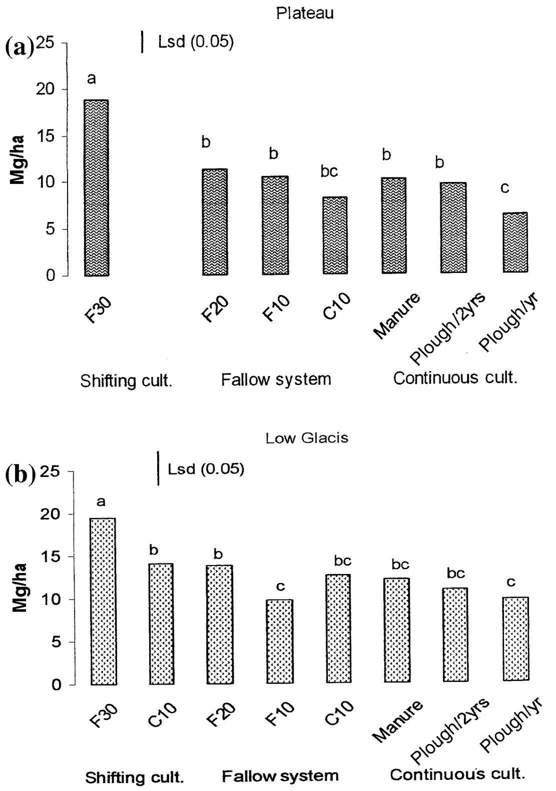

Fig. 4 Soil total carbon stock in a layer 0–15 cm in the different cultivation systems **a** on the plateau and **b** on the low glacis

The cyclical cultivation system did not induce any significant differences in SOC stocks between cropping and fallow phases. The land use change of a 20-year-old fallow led to a decrease in SOC stock, but at a lower rate than that of the shifting cultivation system.

In the continuous cropping system, SOC remained at a steady level under the cumulative effects of rotation, manure supply, and/or cattle penning. Annual ploughing led, however, to a drastic decline in SOC.

The carbon to nitrogen ratio was higher in the ferric lixisol (plateau) than in the ferric luvisol (low glacis) soils (Table 3). In both cases, the carbon to nitrogen ratio was higher in fallow soil than in cropped soils. Soil tillage led to a decrease in the carbon to nitrogen ratio and ploughing-in manure contributed to alleviating this depletion.

Carbon contents in soil particle size fractions

The amounts of carbon in the sand fractions (2,000–200 and 200–50 µm) were about the same in the two soil types, while the carbon contents in the 50–20 and 0–20 µm fractions were different for the two landscapes (Table 4).

The distribution of the SOC in soil fractions had the same trend for the plateau and the low glacis. Thus, the averages of the two landscape SOC contents in the particle size fractions were presented in the different MCS (Fig. 5). The fine-sized particle fraction (0–20 µm) contained 70–80% of total soil carbon. The carbon contents of the MCS (shifting cultivation, fallow system, and continuous cultivation) were not statistically different for the 2,000–200 and 200–50 µm fractions, while the shifting cultivation system had the highest SOC contents for the 50–20 and 0–20 µm fractions.

In the coarse fraction (2,000–200 µm) SOM contents were the highest in the F30 fallows, which was not significantly different from F20 and the manured field in the fallow system and continuous cultivation system respectively (Fig. 5). There were no significant differences between cultivation systems for SOC contents in the 200–50 µm soil fraction. The SOC contents in 50–20 and 0–20 µm soil fractions were higher in the old fallow F30 followed by C10 in the shifting culti-

Table 3 Carbon to nitrogen ratio (*C:N*) and mean clay content in the different cultivation systems

	Shifting system		Fallow system			Continuous system				
	F30	C10	F20	F10	C10	Plough./2 year	Plough./year	Manure	LSD	$P < F$
C:N plateau	19.9a		20.8a	19.0ab	10.8	20.7a	9.3c	12.7bc	6.5	< 0.001
Clay plateau	23.4a		6.9b	6.2b	6.4b	6.9b	6.6b	5.9b	2.1	< 0.001
C:N low glacis	17.0a	11.6b	11.8b	10.2b	12.4b	11.2b	12.3b	13.7ab	4.4	0.005
Clay low glacis	17.2ab	22.3a	13.2b	10.7b	13.2b	17.9ab	11.2b	10.2b	8.6	< 0.007

Numbers followed by the same letter are not statistically different vation system. The lower values of SOC in these fractions were in the annual ploughing of the continuous cultivation system. There was a decreasing trend of SOC content from the shifting cultivation system to the fallow system then the continuous cultivation system (Fig. 5).

Table 4 Soil carbon contents (g kg^{-1} soil) in the different fractions on the two landscapes

	2,000–200 μm	200–50 μm	50–20 μm	0–20 μm	SOC
Plateau	0.40	0.40	0.51	3.01	4.35
Lowland	0.40	0.43	0.70	5.06	6.59
P < *F*	–	–	< 0.001	< 0.001	< 0.001
LSD	–	–	0.10	0.48	0.61

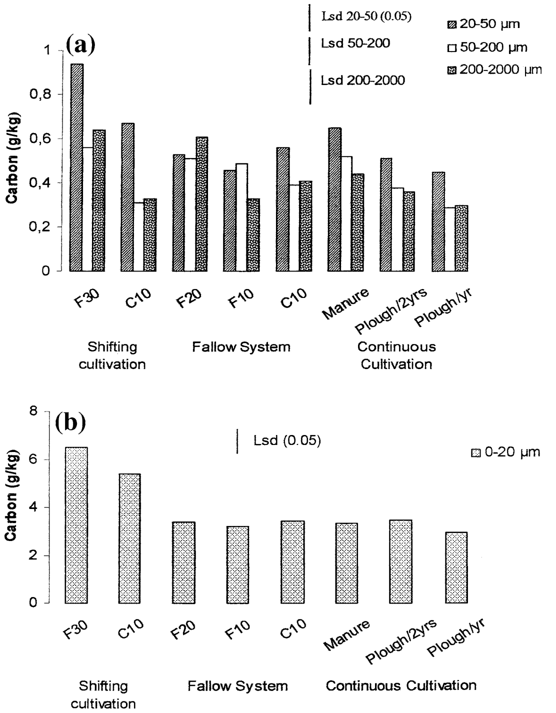

Fig. 5 Soil carbon contents in the different particle size fractions for the cultivation systems. **a** 20–2,000 μm, **b** 0–20 μm

Effects of tillage intensity

The fallow lands contained more SOC than cultivated lands. Ploughing induced a decline in SOC content and the lower it is, the more the ploughing intensity (Fig. 5). Thus, annual ploughing driven by cotton–maize rotations led to the largest losses affecting all soil particle size classes. The carbon of the fine soil fraction (0–20 μm) was affected much more. Supplying of manure, often accompanied by ploughing-in, mitigated the negative effects of intensive soil tillage. All soil particle size classes were affected by manuring, but the change was much greater in the 200–2,000 and 50–200 μm fractions.

Discussion

The importance of soil texture for SOC dynamics

The difference in SOC contents between the plateau and the low glacis may be attributed to their difference in clay content in addition to management factors. Numerous studies have shown that clay content is a relatively important determinant of SOC levels in low activity clay soils. The higher the clay content, the higher the SOM content (Feller 1993, 1995; Feller et al. 1991, 2001). In the context of Bondoukui, lowland clay soils close to the Mouhoun alluvial plain under the influence of forest ecology (more humid soils) contain twice as much carbon than the sandy soils of the plateau. Previous work carried out by Ouattara et al. (1999) has shown that the higher the fine particle content of the soil, the higher the differences between the SOC content of vegetation classes, revealing, therefore, a positive interaction between clay and vegetation (Duval et al. 1993; Albrecht et al. 1998).

Furthermore, because more clay soils lose carbon slowly during the cultivation phase, fine particles of soil not only constitute a simple ‘‘stocking compartment’’ for carbon (Feller et al. 2001), but they also play a protective role for SOC, as well as its coarse fraction associated with soil macro-aggregates (Chan et al. 2002) and its fine fraction (Balesdent et al. 2000; Oades 1984).

Carbon dynamic in MCS

Changes in SOC content according to land uses were assessed comparing soil organic stocks. Organic matter stocks under natural fallows were higher than those of cultivated soils. This is in accordance with their function of soil fertility restoration (Jaiyeoba 1997; Ouattara et al. 1999). But the increase in SOM content according to the age of the fallows remained relatively low with the cyclical cultivation systems. Indeed, at 20 years old, the organic status of these fallows represented only 47% of the equilibrium level reached in the 30-year-old fallows of the shifting cultivation system. This is not in accordance with the findings of Aweto (1981) and Jaiyeoba (1988), who have shown with forest soils that an 8- to10-years fallow period is enough to reach more than 75% of the steady level of SOM content. Such differences can be attributed to various effects induced by plot cultivation history preceding the fallow phase (practice of wildfires, overgrazing during the fallow phase, etc.)

The soil fertility restoration rate is related to the potential of vegetation reconstitution that influences the biogeochemical processes of soil. Thus, a long cultivation period, to which is added the degrading effects of mechanized soil tillage, leads to a decline in vegetative potential (stumps and roots after clearing) as well as the edaphic seminal potential corresponding to the seed bank in the soil (Mitja and Puig 1993). The Bondoukui area fallows were additionally submitted to overgrazing and wildfires, which handicapped vegetation reconstitution (César and Coulibaly 1993).

Considering the anthropogenic features of these natural savannah fallows we agree with Jaiyeoba (1997) that they can no longer play their traditional role of soil fertility restoration. Only the long-term fallows of the shifting cultivation system could play this role. However, this system is unfortunately disappearing from the Bondoukui agricultural landscape due to demographic pressure (César and Coulibaly 1993) and intensification of cultivation practices.

Soil cultivation is inexorably followed by a decrease in the SOC content (Nye and Greenland 1965; Piéri 1989; Lal 2000). The soils of the Bondoukui area did not escape this phenomenon. A decrease in the SOC content generally acts on the whole soil particle size fractions. In soils with a coarse texture, this decrease of around 45% of SOC after 20 years' cultivation represented an annual loss of 2% of SOC compared with the ''savannah shifting cultivation.'' This corresponds to the loss rate (root input minus mineralization) described by Piéri (1989) in his report on these same types of soils in West Africa.

Most studies on SOC kinetics for cultivated soils have shown that decline is faster during the first years following deforestation (Tiessen and Stewart 1983; Taonda 1995; Piéri 1989). The SOC of the coarse fraction, the most biologically labile, is at first most affected. After the first decade of cultivation, SOC stocks in cyclical and continuous cultivation systems seemed to reach a pseudo-equilibrium state, but this occurred more rapidly for sandy soil. The coarse fraction SOC is more sensitive to mineralization than that of the fine fraction, which is linked to clays and often protected in soil aggregates (Chan et al. 2002).

Soil tillage regime and SOC dynamics

The lowest SOC stock was observed in the continuous cultivation system under annual ploughing. This phenomenon affected the different carbon pools and especially the fine fractions of the soil. Balesdent et al. (2000) characterized this impact of ploughing according to three major actions:

- Creation of favorable pedo-climatic conditions for organic substrate biodegradation and/or SOC mineralization
- Incorporation of organic substrates into the soil matrix (soil macro-aggregates), which favors the protection of SOC against the biodegradation process or fast mineralization (Puget et al. 1996; Chan et al. 2002)
- Mechanical destruction of the soil structure under annual ploughing exposes SOC to fast mineralization. This explains its impact on organic carbon content of the fine fraction of the soil (Duval et al. 1993; Balesdent et al. 2000)

Soil macro-aggregates offer protection to SOC, and this ''protection capacity'' increases with SOC content, clay content, and with an absence of annual ploughing.

Organic matter supplies in the form of farmyard manure (animal waste), compost (domestic waste) generally ploughed in alleviates the negative effects of soil tillage on SOM. All soil particle size fractions were significantly affected by ploughing, but it is more accentuated in the 200–2,000 and 50–200 μm fractions (Fig. 5). Feller et al. (1983) characterized these fractions as organic matter ‘‘entry compartments.’’

Conclusion

Soil carbon fractionations showed a difference between the ferric lixisols and ferric luvisols in the Bondoukui area. This difference was expressed in the fine fractions (20–50 and 0–20 μm) and was due to the difference in clay content between the ‘‘sandy’’ lixisols and the ‘‘loamy’’ to ‘‘clay’’ luvisols. In general, SOC content decreased from the fallows of the shifting cultivation system toward the practice with the greater cultivation intensity value (continuous cropping system). Considering the tillage intensity, it appeared that SOC stock decreased from fallow lands to annual ploughing plots. This decrease affected all particle fractions. But if ploughing was associated with organic fertilization, the carbon loss was lower. SOC dynamics are driven by soil type and land use in relation to climate factors. These factors interact to determine the physical, chemical, and biological processes of the SOC dynamic. Understanding SOC dynamics under different agricultural and natural systems in the tropics is still a challenge for the choice of tools and practices that will contribute to an increase in soil carbon sequestration.

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