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Influence of Different Land Management Systems on the Dynamics of Carbon Biodegradability and Nitrogen Mineralization in a Sudanian Savanah Grasslands Soil, Western Burkina Faso

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Abstract

This study aimed to assess soil organic carbon (SOC) and total nitrogen (TN) dynamics under fallow lands influenced by the perennial grass *Andropogon gayanus* and to show how the biological activity is improved during the Sudanian tillage system in the area of Bondoukuy (Western Burkina Faso). Soil samplings were done through cultivated plots (CP), ten (F10) and twenty (F20) years old fallow lands. Measurements were done in thickets and intergrowth areas of the perennial grass in two horizons: the topsoil (0-10 cm) and the subsoil (10-20 cm). Results showed that SOC concentrations are generally higher in the old (0.35%) than in the young fallow lands (0.29%) and in the cultivated plots (0.23%). TN concentrations followed the same pattern (0.022%, 0.017% for the old and young fallows lands and 0.013% for the cultivated plots). The C:N ratio observed (15~20) suggests an important soil organic matter (SOC and TN) maturation state in the fallow lands (F10 and F20) than in the cultivated plots (CP). Soil mineralization is also more important in the two fallow lands than in fields. For the total nitrogen mineralization, we have an important production of mineral nitrogen always in old fallow lands and a positive effect of the thicket on the net mineral nitrogen accumulation ($p<0.05$). The transition from thicket to intergrowth area permits obtaining positive variations which are relatively significant ($p<0.05$). *A. gayanus* fallow lands play an active role in managing SOC and TN dynamics. The most SOC and TN accumulated was found in the topsoil of thickets, where the maximum plant debris is located. Old fallow lands are best conditions for the recovery of SOC and TN from their steady states. Then, when clearing the vegetation for cultivation after the old fallow lands, there is an important input of fresh OM available for plants in the soil for 3 or 4 years. It is recommended to observe the old fallow phase prior to clearing for cropping.

Keywords: savannah, soil organic carbon, total nitrogen, mineralization, dynamics, *A. gayanus*, fallow lands

1. Introduction

The study of soil respiratory activity permits an understanding of the significance of CO_2 emission in the laboratory and the field. The soil CO_2 emission in aerobics conditions is considered the product of an integration of the entire respiratory process. This process results to the global biological activity of the heterotrophic microflora, and then indirectly to the intensity of organic compounds mineralization (Bachelier, 1968). In shorts cropping fallow ecosystems of Western Africa, the restoration of soil fertility has mobilized a lot of attention. Then, the study of soil organic matter (SOM), i.e. soil organic carbon (SOC) and total nitrogen (TN) dynamic during the cropping fallow cycle showed that SOC and TN concentrations are more important under vegetation than between vegetation. This means that dead plant materials (leaves and roots) are an important source of organic matter (OM) (Yoni *et al.,* 2018).

Exogenous organic matter (EOM) incorporated into the soil undergoes enzymatic degradation processes of carbohydrates and lignin. The resulting organic compounds are transformed into simple minerals: this is called mineralization. The kinetics of mineralization is related to the nature of the EOM, environmental factors such as aeration, humidity, temperature, pH, etc., and the accessibility of the organic compounds to micro-organisms (Albrecht, 2007).

Thus, the initial organic matter is transformed into generally more stable compounds (humic substances and humus), but also into carbon dioxide and simple mineral compounds such as ammoniums and nitrates in the case of complete mineralization (Robert, 1996). These nitrogenous mineral elements are indispensable for plant metabolism and determine crop yields (Albrecht, 2007). The dynamics of mineralization and the activity of microbial biomass in soil can be described by the quantification over time of the different degradation products of the EOM (Albrecht, 2007).

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 (Yoni, 1997; Fournier *et al.*, 2000; Yoni *et al.*, 2018). Before starting a new farming session, the farmers in Bondoukuy determine if vegetation has been properly restored using the density and height of *A. gayanus* of the fallow lands as indicators of improvement of the soil fertility (Yoni, 1997; Fournier *et al.*, 2001).

The ability to biodegradation depends on microorganisms' conditions and organic materials brought during fallow. The quality of SOM is shown by the chemical composition of organic materials during the fallow. This quality varies depending on the vegetation species or cultivation methods (Van Vuuren *et al*., 1992) and globally influences organic carbon biodegradation (Berendse *et al*., 1989; Aber *et al*., 1990). We then established two hypotheses. The first hypothesis is that "SOC and TN concentrations and their spatial distributions strongly depend on the ecological history and vary during the post-cultural vegetation successions". It is supposed that SOC and TN concentrations vary during time and space, and were built up during the fallow period. Different studies (Neill *et al*., 1997; Manlay *et al*., 2002 a, b, c) comparing the "cultivation" and the "fallow lands" phases have shown that the balance of nutrient elements is generally negative during the cultivation and positive during the fallowing. This depends on the OM instability (decomposition and humification) and quality (variations between fractions) (Jenkinson et Rainer, 1977; Feller *et al*., 1993; Yoni *et al*., 2018).

The second hypothesis is that "SOC biodegradability and mineral nitrogen potentially available for plants strongly depend on the ecological history and vary during the post cultural vegetation successions". This condition supposes that the OM represents an entire physical material with different chemical compositions which determine its ability to biodegradation. The understanding of SOM dynamics then requires the characterization (chemical, biological, biochemical study properties) of the SOC biodegradability which controls the dynamics of plant nutrient availability (Feller, 1994; Nacro, 1997). The decomposition of this OM tends to contribute strongly to plants' mineral nutrition as opposed to SOC degradation and potential nitrogen mineralization. These two processes' intensity depends on SOM quality which varies according to its state. The expectation is that the soil biodegradability by microorganisms (of SOC and TN) is optimal after the fallowing period than at the end of the cultivation period, because of the accumulation of organic particles from plant debris.

Based on our two hypotheses, it is interesting to know if the vegetation underground production from perennial grasses strongly modifies the condition of the microorganisms' function.

2. Environmental Context

Soil samples were collected in Bondoukuy, located at the northern border of the Sudanian climatic area (11°51'N, 3°45'W) belonging to the "cotton zone" of western Burkina Faso (Figure 1). The climate is typical of the Sudan Savannah zone, with both rainfall and temperatures peaking once a year. With 7 to 8 months of the dry season, the average annual rainfall in Bondoukuy is 850 mm. The relative humidity is low and an extreme drought can be observed. Temperatures peak in April (41°C), and lowest temperatures occur in January (14° C), with another decrease in August (18° C) (Devineau *et al.*, 1997). During the dry season, predominantly bushfires are frequent. Every year, the time of occurrence, intensity and extent of fires seems haphazard, although, on a longer time scale, fires are a relatively predictable phenomenon (Fournier *et al.*, 2001). For centuries, human presence has markedly affected the region. The major activity today is cropping (cotton and cereals), which occasionally includes the traditional practice of fallowing, albeit for increasingly short periods. The second most common activity is extensive animal husbandry following an extensive system. As a result, the area is overgrazed and high demand for aerial biomass by the local rural communities.

The mosaic of the landscape consists of diverse cultivated areas and pasture-fallow lands. The natural vegetation cover of the Bondoukuy area is predominantly composed of woody species like *Isoberlinia doka*, *Terminalia avicennoides*, *T. laxiflora* and *Vitellaria paradoxa* (Guinko, 1984; White, 1986). The dominant grass biome is *A. gayanus*, *Pennisetum pedicellatum* and *Loudetia togoensis* (Fournier *et al.*, 2001).

Soils, above a sandstone substratum, are ferralitic in the upper parts, tropical ferruginous in the middle, and seasonally water-logged in the lower parts (Kissou, 1994; Devineau *et al.* 1997). The geomorphologic diagram is similar to the polygenic glacis system. Different soil types are encountered along the local pedotoposequence unit. Cultivated soils are mainly of the ferruginous leached-out type, usually at least one meter deep, and frequently hydromorphic about 50 cm (Kissou, 1994; Ouattara *et al.*, 2006). Both the indurate and the shallow soil are sandy-silty at the surface and silty-sandy from 15 to about 40 cm depth (Wright, 1985; Ouédraogo, 1998). These soils are characterized by a little-developed structure (Ladmirant and Legrand, 1969).

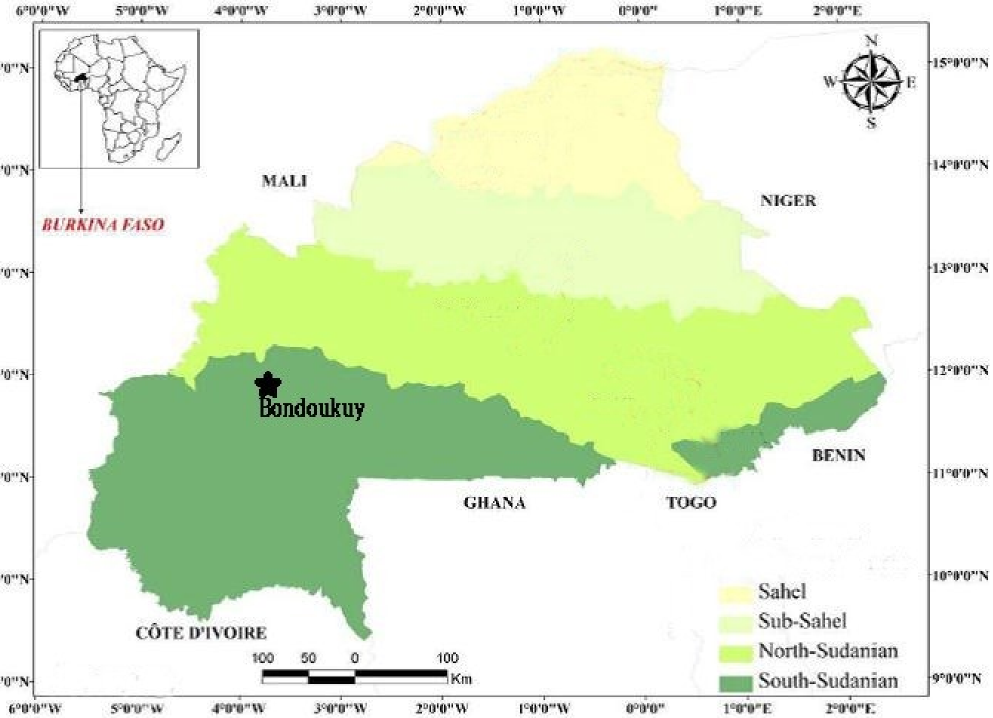


Figure 1. Phytogeographical Map of Burkina Faso, Showing the Study Area (Modified from Guinko, 1984).

3 Materials and Methods

The main criterion in the choice of sites was the presence of *A. gayanus* with a representative density (Yoni *et al.*, 2018). *A. gayanus* is a species which appears in the fifth to the eighth year in the fallow succession. After 10-15 years this grass is dominant in the vegetation of fallow lands. It is replaced by *A. ascinodis* after a successional transition of 20 years of fallow which demonstrates a return to the savannah (Devineau *et al.*, 1997). As a result, we decided to retain and compare 9 “test sites” of 2500 m^2 and 500 m apart: 3 cultivated plots (CP), 3 ten-year fallow lands (F10) and 3 twenty-year fallow lands (F20). The F10 corresponded to *A. gayanus* set up time, whereas the F20 corresponded to *A. gayanus* colonization time and CP are considered as control plots (Yoni *et al.*, 2018) (Figure 2).

Six topsoils (0–10 cm) samples were randomly collected on cultivated fields, the thickets and the intergrowth areas of the fallow lands, using an auger. The sampling approach was based on 0–10 cm (topsoil) and 10-20 cm (subsoil) depth. The soil samples were air dried, sieved through a 2 mm sieve and stored for subsequent analyses.

3.1 Laboratory Measurements-Soil Texture Determination

Particle size measurements are carried out according to the international Robinson pipette method. It is done on fine soil samples (< 2 mm) and gives concentrations of mineral particles after crushing, destruction of the SOM with hydrogen peroxide (H_2O_2) and dispersion with sodium salt. Clay and silt are separated by pipette while coarse particles are sieved at 50 µm.

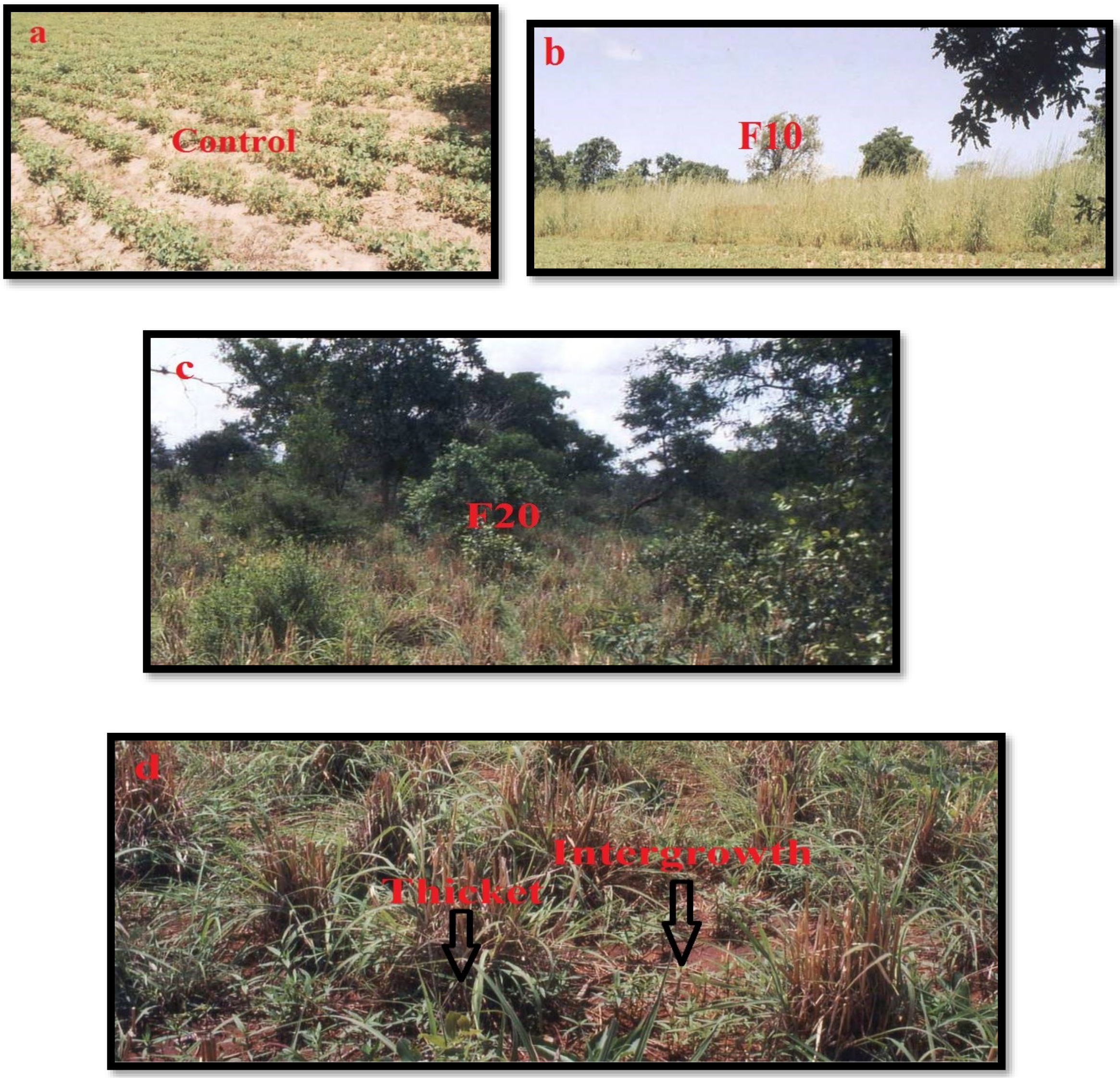


Figure 2. Crop and Vegetation Stages in Bondoukuy Grasslands: a) Cultivated Field (control); b) Young Fallow Land; c) Old Fallow Land; d) Vegetation Cluster (thicket) and Surrounding Intergrowth Area (Yoni *et al.*, 2018).

The resulting three fractions are clay (CL: 0.2-2 µm), fine silts (FS: 2-20 µm) and coarse fractions (CF: 20-2000µm) composed of coarse silts, fine sands and coarse sands. This analysis is performed on the average soil depth (0-20 cm) due to the very sandy nature of the study area.

-Soil organic carbon and total nitrogen contents measurements

Soil organic carbon and TN contents in subsamples were analysed using a Carlo Erba CHN analyser (NA 1500 series 2, Fisons). Results are expressed as % of C or N of dry soil weight. In order to better estimate SOM dynamics in different situations during the cropping fallow system, we have calculated the following variable called "relative increase of SOC (RIC) or TN (RIN) concentrations". This variable is obtained by taking the F20 soil (or the F10) as a reference, then subtracting from a unit base a calculated ratio of the different concentrations brought to percent. The ratio can be those of the CP and the F10 or the F20 depending on the comparison and the depth. For example: **(1-CP/F10)$_{N1}$x100** gives the relative increase of nitrogen concentrations (RIN) of the CP to the F10 plots at the topsoil.

Where CP = cultivated plots; F10 = ten year old fallow; N1 = total nitrogen at the 0-10 cm depth.

-CO_2 measurements

Fifteen g of soil were placed in a 130 ml bottle and brought to an equivalent humidity of 80% (PF 2, 75). The moistened soil was incubated at 28°C for 3 days in the dark. On a fixed date gas samples are taken and injected into a gas chromatograph to measure the CO_2 produced. The data obtained allow the calculation of the mineral organic carbon (Cmin). The results are expressed in µg $C\text{-}CO_2$ g^{-1} soil.

The amount of CO_2 released after a given period depends not only on the amount of organic carbon available, but also on its chemical quality and the degree of protection, particularly by clays. The coefficient of carbon mineralization (Dommergues, 1960) allows us to better determine the resulting accessibility of carbon to microorganisms. It is obtained by calculating the following ratio:

$$\frac{C\text{-}CO_2\ (\mu g\ g^{-1}\ \text{soil})}{C\ (\mu g\ g^{-1}\ \text{soil})} \times 100 \text{ where}$$

$C\text{-}CO_2$ represents the amount of carbon mineralized as CO_2 and

C is the initial amount of organic carbon.

-Mineral nitrogen measurements

After the CO_2 measurement, the flask containing the soil sample is stored for mineral nitrogen measurement. Ammonium and nitrate are extracted with 2M KCl after 30 minutes of shaking (speed: 270 rev. min^{-1}). The extracted solution is filtered through 1.2 µm glass filters (Whatman®). The ammonium and nitrate concentrations of the extracts are determined with a continuous flow colorimeter (Skalar San Plus System). Accumulated ammonium and nitrate are calculated from the difference in ammonium and nitrate concentration between incubated and non-incubated soil samples. Results are expressed as µg $N\text{-}NH_4$ g^{-1} soil, µg $N\text{-}(NO_3+NO_2)$ g^{-1} soil and µg $N\text{-}[NH_4 + (NO_3+NO_2)]$ g^{-1} soil.

By measuring the total mineral nitrogen in the soil, we have a net amount accumulated over some time, but not a gross amount. Thus, the amount of mineral nitrogen obtained during this short period (gross activity) by some microorganisms may have been immobilized by other microorganisms. So, the capacity of the soil to accumulate mineral nitrogen or net mineralization was assessed through the coefficient of "net mineralization" of nitrogen by this formula:

$$\frac{\text{mineral N}\ (\mu g\ g^{-1}\ \text{soil})}{\text{total N}\ (\mu g\ g^{-1}\ \text{soil})} \times 100$$

-Soil pH-H_2O measurements

Soil pH is a factor which influences relative intensities of ammonification and nitrification. The soil pH-H_2O is measured on soil samples in the average horizon of 0-20 cm layer, also called the “active biological layer”, for all plots. The measurement is carried out on a soil/solution mixture in the ratio of 1/2.5.

3.2 Statistical analysis

The experimentation design was based on randomized plots in which the main treatment was the plot stage. All statistical analyses were conducted using the StatView 9.0 software (SAS, 2020). ANOVA (Scheffe’s test, 1959) was performed to test the differences in SOC and TN concentrations across fallow periods. A step-wise linear regression was used to evaluate the effect of SOM concentrations on mineral carbon and nitrogen quantities. Differences were considered statistically significant at $p < 0.05$.

4. Results

4.1 Soil Texture

All the plots are sandy dominant (CP: 89.36 %; F10: 87.04 %; F20: 85.54 %) (Table 1). Table 1 highlights the strong stability of the textural composition during the fallowing and the cultivation cycle. Only the cultivated plots have a smaller clay concentration.

4.2 Variation of Organic Carbon and Total Nitrogen Contents in Intergrowth Area

The analysis of variance shows a very significant plot effect ($P<0.0001$) on the distribution of SOM at both layers 0-10 cm and 10-20 cm. Scheffe's S-test highlights differences between plots based on organic carbon and total nitrogen concentrations at both depths. In the two horizons, SOC contents are higher in the F20 (0.35%) than in the F10 (0.29%) and the CP (0.23%) (Figures 3 a, b, c and d). Total nitrogen contents followed the same pattern (0.022% for F20, 0.017% for F10 and 0.013% for CP) (Table 1). The C: N ratio of cultivated plots to old fallow in the topsoil (0-10 cm) shows a decreasing trend, suggesting a more intense humification of the SOM in the fallow (F10 & F20) than in the fields. This phenomenon is not observed in the deep layer. The calculation of the "relative increase in nitrogen concentrations" shows that 40% of the relative nitrogen stock has been replenished during fallow in the topsoil and about 35% of nitrogen has been replenished in the subsoil (Figures 3 a, b, c and d).

Table 1. Soils' Physicochemical Characteristics Recorded in Intergrowth (standard error is in parenthesis n = 18). Soils with the Same Letter by Column are not Significantly Different at the 5% Level (Scheffé's S test)

	Granulometric fractions (0-20 cm)			0-10 cm			10-20 cm		
Situation	CL (0,2-2µm)	FS (2-20µm)	CF (20-2000µm)	N (%)	C (%)	C:N	N (%)	C (%)	C:N
CP	6.60^{a}	4.10^{a}	89.36^{a}	0.013^{a}	0.250^{a}	20^{a}	0.013^{a}	0.200^{a}	16^{a}
	(3.78)	(2.36)	(51.59)	(0.007)	(0.140)	(11.48)	(0.007)	(0.110)	(9.11)
F10	8.46^{b}	4.52^{a}	87.04$^{a,\ b}$	0.017^{b}	0.31^{b}	18^{b}	0.016^{b}	0.260^{b}	17^{a}
	(4.88)	(2.60)	(50.25)	(0.009)	(0.170)	(10.73)	(0.009)	(0.150)	(10.07)
F20	9.89^{b}	4.56^{a}	85.54^{b}	0.022^{c}	0.380^{c}	17^{b}	0.021^{c}	0.320^{c}	15^{b}
	(5.70)	(2.63)	(49.38)	(0.012)	(0.220)	(9.84)	(0.011)	(0.180)	(9.01)

CP: cultivated plots; F10: ten years old fallow; F20: twenty years old fallow.

CL: Clay particle (%); FS: fine silt (%); CF: coarse fraction (%).

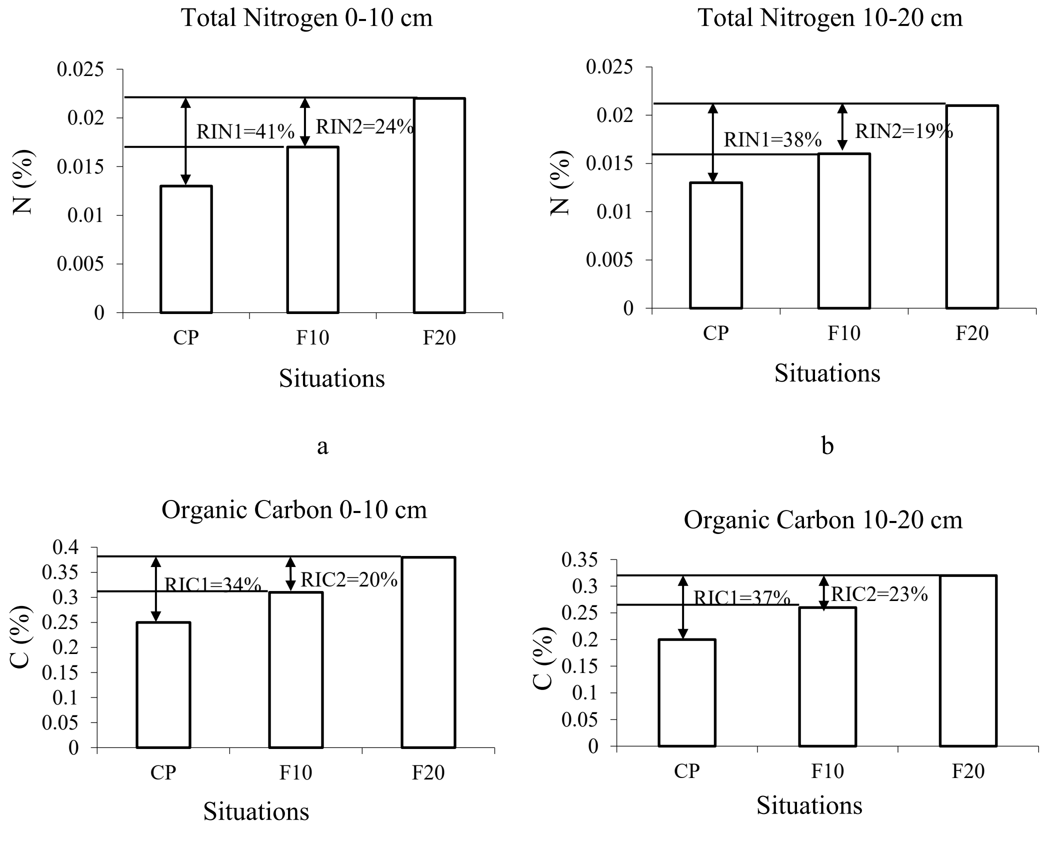


Figure 3. a, b, c, d. Variation of Soil Organic Matter Contents (C, N) in Intergrowth in the Two Soils Horizons during the Fallowing Cropping Period, Results Expressed as % of C or N.

CP: cultivated plots; F10: ten years old fallow; F20: twenty years old fallow.

RIN = "relative increasing concentrations" of total nitrogen between two situations

RIC = "relative increasing concentrations" of organic carbon between two situations

4.3 Variation of Organic Carbon and Total Nitrogen Concentrations in Thickets

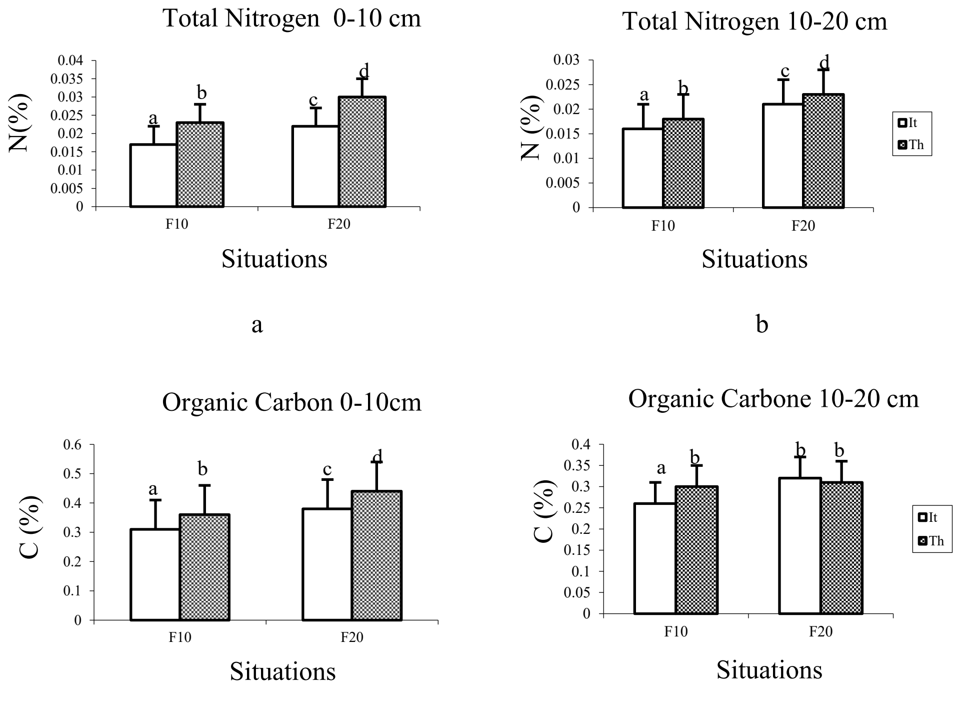
A very significant effect ($P > 0.0001$) of the plot type on the variation in SOC and TN contents in both soil horizons in thickets is obtained by ANOVA. In the topsoil (0-10 cm), Scheffé's S test showed that SOC and TN contents increased significantly from young to old fallows (Table 2). We observe the same trend in the 10-20 cm layer only for TN. C:N ratios in both horizons decrease sharply between young and old fallows, suggesting a more advanced state of SOM evolution in old fallows than in young fallows.

Table 2. Soils Biological Characteristics Recorded in Intergrowth (standard error is in parenthesis n = 18). Soils with the Same Letter by Column are not Significantly Different at the 5% Level (Scheffé's S test)

	0-10 cm		10-20 cm		0-10 cm				10-20 cm				0-20 cm
Situation	$C\text{-}CO_2$	Kc	$C\text{-}C0_2$	Kc	NH_4	NO_3	Nmtotal	Kn	NH_4	NO_3	Nmtotal	Kn	pH (H_2O)
CP	17.08 ^{a}	0.69 ^{b}	16.76 ^{a}	0.84 ^{a}	1.76 ^{a}	0.68 ^{b}	2.44 ^{a}	2.02 ^{a}	2.33 ^{a}	-0.17 ^{b}	2.16 ^{a}	1.73 ^{a}	6.40 ^{a}
	(9.86)	(0.40)	(9.67)	(0.48)	(1.01)	(0.39)	(1.40)	(1.16)	(1.34)	(-0.09)	(1.24)	(1.00)	(3.69)
F10	29.38 ^{b}	0.98 ^{a}	25.48 ^{b}	1.01 ^{a}	1.51 $^{a, b}$	0.45 ^{b}	1.96 ^{a}	1.17 ^{a}	1.50 ^{a}	-0.31 ^{b}	1.19 ^{a}	0.98 ^{a}	6.17 ^{a}
	(16.96)	(0.56)	(14.71)	(0.58)	(0.87)	(0.26)	(1.13)	(0.67)	(0.86)	(-0.18)	(0.68)	(0.56)	(3.56)
F20	35.53 ^{b}	0.92 $^{a, b}$	27.70 ^{b}	0.81 ^{a}	0.13 ^{b}	2.47 ^{a}	2.60 ^{a}	1.17 ^{a}	2.40 ^{a}	0.34 ^{a}	2.70 ^{a}	1.33 ^{a}	6.13 ^{a}
	(20.51)	(0.52)	(15.99)	(0.46)	(0.07)	(1.42)	(1.49)	(0.67)	(1.36)	(0.19)	(1.56)	(0.76°	(3.54)

$C\text{-}CO_2$: accumulated organic carbon ($\mu gC\text{-}CO_2$ g soil^{-1}); Kc: mineralization coefficient of carbon; Nmtotal: Total mineral nitrogen ($\mu gN\text{-}NH_4\text{+}NO_3$ g soil^{-1}); Kn: net mineralization coefficient of nitrogen. CP: cultivated plots; F10: ten years old fallow; F20: twenty years old fallow.

4.4 Comparison of Soil Organic Carbon and Total Nitrogen Contents in Intergrowth and Thickets Areas



a b

c d

Figures 4. a, b, c, d. Variation of Soil Organic Matter Contents (C, N) in Intergrowth and Thickets, Depending of the Depth. Means with the Same Letter are not Significantly Different at the 5% Level (Scheffe's S test). F10: Ten Years Old Fallow; F20: Twenty Years Old Fallow

It: intergrowth; Th: thickets.

ANOVA performed on the data collected in intergrowth and thickets areas shows a significant effect ($P < 0.0001$) of the sampling area (intergrowth and thickets) on the SOC and TN contents distribution. The mean comparison test thus allows us to distinguish between the distribution in intergrowth and thickets depending on the depth (Figures 4 a, b, c, and d). Total nitrogen contents in thickets in both horizons are higher than in intergrowth areas in fallow lands at the same horizons, especially in the 0-10 cm layer. Concerning the SOC, only the 0-10 cm layer differentiates the two positions in the fallows, and the SOC contents recorded in thickets are higher than those obtained in intergrowth (Figures 4 a, b, c, and d).

4.5 Soil Organic Carbon Biodegradability in Intergrowth Area

ANOVA shows a significant effect of the plot type on the CO_2 emission at both depths ($P< 0.0001$). The means comparison test of accumulated CO_2 averaged over three days (Table 2) allows the crops to be contrasted with fallows. It also appears that the carbon mineralization activity is higher in the 0-10 cm layer.

The linear regression is very significant ($P<0.0001$), but the explained variance is relatively small.

Cmin1 = 0.00918 (C) – 1.549 $r^2 = 0.36$ n = 54 (0-10 cm)

Cmin2 = 0.00581 (C) + 7.78 $r^2 = 0.25$ n = 54 (10-20 cm)

The ANOVA performed on the carbon mineralization coefficient (Kc) data shows a significant effect of the plots stage on the carbon coefficient distribution at the topsoil of 0-10 cm (P=0.0142). Hence, the Scheffé'S test does not reveal any significant differences at the subsoil 10-20 cm. At the topsoil, Kc is smaller in the field (CP: 0.69%) than in the fallow lands (F10: 0.98%; F20: 0.92%).

4.6 Potential Mineralization of TN in Intergrowth Area

Scheffé'S test (5% level) does not reveal any significant differences in total mineral nitrogen accumulation between the three plots in the two soil depths (Table 2). In the topsoil, the ammonium accumulation is significantly higher in fields than in the old fallows lands. But the nitrate accumulation is significantly higher in the old fallow than in the young fallow lands and in the fields. In the subsoil, only the nitrification permits to distinguish plots each over with a small accumulation of nitrate in the old fallow lands against an immobilization in the other plots. Then, there is no significant correlation between total nitrogen concentrations and the total mineral nitrogen accumulation (Table 2).

The net mineralization coefficient of the total nitrogen (3 days) decreases with the depth in the fields (0-10 cm: 2.02; 10-20 cm: 1.72) and in the F10 (0-10 cm: 1.17; 10-20 cm: 0.98) (Table 2). But in the F20 the coefficient increases with the depth (0-10 cm: 1.17; 10-20 cm: 1.33). The means comparison test does not show any significant difference in the two depths (0-10 cm and 10-20 cm) and there is no difference between the three plots (Table 2). We do not have correlation between the net mineralization coefficient of TN content and the C:N ratio (r^2 varying from 0.0297 to 0.055).

4.7 Soil pH-H_2O

The soil pH-H_2O varies between 6 and 6.4 (Table 2). All the selected plots' soils then present an acid character. There is no significant means comparison effect, while there is no interaction between the pH and SOM mineral activities.

4.8 Soil Organic Carbon Biodegradability in Thickets

Table 3. Soils Chemical and Biological Characteristics Recorded in Thickets (standard error is in parenthesis n = 18). Soils with the Same Letter by Column are not Significantly Different at the 5% Level (Scheffé's S test).

	0-10 cm			10-20 cm			0-10 cm		10-20 cm		0-10 cm				10-20 cm			
Situations	N (%)	C (%)	C:N	N (%)	C (%)	C:N	C-CO_2	Kc	C-CO_2	Kc	NH_4	NO_3	Nmtotal	Kn	NH_4	NO_3	Nmtotal	Kn
F10	0.023 ^{a}	0.36 ^{a}	20 ^{a}	0.018 ^{a}	0.30 ^{a}	19 ^{a}	31.41^{a}	0.90 ^{a}	28.62^{a}	1.06 ^{a}	3.68 ^{a}	0.35 ^{a}	4.03 ^{a}	1.8 ^{a}	3.76a	-0.300^{a}	3.46 ^{a}	2.17^{a}
	(0.005)	(0.072)	(0.47)	(0.004)	(0.06)	(0.73)	(0.46)	(0.01)	(0.42)	(0.01)	(1.13)	(0.45)	(1.2)	(0.42)	(0.28)	(0.013)	(0.29)	(0.2)
F20	0.030 ^{b}	0.44 ^{b}	15 ^{b}	0.023 ^{b}	0.31 ^{a}	14 ^{b}	31.56^{a}	0.71 ^{a}	26.72^{a}	0.87 ^{b}	10.99^{b}	0.50 ^{a}	11.49 ^{b}	3.83 ^{b}	4.68a	0.003 ^{b}	4.68 ^{a}	2.11^{a}
	(0.003)	(0.053)	(2.38)	(0.002)	(0.04)	(0.73)	(0.77)	(0.14)	(0.76)	(0.20)	(4.14)	(0.28)	(5.14)	(0.62)	(0.78)	(0.047)	(0.78)	(0.8)

N: total nitrogen content (%); C: Soil organic carbon content (%); C:N ratio; C-CO_2: accumulated organic carbon (µgC-CO_2 g soil^{-1}); Kc: mineralization coefficient of carbon; Nmtotal: Total mineral nitrogen (µgN-NH_4+NO_3 g soil^{-1}); Kn: net mineralization coefficient of nitrogen. F10: ten years old fallow; F20: twenty years old fallow.

The ANOVA performed with the CO2 emission data in thickets in the two layers (0-10 cm and 10-20 cm), shows no significant effect of the fallow period on the CO2 production. Means comparison test done on the carbon mineralization coefficient data in the subsoil (10-20 cm) shows that SOM in the young fallow lands presents an organic carbon biodegradability more important than in the old fallow lands (Table 3).

The CO_2 production at the 10-20 cm layer depends strongly on the total organic carbon quantity [Cmin (10-20 cm) = -0.013 C (10-20 cm) + 66.93; $r^2 = 0.69$].

4.9 Potential Mineralization of the Total Nitrogen in Thickets Area

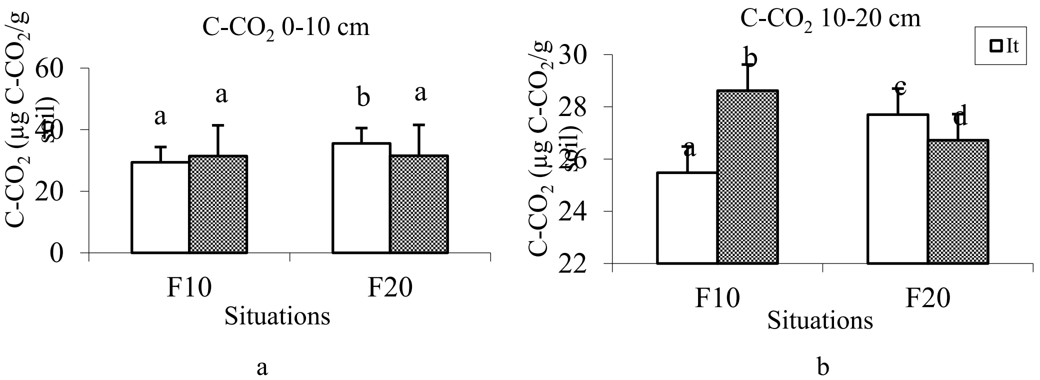
The analysis of variance performed on all the data shows a significant effect of the fallow period on the ammonium and total mineral nitrogen productions in the topsoil, and on the nitrates + nitrites production in the subsoil. The means comparison of Scheffé'S then permits to distinguish the two stages of fallow lands (Table 3). The ammonium production is significantly more important in the old than in the young fallow in the topsoil, while in the subsoil nitrates + nitrites production is significantly more important in the same condition (Table 3). The linear regression done in the topsoil shows the important link between the total nitrogen mineral activity (Nmint) and TN concentration (N%).

Nmint (0-10cm) = 0.0547 N (0-10 cm) – 5.55; $r^2 = 0.63$.

The ANOVA performed on the data shows a significant effect of the fallow lands stage on the distribution of the net mineralization coefficient in the topsoil. The means comparison test of Scheffé permits to distinguish the fallow lands each over in the topsoil and also shows that the net mineralization activity of the nitrogen is significantly more important in the old than in the young fallow lands (Table 3).

4.10 Comparison of Soil Organic Carbon Biodegradability in Intergrowth and Thickets Areas during the Fallow Lands Succession

The ANOVA performed on the entire data of the CO_2 emission in intergrowth and thickets areas is not significant at the topsoil, while in the subsoil there is a significant effect ($P<0.0001$) of the area on the CO_2 production. The Scheffé's test done at the 10-20 cm layer shows that for the young fallow lands, the thicket area presents more important CO_2 production than the intergrowth area. While in the old fallow lands the intergrowth area presents more important CO_2 production than the thicket area (Figures 5 a and b)



a b

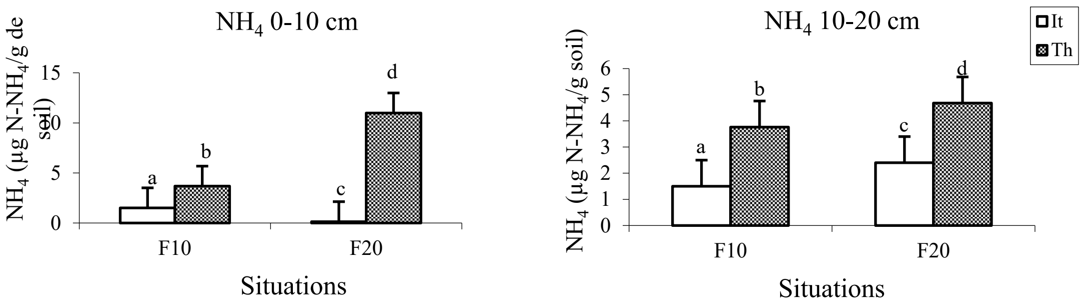
Figures 5 a, b. Comparison of Soil Organic Carbon Biodegradability in Intergrowth and Thickets during Fallow Lands Succession. Results Expressed as µg C-CO_2 g^{-1} Soil

It: intergrowth; Th: thickets. F10: ten years old fallow; F20: twenty years old fallow.

4.11 Comparison of the Nitrogen Mineralization in Intergrowth and Thickets Areas

- Ammonium (NH_4)

The ANOVA performed on the entire data of ammonium in intergrowth and thickets areas shows a significant effect of the two areas (intergrowth and thickets) on the NH_4 production during the fallow lands succession in the two depths ($P<0.0001$). The Scheffé test shows that in the two fallows lands, there is more production of NH_4 in thickets than intergrowth (Figures 6 a and b).



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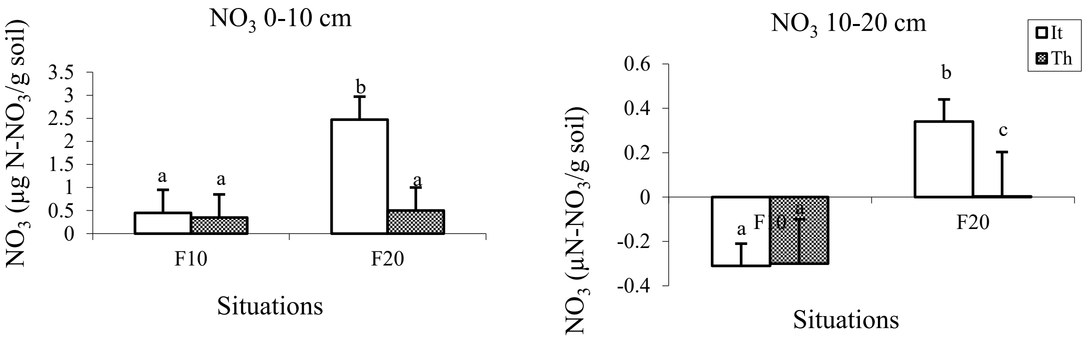
Figures 6. a, b. Comparison of NH_4 production in intergrowth and thickets during fallow lands succession. Results expressed as µg N-NH_4 g^{-1} soil.

It: intergrowth; Th: thickets. F10: ten years old fallow; F20: twenty years old fallow.

- Nitrate (NO_3)

ANOVA done on the entire data of nitrates + nitrites in intergrowth and thickets areas does not show any significant effect of the area on the NO_3 production during the fallow lands succession (Figures 7 a and b).



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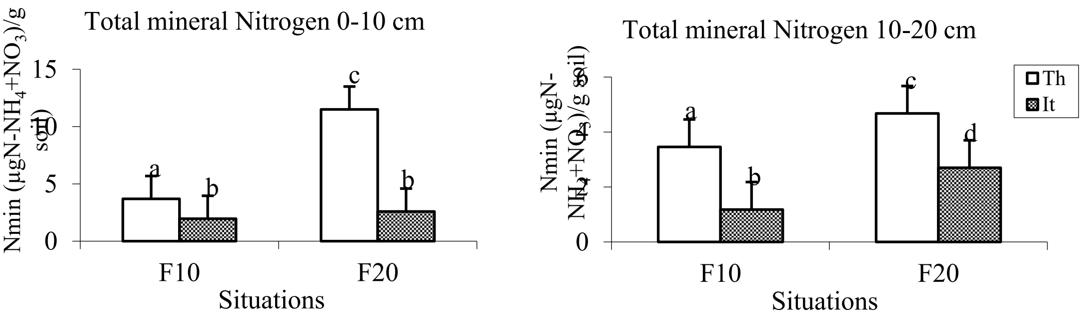
Figures 7. a, b. Comparison of NO_3 Production in Intergrowth and Thickets during Fallow Lands Succession. Results expressed as µg N-NO_3 g^{-1} soil

It: intergrowth; Th: thickets. F10: ten years old fallow; F20: twenty years old fallow.

-Total mineral nitrogen (Nmint = NH_4+NO_3)



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Figures 8. a, b. Comparison of the total mineral N potential mineralization (Nmintotal) in intergrowth and thickets during fallow lands succession. Results expressed as N-(NH_4+NO_3) g^{-1} soil. It: intergrowth; Th: thickets. F10: ten years old fallow; F20: twenty years old fallow

ANOVA performed with all the data of Nmint in intergrowth and thickets areas shows a significant effect of the two areas (intergrowth and thickets) on the Nmint production in the two depths (P=0.003). Means comparison test of Scheffé'S also reveals that in the two depths the thicket area produces more Nmint than the intergrowth area during the fallow lands succession (Figures 8 and b).

5. Discussions

5.1 Texture Role

The clay concentration varies from 2 to 3% during the fallow crop cycle in the 0-20 cm horizon. Fallow lands (F10 and F20) have higher clay concentrations than cultivated plots. This suggests that: (i) cropping alters soil texture, resulting in clay losses associated with OM; (ii) and that returning to fallow for varying lengths of time improves soil texture and therefore clay concentration.

Mechanisms of increasing clay quantity deserve further study, but it is probably linked to the soil faunal activities, termites and particularly earthworms. Indeed, it has been frequently shown that termites' (Mando, 1997; Mando et Miedema, 1997; Sarr et *al*., 1998; Subbian *et al*., 2000) and earthworms' (Pashanasi *et al*., 1992; Norgrove *et al*., 1998; Scullion et Malick, 2000) populations' density and diversity are greater under spontaneous vegetation than under cultivated fields. Termites' building activity and the ingestion of organic and mineral particles by earthworms are thus very important in fallow lands. This can produce an accumulation of clay particles in the superficial soil horizon.

5.2 Dynamics of Soil Organic Matter (C and N) during the Cultivation and Fallowing Cycle

The assessment of soil organic carbon and total nitrogen contents shows that SOM stocks increase during the fallow period. There is a relative accumulation of organic carbon and total nitrogen contents in the soil after ten to twenty years old of fallowing, compared to the cultivated plots. According to Glaser *et al*. (2001), the nitrogen up taken by plants and troubles caused by soil preparation led to a strong decrease in total nitrogen concentrations of these soils compared with fallow lands soil like ours. Small SOM contents of cultivated plots could be due to rapid mineralization of the SOM leading to a net loss of organic compounds. The loss of clay particles can also contribute to small SOM contents of cultivated plots as we have already seen. The reconstitution of SOM over time is very important. When comparing fallow lands and cultivated plots reconstitution, we have a "relative increase contents" of 24 % for the total nitrogen and 20 % for the organic carbon in the topsoil in young fallow lands; in the subsoil, we have 19 % for the total nitrogen and 23 % for the organic carbon always in young fallow lands. This difference underlines fallow lands' significant role in the total SOM stock reconstitution. The comparison between cultivated plots and old fallow lands gives "relative increase contents" about 41 % for the total nitrogen and 34 % for the organic carbon in the topsoil, while in the subsoil we obtain 38 % for the total nitrogen and 37 % for the organic carbon.

The capacity of the total SOM reconstitution is then helped by long fallow periods. Our observations concur with those obtained by Glaser *et al.* (2001). This SOM accumulation during time is probably linked to the reconstitution of the physical capacity of organic compounds storage on the clay created by the termites and the earthworms' activities, but also by higher primary production of vegetation under fallow lands (about 3.5 t MS.ha-1 in Sahelian-Sudanian zone) and a modification of the chemical quality of vegetation particles. The significant increase of organic carbon and total nitrogen contents between young and old fallow lands, with a constant clay concentration shows the evidence role of the vegetation cover, and also the quantity and quality of plant debris in SOM build-up.

5.3 Effects of the Perennial Grass Andropogon Gayanus

The transition from the intergrowth to thickets areas permits obtaining positive variations which are relatively significant. Then the calculation of the "relative increase contents" on the intergrowth and thickets areas data in the fallow lands show that:

(i) in **young fallow lands**, at the 0-10 cm depth, the transition between the two positions produces a "relative increase contents" of 26 % of nitrogen and 14 % of carbon; the same transition in the subsoil (10-20 cm) gives an "increase" of 12 % of nitrogen and 13% of carbon;

(ii) in **old fallow lands**, in the topsoil, the transition between the two positions produces a "relative increase contents" of 27 % for nitrogen and 14 % for carbon, while in the subsoil the same transition produces a small "relative increase contents" of 9 % for nitrogen, but for carbon the transition leads to small variations.

As we hypothesized, soil organic matter quantities present in thicket areas are more significant than those present in intergrowth areas in the fallow lands. Old fallow lands are those which have the most SOM quantities. They strongly participated in SOM (C and N) build-up only at the superficial soil layer. These observations follow the same pattern as Somé (1996). Young fallow lands also contribute to the total nitrogen reconstitution at the superficial layer where the increase of nitrogen contents is higher than carbon contents.

Despite the annual fire regime which reduces the return in the soil of vegetable particles, the fallow lands' role remains very significant in the reconstitution of SOM stocks. In old fallow lands which are dominated during their vegetable succession by perennial grasses, important SOM quantities found there may well be derived from perennial grass root decay and from shed material from trees (principally leaves). High clay contents in the old fallow lands also permit a high SOM fixation.

It is very important to take into account the origin of the herbaceous and ligneous organic material in the total SOM reconstitution. Nacro (1997) in his study comparing the savannah and forests ecosystems, has shown that the forest SOM was mostly composed of tree leaves relatively rich in nitrogen (0.6 to 0.9 % N), while in the savannah the SOM was mostly composed of herbaceous leaves poor in nitrogen (0.4 to 0.5% N). In our case, where the old fallow lands are dominated by trees, Nacro's (1997) SOM build-up schema can be applied. For its verification, we must approach the question of the herbaceous and ligneous root production and access the relative contribution of both ecosystems in the SOM build-up. A follow-up of the natural affluence in SOM C13 can be very useful, in the case that most of the grasses, at least perennials, are characterized by a C4 photosynthesis type. Figure 9 shows a theoretical organic matter stock evolution over time. The old fallow lands stage stocks a small OM in the soil. But SOM stocks obtained at the end of the young fallow lands stage can be sufficient for lands clearing. Land clearing after the end of the old fallow land stage permits injecting into the soil an important quantity of fresh organic matter, which will be a benefit for cultivation during their first 2-3 years.

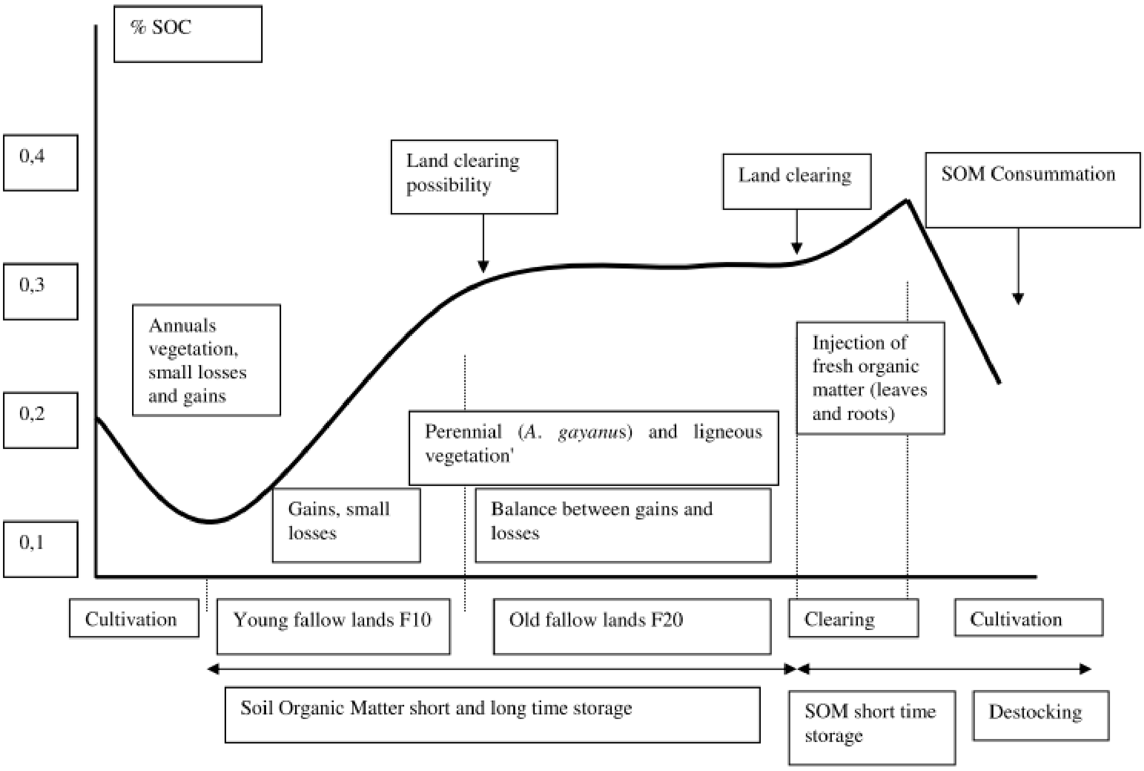

Figure 9. Theoretical Dynamics of SOM during the Fallowing Cropping System under a Semi-arid Tropical Climate

5.4 Dynamic of the Organic Carbon Mineralization

The dynamic of the SOM mineralization has been observed through studies of the single mineralization of the organic carbon and total nitrogen in laboratory standard conditions. Organic carbon mineralization is more important in the fallow lands (F10 and F20) than in the fields. Fallow lands then lead to an increase in the organic carbon quantity in soil easily absorbed by microorganisms. The absence of differences between old and young fallow lands suggests that the fact to lie fallow is more important than the fallow stage in the global mineralization activity of the organic carbon. The fallow land appears as an efficient technic in soil organic carbon reconstitution. Linear correlation coefficients (r^2) obtained in the two soil layers (0-10 cm and 10-20 cm) are small compared to those obtained by other works in tropical soils (Bachelier, 1968; Perraud, 1971; Feller, 1994). This suggests that the activity of respiration not only depends on the organic carbon contents but also on other factors, for example, the OM's physical protection by the clay. So, the soil texture seems to be the important parameter which influences organic carbon availability (Anderson *et al*., 1981; Feller *et al*., 1991; Hassink, 1992). Oades (1989) explains that the sequestration phenomenon of the easily absorbed organic carbon in soil aggregates or by clay adsorption can take this easily absorbed organic carbon away from microorganism activity.

The total absence of variability in carbon mineralization coefficients between the fallow lands stage suggests that the global accessibility of the organic carbon is not influenced by the fallow lands stage. However, our protocol relies on the use of sieved samples, the possible SOM protection by soil aggregates was for a majority deleted. The mineralization coefficients may reflect mostly the chemical accessibility of the OM which varies with the fallow lands stage. This chemical quality of the SOM can be evaluated by the C: N ratio. But according to the absence of correlation between the C:N ratio and the carbon mineralization coefficient in a short time, a question may be asked about this criteria's relevance in predicting for a short time the potential mineralization of the organic carbon as Nacro (1997) underlined before. The fallow lands' role can also be perceived through comparisons of the organic carbon mineralization both in intergrowths and thickets areas. The carbon mineralization process in fallow lands is influenced by many factors like the chemical and physical environment of the microorganism and the vegetable cover. Significant differences are observed between the two positions only in the subsoil (10-20 cm). The carbon quality and the biochemical nature of the OM to be decomposed could be the most factors which explain the lack of differences between the two positions in the topsoil (0-10 cm). The results suggest that vegetation influences carbon accumulation, but not its quality, which remains constant between fallow stages. On the other hand, in terms of quality, the SOM is totally transformed at the young fallow stage.

5.5 Dynamic of the Total Nitrogen Mineralization

In all selected plots the total mineral nitrogen accumulation in thickets areas is extremely small during the agricultural fallowing cycle since it does not reach 3 ppm in 3 days. At the topsoil (0-10 cm) the essential of mineral nitrogen accumulated is on ammonium form in fields and young fallow lands and on nitrates + nitrites form in old fallow lands. While at the subsoil (10-20 cm), the essential mineral nitrogen is in ammonium form for the three selected plots (CP, F10 and F20). Our results do not follow the same pattern as those of De Rham (1973), Nacro (1997), Abbadie and Lepage (1989), Abbadie and Lensi (1990), Lensi *et al*. (1992) and Leroux *et al*. (1995) who shown an absence of nitrification under perennial grasses, in intergrowth and thickets areas. These authors have worked in a humid savannah and the lack of nitrification was due to an active seeking for nitrifying by perennial grasses themselves (Lata, 1999). In our case, we observed the opposite phenomenon, as the balance between ammonification and nitrification shifted in favour of nitrification at the old fallow stage in the topsoil (0-10 cm).

According to Haynes (1986), nitrification influences the balance between the different mineral forms of nitrogen and the potential loss of nitrogen by the ecosystem. Nitrification can therefore be considered as a process limiting or promoting ecosystem functioning. The role of nitrates is then perceived differently according to authors (Lata, 1999; Tavernier, 2003). The production of nitrates + nitrites can lead to nitrogen losses through denitrification and leaching, due to the mobility of anions in soils (Lata, 1999). For Haynes and Goh (1978), nitrification can lead to the acidification of soil around the roots through the production of protons. The same authors have shown that nitrate's presence can also reduce the toxic effects of Aluminium on the plant, or reduce ammonium losses by clay adsorption and volatilization in the soil at basic pH (Haynes and Sherlock, 1986). The production of nitrate + nitrite previously depended on the availability of ammonium. In natural vegetation, plants' nutrition by ammonium can decrease nitrate production because nitrifying bacteria are considered weak competitors for NH4 (Jones and Richards, 1977; Schmidt, 1982). The ammonium not immobilized by microorganisms in the rhizosphere of perennial grasses is rapidly absorbed by the roots, often limiting nitrification in grassy ecosystems (Huntjens, 1971). On the other hand, in the case of a disturbance of the natural vegetation cover, for example during deforestation, nitrifying organisms have easy access to ammonium, and the nitrification potential increases while significant leaching losses occur (Vitousek, 1981). In our selected soils, the production of nitrates + nitrites in the subsoil (10-20 cm) is insignificant both in intergrowths and thickets areas. This lack of nitrifying activity can be explained by three hypotheses.

(i) Nitrate is a result of ammonium oxidation (nitrification). The observed absence of nitrifying activity may simply be due to the fact that in deep layers oxygen is scarce. In this case, few microorganisms are therefore able to convert ammonium into nitrate.

(ii) Where ammonium is limited for nitrifying microorganisms to 10-20 cm, there is an absence of nitrate production at this depth. Since ammonium is an important substrate for nitrifying microorganisms, under these conditions there is no nitrate production.

(iii) Competition between roots of perennial grasses and ammonium nitrifying micro-organisms may also result in a lack of nitrification. This competition has not been studied here, but the high nitrate production observed in intergrowth compartments of fallow plots suggests that there is a competition for ammonium between nitrifying microorganisms and herbaceous plants, which may explain the lack of nitrate.

We have also a significant production of mineral nitrogen in the old fallow and a positive effect of the thickets areas on the net accumulation of mineral nitrogen. The same effect was observed in the rate of organic carbon mineralization. This demonstrates the importance of herbaceous vegetation in both qualitative stock recovery and in improving the biodegradability of the SOM. However, this effect of improving the biodegradability of the SOM is still located under the perennial grass clumps.

6. Conclusion

According to our results, *A. gayanus* fallow lands play an active role in managing SOM dynamics. A significant amount of SOM is concentrated in the topsoil where the maximum amount of plant debris is found. Concerning the sampling area (intergrowth and thicket), old fallows have more SOM compared to young ones. Comparing the data of intergrowth and thickets areas the important role of herbaceous vegetation cover in the reconstitution of the SOM stock is verified.

In the fallow cropping system practiced on sandy soils, we propose an objective management indicator by observing the evident organic condition in old fallows. Former fallows have much higher amounts of SOM than other situations studied. As pointed out by Feller (1994), the organic level of natural vegetation, such as grasslands and old fallows (> 30 years), corresponds to a stable state. Therefore, we can assume that our old fallows represent these natural vegetations, with the same physiognomy, and their organic level has reached an equilibrium state while waiting for new agricultural activity.

The fallow land is also an effective practice for the increase of biological nitrogen mineralization and modifying organic carbon mineralization. At this stage of our study, it seems like this increase is a progressive accumulation of organic compounds than an important modification of their quality. Vegetation has an important effect on SOM quantity input into the soil and a weak effect on the modification of the SOM chemical composition. This SOM is susceptible to decomposing more or less quickly in time.

At the end of the fallow lands period, the mineral nitrogen form which is dominant on the soil surface is nitrate, a very labile form of nitrogen because of denitrification risks. A question may be asked about the impact of minerals elements fluxes coming from the SOM mineralization during the cultivation phase while these fluxes are always very low. Consequently, the fresh vegetation debris coming from the clearing for cultivation may have a very important quantitative impact at this moment, which is suitable to specify and can sometimes be superior to the total soil organic matter impact.

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