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Distribution of soil carbon according to pedological profile in the Sudanese savannah Agro-systems of Bondoukuy, western Burkina Faso

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Abstract

A study was conducted to examine the vertical distribution of soil organic carbon (SOC) in savannah agrosystems within the cotton farming region of Burkina Faso. The study was conducted on plots belonging to two village lands and two distinct morpho-pedological environments. The first area is characterised by a sandy flatland with light ferruginous soils and a low content of SOC. The second area is distinguished by a sandy-loam lowland with heavier soils and a high content of SOC. A total of 13 plots, comprising natural vegetation, crops or fallow land, were sampled along transects. The history of each plot, whether cultivated or in spontaneous vegetation, was obtained through surveys and field observations. The variability of the soil was addressed by the study of 13 profiles. The soil organic carbon (SOC) content was determined for each distinct horizon in the profiles, and a five-fraction granulometry was conducted on the composite horizon 0-20 cm in the 13 plots. The findings indicate that soil organic carbon (SOC) concentrations are higher in the lowland area than in the flatland area. The results demonstrate that the lowland area is characterised by a prevalence of hydromorphic tropical ferruginous soils, which exhibit elevated levels of carbon compared to ferruginous soils with iron sesquioxide and ferralitic soils in the flatland area. The content of fine elements serves to confirm the names of the two morpho-pedological environments. Furthermore, it elucidates the underlying causes of the observed variability in soil organic carbon (SOC) content, which is evident between the two environments. The other primary explanatory variables are soil type (i.e., moisture levels and waterlogging), vegetation type, and the use of the environment through cropping systems. It is notable that there are considerable fluctuations in carbon between the crop and fallow stages in these areas, although the variation is relatively low (+3%). Additionally, some plots with relatively high C content received substantial quantities of manure. The carbon content of the soil tends to decrease as a result of the specific cropping system and the way in which the land is used. As the predominant practice of farming since the 1950s has been shifting cultivation, and given that the land under permanent cultivation is the most clayey, the loss of soil organic carbon (SOC) following a change in land use is considerably less than that predicted by current models. In consideration of the dynamics of land use since 1950, it can be posited that a maximum of 3% of carbon in arable soils has undergone a slight reversible process of disappearance, occurring primarily in the 0-20 cm horizon and amounting to a mere 0.5t/ha. Nevertheless, this decline would have ceased (end of the labile C stock, maintenance of fallow cultivation on poor land) were it not for the possibility of increased tillage intensity.

Keywords: Agrosystem; Carbon; Sudanian savannahs; Hydromorphic Soils

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1. Introduction

Tropical soils are estimated to contain approximately one-third of the world's soil organic carbon (SOC) [1]. The rapid changes in tropical land use, driven by economic development and rural population growth, represent a significant factor influencing soil organic carbon (SOC) levels. The deforestation and subsequent cultivation of different forest environments in the vicinity of the climax results in a loss of 15 to 40% of soil organic carbon (SOC) over a depth of 1 m between 2 and 8 years after deforestation [2, 3]. It is therefore of concern that tropical environments may act as a net source of CO_2 rather than a carbon sink. Tiessen *et al*. [4] have drawn attention to the existence of contrasting patterns between regions with similar climates, which they attribute to differences in land use systems. They argue that the current dynamics of soil organic carbon (SOC) must therefore be addressed on a regional basis. The sub-humid and semi-arid tropical zones, particularly the savannahs, are impacted by these issues due to their extensive surface area. However, the soil organic carbon (SOC) content is typically low. As stated by Manlay [5], a soil organic matter (SOM) carbon concentration of 4.3 $g.kg^{-1}$ is equivalent to a carbon accumulation of 51 $t.ha^{-1}$ at a depth of 0-40 cm in sandy soil under old fallow conditions. The epigeous and hypogeous biomass comprises approximately 29 $t.ha^{-1}$ of carbon, a portion of which is subject to annual combustion. Consequently, on a sandy soil, 2/3 of the organic carbon is retained. This notable heterogeneity necessitates a focused approach to the distribution of soil organic matter (SOM).

The vertical distribution of organic carbon is more regular in forests, where the majority of this substance is found in the surface horizons [6, 7]. The SOC content is the result of a dynamic equilibrium, in which inputs and losses are in balance, with turnover buffer reserves of different durations [8]. This equilibrium is highly dependent on texture, as fine elements play a crucial role in protecting soil organic matter (SOM) from mineralisation [3, 9]. In accordance with the findings of Dabin and Maignen [10], the composition of the soil parent material and the structure of the soil itself are also found to exert an influence on the content of soil organic matter. Serpantié [11] emphasises the significance of soil type, noting that hydromorphic soils tend to exhibit higher levels of organic matter than other soil types. Furthermore, humidity in the climatic regime has been identified as a factor that contributes to increased fertility [12]. Furthermore, soil organic matter (SOM) is subject to variation as a consequence of land use. In pseudo climatic plant environments, the presence of crops has been observed to result in a reduction of SOM, while fallow periods have been identified as an intermediate state [9, 11].

The annual coefficient of net loss of organic matter under cropping following an initial forest situation is approximately 4.7% in sandy soils and 2% in heavier soils [6]. From Greenland and Nye [13] to Manlay [5], numerous authors have investigated fluctuations in soil organic matter (SOM) during crop-fallow cycles, yielding highly variable results but generally small amplitudes in sandy soils [5, 9, 11, 14]. Studies of 'carbon flows' in terroirs have been conducted in Senegal [5], Cameroon [15] and Uganda [16], with a particular focus on specific soil types. However, these studies did not address soil variability.

There are several reasons why it is challenging to integrate this knowledge of soil carbon variation into the discourse on global change and savanna fertility. Indeed, these studies have predominantly concentrated on fundamental states of occupation (cropping, fallow, 'length of cropping') as opposed to medium-term management practices. There is a paucity of emphasis on the average effects of cropping systems on different soil types. It is therefore necessary to conduct further research into the instantaneous functioning of a terroir in relation to soil variability, as opposed to investigating integrated medium-term mechanisms for homogeneous zones. Furthermore, the evolving cropping systems of village areas must be considered. It is therefore assumed that each cropping system is associated with a 'quasi-stable' average level of soil organic matter (SOM) and that its distribution is strongly linked to soil variability. The fundamental methodology entails the examination of terroirs comprising disparate soil types, with the objective of establishing comparisons between SOC levels. The results will serve as a reference point for the study of the vertical distribution of SOC in soil, as well as for the provision of consultancy and management services to agro-ecosystems

2. Material and methods

2.1. Study site

The study was conducted in the Bondoukuy region (Mouhoun Province, 11°51'N; 3°46'W), which is representative of the former cotton-growing areas of Burkina Faso, located in the central part of the Sudan zone (rainfall: 900 mm from May to September) (Figure 1).

The study focused on two distinct environmental types: (1) the supposed 'sandy flatland', which is characterised by very light, sloping, ferruginous soils with low desaturation (Alfisol, USA, or Lixisols, FAO), where fallow practices are employed alongside remnants of shifting cultivation and a few fields under permanent cultivation, occasionally with the use of organic fertilisers. (2) The supposed 'silty plains or lowland' with hydromorphic soils and sandy clay Lixisols, where migrants engage in permanent cultivation with intensive tillage, without restitution. The population density does not tend to increase significantly on sandy and gravelly soils, largely due to the fact that migrants are generally not inclined to seek out such environments and local communities are often resistant to external pressures to relinquish their traditional territories [17]. The integration of extensive livestock farming and agriculture based on cotton-cereal succession is moderate. This is evidenced by the presence of draught cattle, sedentary bredding grazing on fallow land, crop residues and uncultivated land, fertilisation practices reserved for the better-off, transhumance during the dry season following fires that destroy pasture biomass and lack of water.

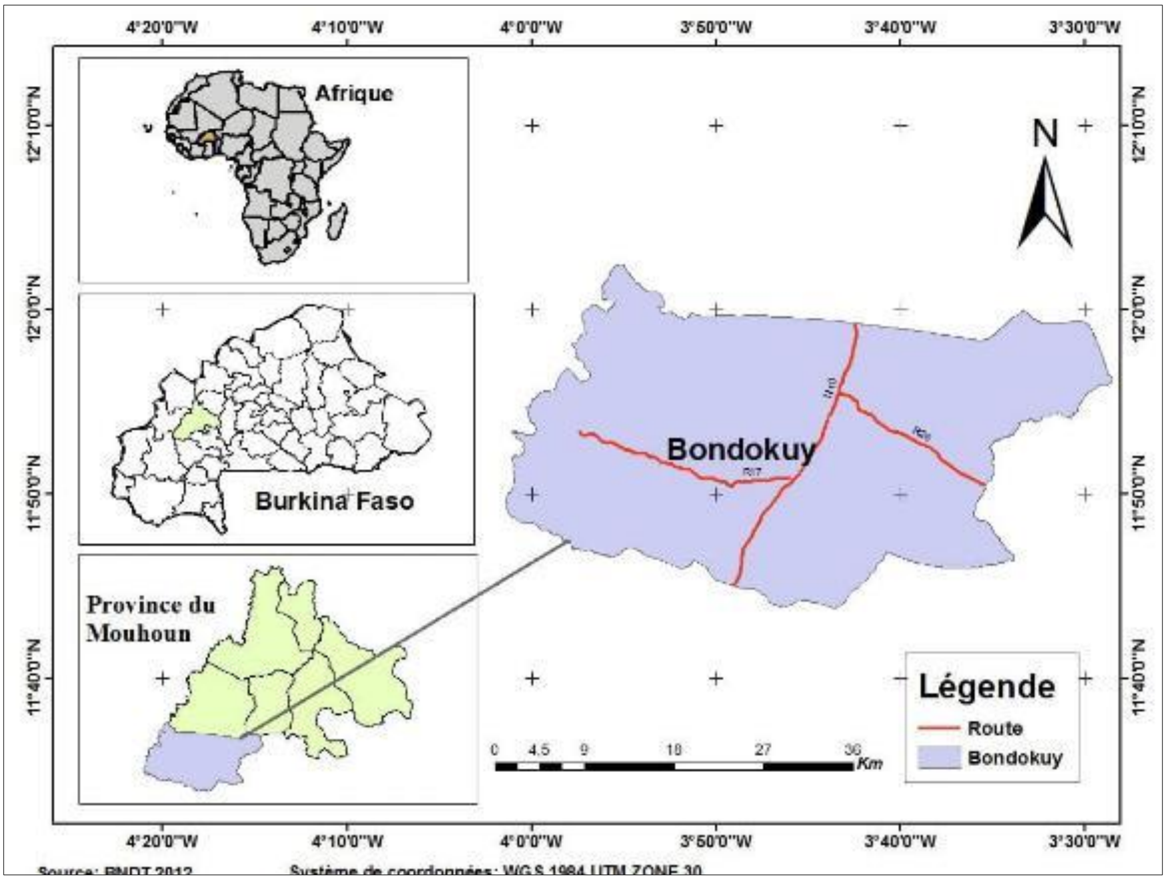

Figure 1 Study area map

2.2. Data gathering and analysis

The research concentrated on the vertical distribution of soil carbon (C) content in a series of contiguous terroirs. The variability of soil characteristics was examined along a transect measuring 5 km in width and 30 km in length, extending from the flatland to the lowland. The aforementioned transect encompasses a multitude of terroirs and an area characterised by pseudo-climactic savannah. The classification and identification of all soils was conducted in accordance with the French classification system [18], with the results subsequently cross-referenced against the global reference base [19] and the national guidelines of [20].

The terroirs crossed and the activities carried out there are described on the basis of general observations (cultivated areas or fallow vegetation) and surveys. The objective is to enhance comprehension of the way in which the environment is used and to elucidate the disparate levels of carbon obtained.

In order to compare the two types of environment and to study the vertical distribution of carbon in the soil thickness, soil profiles were made for each environment according to the type of land use (cultivated or fallow). In the soil profiles, soil samples were taken from each homogeneous horizon. The C content of each homogeneous horizon was determined using the modified Walkley-Black method [21]. Granulometric analysis by sedimentation, after destruction of the organic matter, using the pipette method on an automatic granulometer with 5 fractions according to the Atterberg scale (Clays: 0-2 µm, fine silt: 2-20 µm, coarse silt: 20-50 µm, fine sands: 50-200 µm and coarse sands: 200 µm-2 mm) [22] was carried out. This analysis concerned composite soil samples taken at a depth of 0-20 cm, as this layer corresponds to the depth mainly explored by roots. The data were subjected to an ANOVA using the GLM type III procedure with an alpha level of 5% [23].

3. Results

3.1. Types of occupation

The field observations allowed us to identify the following types of vegetation (Table 1). In the lowland area: 2 uncultivated plant formations consisting of old fallow land more than 30 years old, with a physiognomy similar to that of savannah or pseudo-climax, of 5 ha each; 2 cultivated plots of 3 ha each in transition to permanent cropping for 11 to 15 years; and 3 plots of 2.5 ha each in permanent cropping for 16 to 25 years. On the flatland area: 2 plots of 2 ha each in a fallow cropping system, i.e. 10 years of cropping followed by 10 years of fallow (C10J10) or 10 years of cropping followed by 20 years of fallow (C10J20); 2 plots of 1.5 ha each in shifting cultivation, all from very old fallow of 30 years; and 2 plots of 1 ha each in permanent cropping with permanent manure.

Table 1 Descriptions of the types of occupancy found in each terroir

Terroirs	Descriptions
Lowland	Vegetation closed of the forest type, with woody cover exceeding 80%, or of the open savannah variety, representing a pseudo-climax, LL1 and LL2
	Plots in transition to permanent cultivation for 11 to 15 years, LL3 and LL4
	Plots under prolonged permanent cultivation for 16 to 25 years, LL5, LL6 and LL7
Flatland	Fallow cropping system (C10J20 and C10J30), FL1 and FL2
	Plots in shifting cultivation from very old fallow lands of 30 to 40 years, FL3 and FL4
	Plots under permanent cultivation with manure added, FL5 and FL6

3.2. Soil types

For the soil study, 13 soil profiles were carried out, 7 on the lowland terroir and 6 on the flatland (Table 2). The results of the granulometric fractionation has enabled to classify and then identify the soils of the different terroirs on the basis of their texture [18-20]. On the basis of the fine element content (FE = C + FS < 20 µm), we distinguish (i) light soils, 7-15% of FE, most of which belong to the flatland terroir and a minority to the low-land terroir, and (ii) heavy soils, 35-46% of FE, found only in the lowland terroir. According to the classifications used, the flatland terroir contains the main types of leached or impoverished tropical ferruginous soils with stains and concretions, and low and medium desaturated ferralitic soils with iron and manganese sesquioxides. The lowland terroir is essentially composed of the main types of hydromorphic tropical ferruginous soils with low humus and pseudogley with stains and concretions (Table II).

Table 2 Granulometric characteristics (0-20 cm) and soil pedological designation of the plots in the studied areas. Means with the same letter per column are not statistically significant (n=13, P<0.005), standard error in parentheses

		Texture (%)				
Terroirs	**Plots**	**C**	**FS**	**CS**	**FS+CS**	**Pedological designation**
Lowland	LL1	26.60a (2.80)	19.75a (2.34)	18.70a (3.77)	34.95a (4.58)	Hydromorphic tropical ferruginous forest soils
	LL2	26.13a (3.33)	16.30a (3.02)	24.88b (5.09)	32.69a (2.62)	
	LL3	23.88a (4.43)	16.00a (4.01)	24.60b (6.10)	35.52a (3.73)	Leached tropical ferruginous soils with stain and concretions
	LL4	23.63a (3.4)	14.10a (2.34)	20.49a (2.79)	41.78a (4.50)	
	LL5	23.30a (2.83)	13.30a (5.06)	19.30a (1.83)	44.10b (8.47)	Deep hydromorphic tropical ferruginous savannah soils
	LL6	22.34a (3.43)	13.25a (6.04)	19.80a (0.72)	44.61b (9.38)	
	LL7	22.00a (1.06)	13.13a (5.06)	19.77a (1.83)	45.10b (8.47)	
Flatland	FL1	10.00b (2.44)	4.93b (0.97)	9.62c (1.57)	75.45c (0.78)	Ferralitic soils
	FL2	9.53b (3.57)	4.30b (1.27)	8.35c (2.05)	77.82c (1.05)	
	FL3	9.50b (1.63)	4.00b (1.37)	17.12a (0.33)	69.38c (0.88)	Hardened tropical ferruginous soils (sometimes hydromorphic)
	FL4	7.75b (4.30)	3.65b (0.50)	11.45c (1.87)	77.15c (7.8)	
	FL5	7.41b (4.75)	2.75b (1.75)	10.80c (3.07)	79.04c (6.50)	Modal tropical ferruginous soils
	FL6	5.00b (2.17)	2.50b (1.5)	13.70c (2.27)	78.80c (5.47)	

Legend : C : clay (0-2 µm); FS :Fine silt (2-20 µm); CS : Coarse silt (20-50 µm); FS : Fine sand (50-200 µm); CS : Coarse sand (200 µm-2 mm)

3.3. Types of vegetation

The results of the surveys and field observations were used to definitively characterise the vegetation. The woody vegetation of uncultivated areas on heavy, wet soils is dense and closed (LL1 and LL2). In contrast, light, dry soils are more commonly covered by loose, shrubby or bushy vegetation (FL1 and FL2). The physiognomy is more contrasted on wet soils. On hydromorphic and deep soils, there are three very distinct cases. (i) Those that are currently densely wooded or have just been cleared, generally gallery forests and spring forests based on hemi-ombrophilous and riparian biotope species. (ii) Those that have already been cleared, but had a dense forest cover in the 1950s. This recent ecological history is evidenced by the presence today of remnants of dense forests and, in the resulting wooded parks, remnants of fire-sensitive species such as certain Mimosaceae (*Acacia* arborescens, *Albizzia*, *Dichrostachys*) or *Anogeissus leiocarpus*. (iii) Those which, in the 1950s, bore a savannah with copses. These are floodplains with *Andropogon gayanus* var *bisquamulatus* and *Hyparrhennia* spp. and termite mounds with groves.

3.4. Variations of carbon contents

At the profile level, the carbon (C) always decreases with depth, varying between 50 and 90 cm in the lowland terroir and between 30 and 90 cm in the flatland terroir (Table III). The profiles are similar at the surface and at depth. Two groups can be distinguished: the sandy profiles of the flatland, which are poor in C, and the clay-loam profiles of the lowland, which are twice richer (Table 3). The hydromorphic profiles (LL) are exceptional in that they have high C contents at the surface and low values at depth. The sandy profiles (FL), on the other hand, have stable levels with depth.

Table 3 Carbon contents (g.Kg^{-1}) of soil profiles. Means with the same letter per column are not statistically significant (n=78, P<0.005), standard error in parentheses

Terroirs													
	Lowland							Flatland					
Depth (cm)	**LL1**	**LL2**	**LL3**	**LL4**	**LL5**	**LL6**	**LL7**	**FL1**	**FL2**	**FL3**	**FL4**	**FL5**	**FL6**
0-10	10.5a (1.9)	7.8a (0.6)	7.5a (0.52)	7.1a (0.55)	6.8a (1.3)	6.6a (1.33)	6.5a (1.4)	5.8a (1.01)	4.2a (0.46)	4.1a (0.43)	3.8a (0.35)	3.5a (0.68)	2.2a (0.23)
10-20	7.8b (0.9)	6.8a (1.3)	6.5a (0.6)	6.9a (0.88)	6.3a (0.9)	5.0a (0.98)	5.5a (0.88)	4.2a (0.89)	3.5a (0.53)	3.5a (0.38)	3.2a (0.42)	3.0a (0.6)	2.0a (0.2)
20-30	6.9b (0.8)	5.8b (0.6)	5.7a (0.5)	6.5a (0.7)	5.0a (0.75)	4.8a (0.65)	4.2b (0.57)	3.5b (0.4)	2.8a (0.5)	3.2a (0.35)	3a (0.38)	2.8a (0.65)	1.8a (0.18)
30-40	6.7b (0.9)	5.6b (0.42)	5.2b (0.48)	6.4a (0.52)	4.3b (0.55)	4.5a (0.55)	3.9b (0.3)	-	2.5a (0.45)	3.1a (0.28)	3a (0.23)	2.7a (0.59)	1.7a (0.22)
40-50	6.5b (0.75)	4.8c (0.38)	4.8b (0.38)	6.2a (0.45)	3.8b (0.4)	4.3b (0.5)	2.8b (0.28)	-	2.0a (0.42)	3.0a (0.2)	3a (0.21)	1.7a (0.6)	-
50-60	5.8b (0.6)	4.2c (0.3)	-	-	3.5b (0.21)	4.2b (0.45)	-	-	-	3.0a (0.31)	2.9a (0.18)	1.65a (0.56)	-
60-70	5.5b (0.5)	-	-	-	3.4b (0.27)	-	-	-	-	2.8a (0.25)	2.8a (0.22)	1.5a (0.6)	-
70-80	4.5c (0.3)	-	-	-	-	-	-	-	-	-	2.8a (0.18)	-	-
80-90	3.9c (0.3)	-	-	-	-	-	-	-	-	-	2.8a (0.21)	-	-

Hydromorphic soils (10 to 40 cm deep when the pseudogley appears), located at the bottom of slopes close to the thalweg or in flood-prone areas, are distinguished from all other soils by their higher C content, especially in their forest variant (LL1 and LL2). Overall, there is a progression according to waterlogging and humidity: hydromorphic soils are the richest in C, and leached ferruginous soils with patches and concretions (LL3 and LL4) (pseudogley between 40 and 60 cm) have more C than 'modal ferruginous' soils (FL5 and FL6), which are reddish, draining and aerated. Some of the indurated soils are hydromorphic just above the induration, when it is not very permeable and the soil is silty. Among the ferrolitic soils, the silty soils (FL1) in the foothills have the highest content in the surface horizons. More than the soil type, it is the position in the landscape that has favoured this accumulation.

According to the type of management, in the lowglacis area, the pseudo-climaxes (LL1 and LL2), the plots in transition to permanent cropping and the plots under long-term permanent cropping have the best C rates at the 0-20 cm layer. On the other hand, on the plateau area, the plots in fallow (FL1 and FL2) and those in shifting cropping (FL3 and FL4) have the best carbon levels at the same layer. In the soils of the plateau, shifting cultivation is a transitional phase before permanent cropping with manure. Permanent cropping (FL5 and FL6) has an even lower carbon content, but is little different from the transition, suggesting a relative equilibrium. The carbon loss after fallow is therefore high in the transition phase and then decreases.

A simple linear regression shows the influence of clay + fine silt content on C distribution in the 0-20 cm horizon (Figure 2). The regression line clearly contrasts the terroir of the lowland (LL) with that of the flatland (FL) in terms of texture and carbon content.

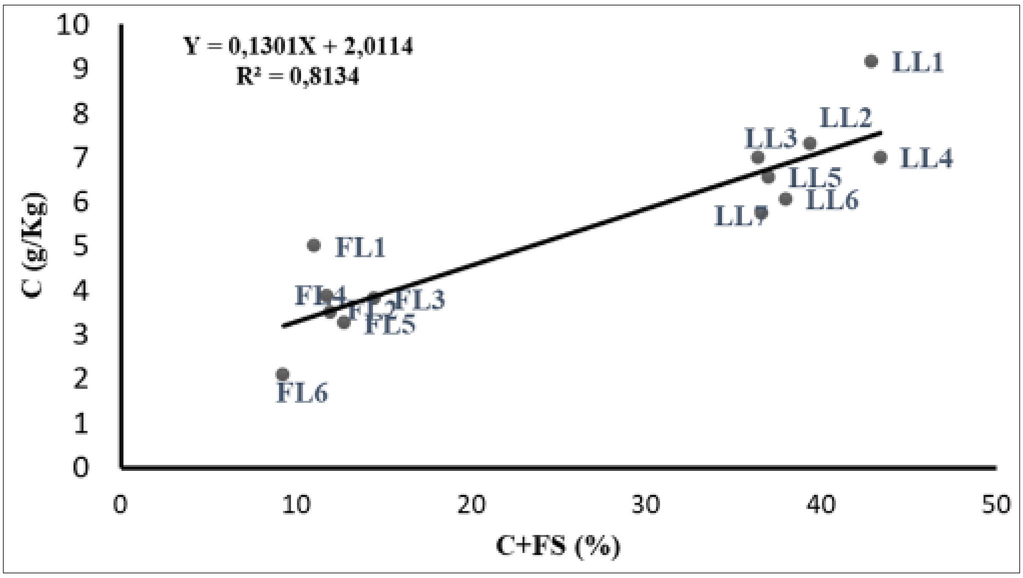

Figure 2 Carbon distribution according to texture at the 0-20 cm depth

The contents vary from 1.5 g/Kg to 10.5 g/Kg C, with an average of 5.4 g/Kg C. The variability of C increases with the level of fine elements. There is therefore a significant correlation ($p<0.0005$) between the C content and the fine element content ($b= 2.0114$; $R^2=0.8134$). The correlation with the level of fine elements is better for the heavy soils of the lowland terroir (LL) than for those of the flatland (FL).

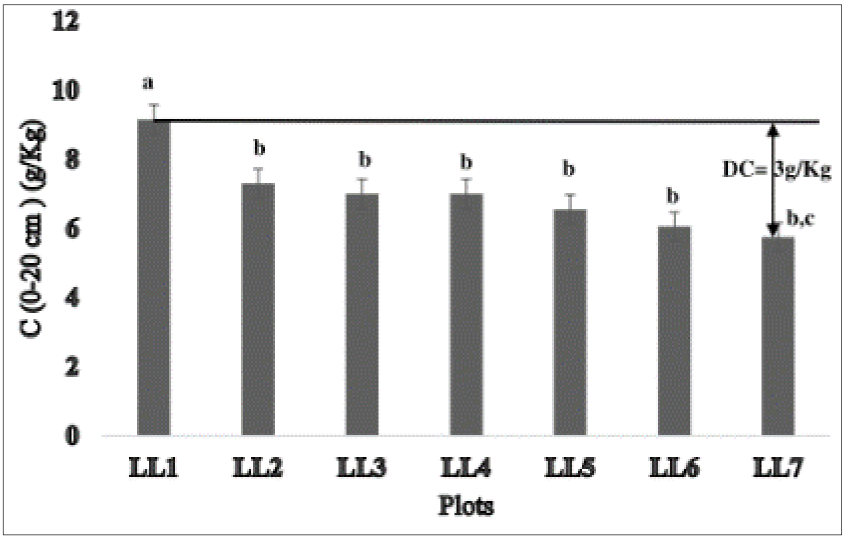

Figure 3 Carbon content and relative difference (DC) (g/Kg) over 0-20 cm in the lowland (LL) plots. Means with the same letters are not statistically significant (n=7, P< 0.005)

In order to better understand the vertical distribution of carbon in the 0-20 cm layer depending on the type of use, we created the DC variable, which is the difference between the highest and lowest C content of the different plots. This variable is calculated for each terroir and can be considered as a relative gain or loss depending on the situation. For the lowland area, the pseudo-climaxes (LL1 and LL2) are considered to be the remnants of C-rich soils. On the flatland area, the fallow plots (FL1 and FL2), which represent the high C content of the soil, are contrasted with the plots under permanent cultivation with manure (FL5 and FL6), which have a low C content of the soil. The change from pseudo-climax to permanent cultivation for 25 years therefore causes a loss (LL1 to LL7) of 3 g/Kg C in the lowland (Figure 3), and conversely the change from LL7 to LL1 causes a gain. On the flatland, the difference between the 2 predefined situations is also 3 g/Kg C (Figure 4). In other words, there is a gain from permanent to fallow plots (FL6 to FL1) and a loss in the opposite direction (FL1 to FL6).

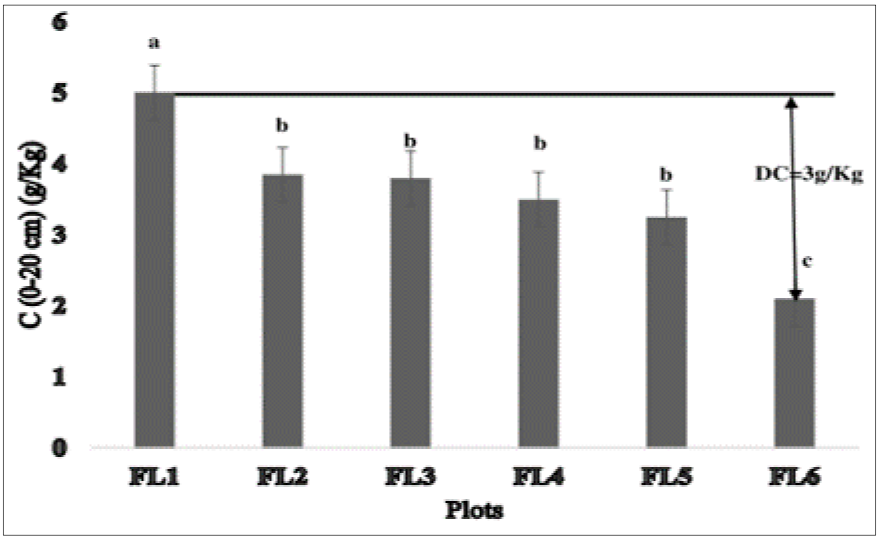

Figure 4 Carbon content and relative difference (DC) (g/Kg) over 0-20 cm in the plots on the flatland (FL). Means with the same letters are not statistically significant (n=6, P< 0.005)

4. Discussion

4.1. Combined role of vegetation and texture on vertical carbon distribution

Carbon content is highly variable in the surface layers, which means that the average content over at least 0-20 cm must be taken into account. The surface layer therefore overestimates the total carbon content. Planting crops and then leaving the soil bare by eradicating vegetation for about ten years depletes the 0-20 cm horizon in particular. If cropping intensity is increased, the inertia of the deep horizons will greatly overestimate the estimated losses above 1m. The fine elements (FE), which correlate with the C content, make it possible to distinguish between the two areas studied and, indirectly, the vegetation types. In dry savannah soils, FE plays a secondary role, whereas in wet forest soils it is essential. The slope b of the regression line C (g/Kg) = f (C+FS %) decreases from wet to dry and from the most forested to the most grassy. There is therefore a positive interaction between vegetation and fine elements. This interaction implies that fine elements do not act as storage 'containers', as is sometimes suggested, but play a dual role in facilitating humification and protecting SOM. Although carried out in a small region, our results are applicable to many areas of Sudan. Ferruginous soils are the most common, and the textural ranges at Bondoukuy are wider than those found in many Sudanese terroirs. The existence of a balanced carbon level under climatic forest [24] or in an anthropogenic climax such as savannah is accepted [25]. Under open Sudano-Guinean forest in Cameroon on modal leached ferruginous soils or concretions at the top of the slope (rainfall = 1400 mm), C content is 8 $g.kg^{-1}$ for 20% of FE, 5 $g.kg^{-1}$ in grass savannah on hydromorphic soil at the bottom of the slope (same texture) and 15 $g.kg^{-1}$ on lowland soil with gley at 44% of FE [26]. Forested savannah soils on new land in Senegal contain 3.7 $g.kg^{-1}$ C at 14% of FE [27]. Siband [28], under the dry dense forest of Casamance (rainfall = 1300 mm), gives a content of 8 to 10 $g.kg^{-1}$ C for 15% of FE. These regional data are very similar to the pseudo-climatic data obtained at Bondoukuy and the effects of texture, soil and vegetation. It is suggested that the former fire-sensitive dense forest, of which only relics remain near watercourses and springs and on termite mounds and collapsing armour, gave way to savannah at some distant time as a result of climatic changes and then fire.

4.2. Role of cropping systems

4.2.1. Extended and permanent cropping

In a pseudo-climatic situation, permanent cropping without restitution leads to a drastic decrease in organic matter levels [28, 29]. The annual decomposition constant k of soil organic matter under cultivation is 3.3% after forest and 4.5% after savannah [24]. Soils with the fastest decomposition of organic matter are sandy soils. The apparent k coefficient (i.e. the observed net loss) in traditional cultivation is 4.7% in sandy soils and 2% in sandy-loamy soils [6].

In Bondoukuy, we only have examples of recently cleared lowland forests, which makes it impossible to calculate this loss accurately. This remains an exceptional situation and is therefore of little use for our considerations on the dynamics of C.

After forest fallow, the accumulated organic matter remains available for mineralisation activated by tillage for longer than after savannah, which explains the popularity of these soils. Equilibrium (or rather a very slight decrease) is reached after 20 years with a deficit of less than 3 g/Kg compared to the average level of the crop-itinerant for heavy soils and for sandy soils. Annual deep ploughing (with a tractor) exacerbates this depletion, but the dilution effect of a thorough cultivation profile must also be taken into account. The C conditions recorded in permanent crops are compatible with measurements made in other contexts in the same region. The long-term experiment (1960-1990) at Saria (central region of Burkina Faso, P = 800 mm; FE = 12%) [6, 30, 31] provides an opportunity for comparison. Several treatments were compared for sorghum monoculture with manure and mineral fertiliser. In 1960, the soil was left fallow with 3.7 $g.kg^{-1}$ C. During the first decade, the soil lost 2.65% per year, which can be compared to the transition from shifting cultivation to fallow. In the second decade, the soil loses 1.6% per year and in the third, 0.7% per year. If we assume that pseudo-organic equilibria have been reached after thirty years, the level of SOC reached as a function of the dose of manure is a linear function, the intercept of which can be considered as the very stable organic matter content of the soil. The loss is 3 g/Kg for permanent crops with manure on the sandy soils observed at Bondoukuy. There is therefore a correspondence between the Saria experiment and our plots on the Bondoukuy plateau, in a real environment. Permanent cropping after old fallow on sandy soils therefore only loses 3 g/Kg of surface MOS, and this is a maximum. On the other hand, it is assumed that mineralisable MOS (organo-coarse, organo_silt) are effectively consumed during permanent cropping, which requires mineral supply and organic inputs. Regular fertilisation therefore raises soil levels, sometimes to the level of shifting cultivation. According to the abacus for the Saria trial, maintaining soil content at the level of 'savanna shifting cultivation' requires 6$t.year^{-1}.ha^{-1}$ of manure. However, plots heavily amended with organic manure are still rare in our sample.

4.2.2. Shifting cultivation

The practice of "shifting cultivation" on the flatland terroir introduces a balance at an organic level that is more intricate than the pseudo-climax "fallow". A loss of 3 g/kg was observed. This value is likely to be an underestimate, given that the shifting cultivation in our sample is primarily composed of 30-year-old forest fallows and 10-year-old crops. The sample lacks young fallows of 10 to 20 years. Nye and Greenland [24] observed a reduction of 25% in the level of the climax in humid forest zones. In our case, we may posit a loss of -7% if we start with the pseudo-climax on the lowland terroir and progress towards shifting cultivation on the flatland. It can be extrapolated that the soils will have lost almost a quarter of their C content by the transition from savannah to shifting cultivation. This finding is corroborated by the research of Peltier *et al.* [32] in the Democratic Republic of the Congo and Harmand *et al.* [33] in Cameroon. They all emphasised the loss of SOC content during the clearance of a climax savannah for the practice of shifting cultivation. In the case study area, shifting cultivation was a common practice in the 1950s, with a relatively low population density of 10 inhabitants per square kilometre. Nevertheless, 10% of pseudo-climax environments persisted (buffer zones, protected forests, marginal soils), half of which have since been replaced by classified forests that were previously under shifting cultivation. Since that time, there has been a precipitous decline in the practice of shifting cultivation, which is now confined to a mere handful of instances, comprising fallows that are between 30 and 40 years old and recent clearings. The issue is that this scarcity confers significant economic importance upon these remnants, leading to increased harvesting and greater emphasis on woody plants.

4.2.3. Fallow cropping system

The majority of the flatland area is under fallow cropping, with a 10-year cultivation and 10-year fallow period (C10J10) or a 10-year cultivation and 20-year fallow period (C10J20). The transition from shifting cultivation to fallow cropping system has been observed to result in a reduction in average soil carbon content. A reduction in carbon content of -3 g/kg was observed in both light and heavy soils at a depth of 0-20 cm. In terms of quantity, the loss of carbon is comparable. However, in heavy soils, fallow cropping is rarely observed, as both migrants and natives have directly transitioned from shifting cultivation to permanent cultivation. The loss of 3 g/kg therefore only concerns flat-land situations where the population density is 20 inhabitants/km^2. Yoni *et al.* [3, 9] corroborate these findings with more precise observations, confirming a positive variation in C during the fallow phase in non-degraded areas. It is emphasised that this regeneration is primarily associated with the mineralisation of organic-coarse fractions during the cultivation phase, with a secondary influence observed in the organo-silty fractions that underwent partial mineralisation during the initial phase of the fallow. In combination with the mineralisation of underground litter from clearing, and the effects of weeding and deworming, this modest gain in MOS, and its local concentration at the level of tufts, stumps and termite mounds, are expected functions of fallows for farmers in light soils. Indeed, several studies

[34, 35, 36] have corroborated the crucial role of the fallow crop system, as observed in our study. The provenance of the substrate and its geographical location are both significant factors in understanding the distribution of SOC.

4.3. Carbon stock dynamics according to the terroir

In the silty-sandy lowlands (one quarter of the department of Bondoukuy), cropping systems have undergone a transition from shifting cultivation to permanent cultivation over the past 20 years [17]. This transition has resulted in a loss of 3% of the carbon content between 0 and 20 cm. Subsequent losses are minimal due to the rarity of annual ploughing practices, which are linked to corn-cotton rotations that could exacerbate losses [37, 38]. This is largely due to the difficulties small farmers endure in obtaining fertiliser for corn.

The cropping systems on sandy flatland that have also lost 3% of their content (a shift from shifting cultivation to fallow cultivation) are currently undergoing a gradual and localised transition from fallow cultivation to extended cultivation. This extension remains uncommon, as extended cultivation on sandy soils necessitates the control of weeds and fertilisation, which are only economically viable for a select group of affluent farmers [11]. The maintenance of fallow cultivation therefore has the additional benefit of preserving not only shrub carbon but also 3 g.kg-1 of soil organic carbon (SOC).

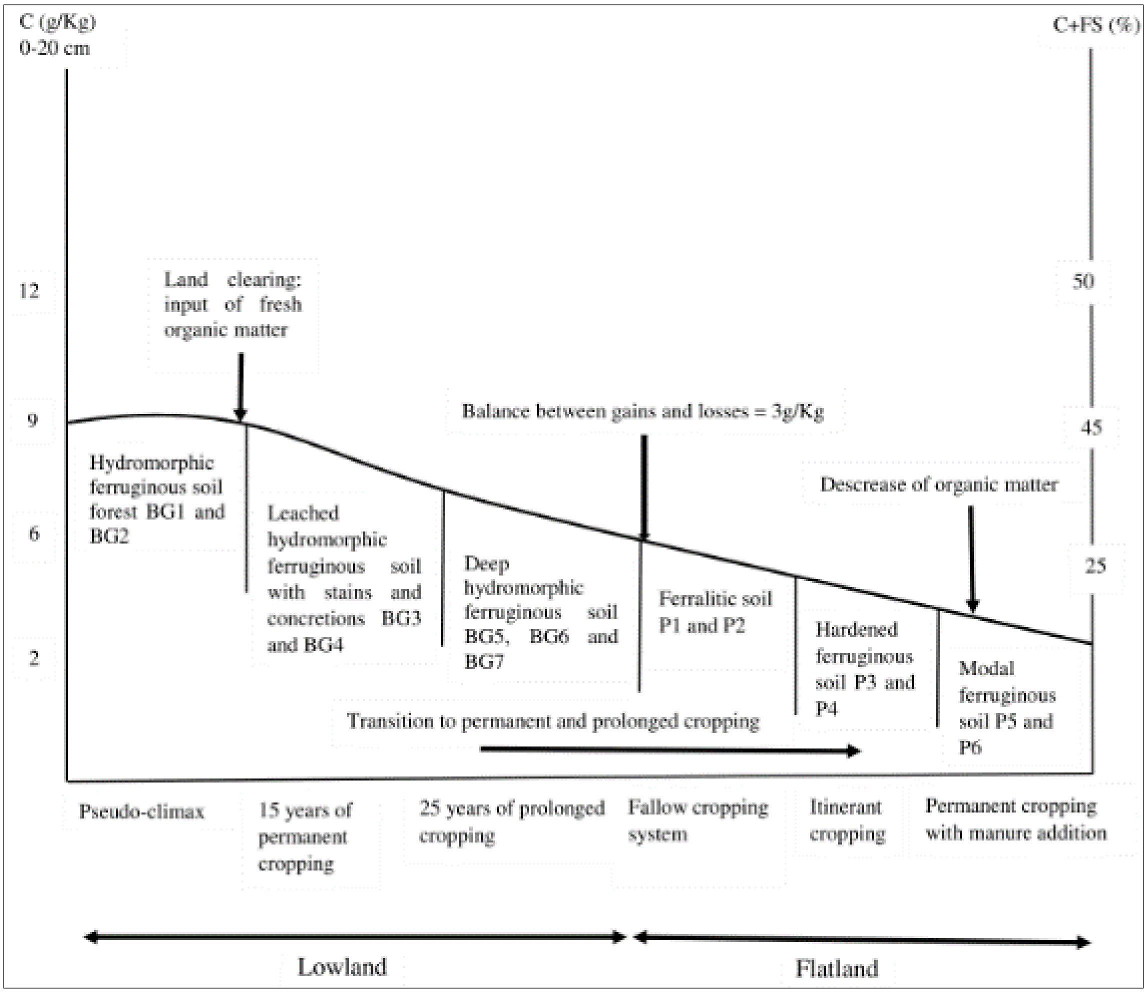

Figure 5 Theoretical vertical distribution of carbon in the Bondoukuy area under a semi-arid Tropical climate

We therefore only have to deplore the disappearance of 3% of the average C content on the surface, on all the arable lands of the "cotton" savannahs. It should be noted that this figure is only an approximation. It is evident that there are secondary losses and gains. The degradation of fallow land in the vicinity of villages represents a source of losses. A proportion of the losses observed in cultivated areas can be attributed to erosion rather than mineralisation [39]. This eroded carbon is not lost from the system, but rather transferred to other locations, such as lowlands or spreading areas. Furthermore, instances of cultivation amended with organic manure, though uncommon, must be considered. If we consider the mean value of 5.5 g/kg of C on 0-20 cm (calculated from the 13 plots), the actual loss is relatively low in comparison to the annual loss of 4.7 to 2 g/kg of C under cultivation, which is currently incorporated into the models. This represents a considerable increase when considered alongside the losses associated with deforestation during the same period. A significant current slowdown in these losses is anticipated, or even a cessation in the near future, due to the lack of unstable carbon in the soils and economic considerations for prolonged cultivation on light soils and intensive ploughing on heavy soils. The consumption of SOC is constrained by socio-economic factors at this point. Conversely, the regions designated as "pioneer zones," which are characterized by advanced agricultural development and high rates of immigration, will be the primary locations for these losses. Nevertheless, deforestation will persist in developed regions, where population growth is currently relatively modest. It is therefore the latter which will contribute the most to the loss of carbon from the environment in the absence of reforestation. The work of Javed *et al.* [40] and Ballo *et al.* [41] has also identified these aspects.

The impact of terroir on carbon distribution can be modelled using our data (Figure 5). On a hydromorphic soil, the initial clearing of a pseudo-climacic savannah facilitates the substantial input of organic matter into the soil. This enables the practice of permanent cropping for a period of 15 years on a leached hydromorphic soil. This cropping process is further intensified on deep hydromorphic soil over a period of 25 years. The activity undertaken on the lowland serves to reduce the initial stock by 3%. This represents the transitional phase towards the flatland terroir, characterised by poor soil quality, where fallow cropping system is the predominant practice, with the objective of restoring the soil. Concurrently, the intensive exploitation of the soil through shifting and permanent cultivation, coupled with the addition of manure, has resulted in a notable decline in soil fertility. Despite their low carbon content, the flatland soils are conducive to agricultural practice. This is made possible by the use of many technics and the continuous incorporation of organic manure.

5. Conclusion

The aim of this study is to assess the carbon content of two terroirs with different soil types in order to establish comparisons. The results of this study demonstrate that it is posible to estimate carbon losses in the soils of cotton-growing regions. In contrast, forest soils, pseudo-climaxes and crops amended with organic manure can be excluded from consideration, given their low representation. The morpho-pedological situation is of significant consequence. Indeed, flatland soils are observed to exhibit a lower concentration of carbon than soils situated in lowland plains. The crop system exerts a considerable and pronounced influence. This amplitude is amplified when the soil is humid. The distinction between humid and dry soils is rendered inconsequential when the crop in question persists. This suggests that the organic matter accumulating in humid soils in temporary systems is not particularly stable. Consequently, there is a reduction in carbon levels in line with increasing crop intensity. The stages of fallow cropping system do not emerge as significant factors in the variation of the data. Conversely, the analysis by terroir and by soil indicates that the effect is nevertheless relatively limited in scope.

Further research is required to provide a comprehensive evaluation of SOC losses in agricultural systems. For instance, it would be beneficial to examine the future of agricultural production itself. This is because, in contrast to food production, fibre production is metabolised in the short term and preserved and recycled over long periods.

Compliance with ethical standards

Disclosure of conflict of interest

The authors of this article declare that there is no conflict of interest.

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