Tropical Ecology **58**(4): 823-832, 2017
ISSN 0564-3295

www.tropecol.com

Spatial and temporal variation of black cotton soil organic carbon in Guinean forest zone in West Africa

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Abstract: The overall objective of the research was to generate soil organic carbon (SOC) reference data for the benefit of the REDD+ initiatives. In this study, SOC was derived from direct measurements of organic matter (OM) content in soil. Six hundred and seventy five soil samples were collected to 30 cm depth in black cotton soil and across three vegetation types including undisturbed forest, degraded forest and fallow in a Guinean forest zone in West Africa. The samples were analysed for bulk densities and for soil OM using loss-on-ignition method. Between 12% and 21% OM per soil mass was found at all layers, 0–10, 10–20 and 20–30 cm, suggesting that black cotton soil was organic soil. OM and C contents and SOC were higher in the upper soil layer and decreased with depth. The highest values of these soil factors were detected in undisturbed forest. The low variation of these soil factors within each vegetation type and their fairly homogeneous spatial distribution across vegetation types confirmed that soils in degraded forest and fallow reached equilibrium, considering undisturbed forest as reference. The lowest bulk density (BD) was found in the top 10 cm layer of the soil depth. There were no significant differences between the mean values of BD observed at the same horizon across vegetation types.

Key words: Benin, bulk density, carbon stock, loss-on-ignition, soil pool, tropical forest.

Soil organic carbon (SOC) is an important carbon pool, which accounts for about three times the amount of carbon in vegetation (IPCC 2007; Kumar *et al.* 2013; Lal 2004; Wang *et al.* 2004). Its influence on the global climate change is also important because the processes leading to carbon accumulation in soil, including litter fall and decomposition, are influenced by climatic conditions (Bargali *et al.* 2015; Salgado *et al.* 2015; Thomas *et al.* 2014). Very little attention has been given to this carbon pool in tropical forest in Africa (Henry *et al.* 2009) in order to acknowledge the issue of the global carbon cycle (Guendehou *et al.* 2013). Our assessment suggests that the main cause of this lack of attention is related to the difficulty in implementing large scale sampling for measurements and modelling soil carbon flux in tropical forest ecosystems.

Due to this lack of data, most countries in Africa are not able, at the moment, to report to the United Nations Framework Convention on Climate Change (UNFCCC), soil organic carbon using country-specific data. The default data from the 2006 IPCC Guidelines (IPCC 2006) these countries use are not always representative of their national circumstances. Soils are classified as either mineral or organic types depending on the amounts of organic matter they contain. Organic soils contain approximately 12 to 20% organic matter by mass (Brady & Weil 1999) and all other soils are classified as mineral soil types (IPCC 2006). Both organic and inorganic forms of carbon are found in soils, but given that the organic carbon is more subject to modifications, a lot of attention is given to changes in soil organic carbon stocks (IPCC 2006).

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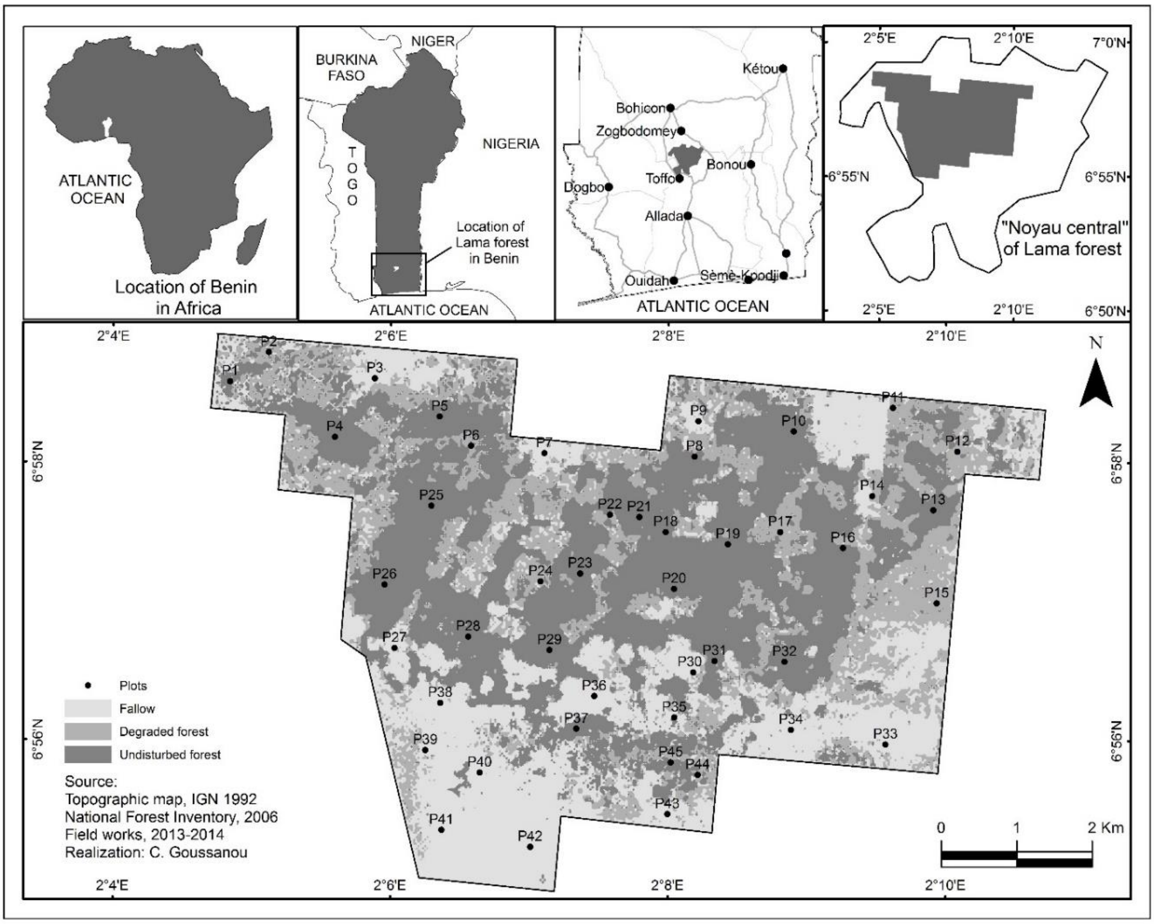

Fig. 1. Location of the study area.

Two approaches, including direct measurements and modelling are used to estimate SOC and its change in forest ecosystems. These approaches are complementary as results from direct measurements are usually used to validate predictions from modelling. Soil sampling is a laborious and time consuming activity especially the first direct measurements of soil carbon which require large scale sampling to detect and account for the large variability in SOC and to provide guidance on future sampling approach.

The need for more reliable soil carbon monitoring system has increased as developing countries have started to construct their forest reference emission levels/forest reference levels (FREL/FRL) as part of the REDD+ process related to mitigation actions in the forest sector. At the moment, countries that have submitted their FREL/FRL to the UNFCCC planned to include soil pool in future submissions as part of the stepwise approach when reliable data become available. Volkoff *et al.* (1999) carried out an assessment of SOC in Benin and determined carbon stock average for some soil types according to soil depth (0–20 cm, 0–50 cm and 0–100 cm) and its variability using historical database developed in 1960–1970. Azocli *et al.* (2015) determined carbon content under cropland and forest. These studies on soil carbon in Benin did not address temporal and spatial variation in carbon stock and it was not clear whether they were conducted in natural forest. The overall objective of this study was to generate SOC reference data for the benefit of REDD+ initiatives. The specific objectives were to assess the spatial (vertical and horizontal) distribution of the SOC and to study its temporal dynamic in semi-deciduous forests. It also intends to verify the hypothesis that after a long period of disturbance soil carbon reaches equilibrium.

The study was conducted in the Lama forest reserve, a semi-deciduous forest ecosystem located in southern Benin (Nagel *et al.* 2004) between 6°55′ and 7°00′N and 2°04′ and 2°12′E (Fig. 1). The forest covers an area of 16,250 ha including 4777 ha of natural forest entirely protected referred to as the 'Noyau Central'. The climate in the study area is classified as tropical moist according to the definition of climate regions by the IPCC (IPCC 2006). The monthly average temperatures vary from 25 to 29 °C and the mean annual rainfall is 1200 mm. Monthly rainfall exceeds 100 mm except for January, February and March, which are the warmest months. Two rainy seasons occur between mid-March and mid-July and between mid-September and mid-November.

The soil in the area is a hydromorphic clayey vertisol of black cotton soil (40–60% of clay) characterized by poor drainage and a pH range of 5–5.5 in the 0–30 cm horizon (Küppers *et al.* 1998). Von Bothmer *et al.* (1986) described the soil in Lama forest as rich in calcium (Ca) and magnesium (Mg) due to a "granito-gneissic" parent material from the secondary and tertiary ages. The mean altitude in the forest is 60 m above sea level. During the rainy season, the swelling of the clay result in mud on the forest floor.

The vegetation types include an undisturbed forest, a degraded forest and fallow (Bonou *et al.* 2009). The land classification was based on the extent of historical deforestation activities that have affected this natural forest. Between 1946 and 1987, 9000 ha of the natural forest was converted to cropland (Emrich *et al.* 1999). The undisturbed forest refers to the part of the study area that has remained intact while degraded forest and fallow refer to areas that were subjected to low perturbations and severe disturbances respectively. Since the interruption of agricultural activities in 1987, protection measures including some afforestation activities, through tree plantation, have taken place in areas previously disturbed. Applying the default transition period of 20 years (IPCC 2006), degraded forest and fallow that were reconverting from cropland to forest land have been classified under categories degraded and fallow. In 1986, the areas reported by Von Bothmer *et al.* (1986) were 3784 ha for undisturbed forest, 5827 ha for degraded forest, 5800 ha for fallow land and 840 ha for plantation forest. The undisturbed and degraded forests are dominated by tree species such as *Afzelia africana* (Sm.), *Ceiba pentandra* (L.), *Diospyros mespiliformis* (Hochst. Ex A.DC.), *Dialium guineense* (Wild), *Mimusops andongensis* (Hiern.), *Celtis prantlii* Priemer ex Engl., *Holarrhena floribunda* (G. Don) Durand and Schinz, *Malacantha alnifolia* (Baker) Pierre, *Drypetes floribunda* (Müll. Arg.) Hutch., and *Cynometra megalophylla* (Harms). The fallow is characterized by open canopy forests contain dominant species such as *Anogeissus leiocarpa* ((DC.) Guill. & Perr.), *Lonchocarpus sericeus* (Poir.) Kunth, *Albizia zygia* (DC.) J.F.Macbr. and *Ficus sur* (Forssk.). The dominance of the tree species was determined based on the importance value index (Goussanou *et al.* 2016). The plantation is composed of species such as *Tectona grandis* L.f. and *Gmelina arborea* Roxb.

The plots used in this study were those established for biomass measurement by Goussanou *et al.* (2016) i.e. forty-five permanent plots of 50×50m square distributed proportionately in the area of each vegetation type of the Lama forest. According to the distribution, 20, 10 and 15 plots were installed in undisturbed forest, degraded forest and fallow respectively. More details on plots establishment can be found in Goussanou *et al.* (2016).

Within each plot, five sample points were used. Samples were taken at each corner and in the centre using a soil corer (2 cm diameter and 30 cm length). The top-most loose litter layer was discarded. Soil samples were taken vertically from surface up to a depth of 30 cm and divided into three layers: 0–10 cm, 10–20 cm and 20–30 cm and put in plastic bags. This depth was considered sufficient because the organic carbon in the top 30 cm layer is often the most chemically decomposable, and the most directly affected by natural and anthropogenic disturbances (IPCC 2006), the sampling was limited to this depth. In total 15 samples were taken in a plot. This amounted to 675 samples for all plots. Fresh mass of each sub-sample was taken in the field using electronic hand scale (with an accuracy of 0.001g) before taking them to laboratory.

Sub-samples were oven-dried at 50 °C to constant weight (during 72h) to get rid of humidity and determine water content (Eq. 1). An assumption was made that drying samples at this moderate temperature would minimize the loss of material, in particular, of volatile organic compounds, likely to occur at higher temperatures. Oven-dried samples were reweighed with an electronic scales (Ohaus Pionneer Analytical Model scale with an accuracy of 0.001g) to determine the dry mass and then the bulk density taking into account the known volume of the soil corer used to collect the sample (Eq. 2).

In order to determine the organic matter content in soil sub-samples, the method of loss-on-ignition (LOI) was carried out (Ghabbour *et al.* 2014; Hoogsteen *et al.* 2015). Composite samples (i.e. mix

Table 1. Mean bulk density of soil depth across vegetation types; bulk density range includes all measurements without modification.

Vegetation types	Soil depth (cm)	Number of soil samples	BD (g cm^{-3})		
			Range	Mean (standard deviation)	CV (%)
Undisturbed forest	0–10	100	0.97–1.35	1.15 (0.10)	8.51
	10–20	100	1.11–1.5	1.30 (0.11)	8.51
	20–30	100	1.26–1.64	1.42 (0.10)	7.15
Degraded forest	0–10	50	1.04–1.28	1.15 (0.07)	6.42
	10–20	50	1.18–1.47	1.31 (0.10)	7.54
	20–30	50	1.29–1.58	1.41 (0.10)	7.41
Fallow	0–10	75	0.99–1.25	1.15 (0.09)	7.46
	10–20	75	1.18–1.42	1.33 (0.06)	4.38
	20–30	75	1.30–1.51	1.42 (0.06)	4.14

of the five sub-samples taken from the same soil depth within the same plot) per depth and per plot were used for the LOI. Composite samples were used in order to reduce the number of individual samples to analyse. An assumption was made that composite samples do not affect the accuracy of the organic matter measurement. In this study, 5g of each oven-dried sub-sample were placed in a ceramic crucible, previously dried, and combusted at 550 °C for 4 hours in a muffle furnace (Nabertherm GmBh LV 5/11/B180) as described by Wright *et al.* (2008). Following the ignition in the muffle furnace, the crucible containing the residue composed of ash was weighed and the mass of ash was determined by subtracting the mass of the empty crucible. During the ignition, it was assumed that all the organic material was combusted.

The water content of the sub-samples was determined using Eq. (1).

$$WC = (M_1 - M_2)/M_1 \qquad \text{(Eq. 1)}$$

Where WC (g/g) is the water content of sub-sample, M_1(g) = mass of wet sub-sample measured in the field, M_2(g) = oven-dry mass of sub-sample.

The bulk density of sub-samples was estimated from Eq. (2)

$$BD = M_2/V \qquad \text{(Eq. 2)}$$

Where BD (g cm^{-3}) is the bulk density of the sub-sample, V = volume of the sub-sample, derived from the dimensions of the corer (V = 31.4 cm^3), M_2 as defined in Eq. (1)

The organic matter content of the samples was estimated using Eq. (3)

$$SOM = [(M_2 - M_3)/M_2] \qquad \text{(Eq. 3)}$$

Where SOM (g/g soil) is the soil organic matter content of the sub-sample, M_3 = mass of ash (g) after ignition at 550 °C, M_2 as defined in Eq. (1)

The soil organic carbon stock was computed by applying Eq. (4)

$$SOC = SOM \times BD \times D \times (1 - fragment) \times CF \times 10^{-2} \qquad \text{(Eq.4)}$$

Where SOC (t C ha^{-1}) is the soil organic carbon stock in the depth increment D, D = depth increment (10 cm), $fragment$ = proportion of coarse-fragment free soil, in this study, $fragment = 0$, CF = conversion factor to convert soil organic matter to carbon; CF = 0.58 (IPCC 2006; Sakin 2012; Tesfaye *et al.* 2016).

Statistical parameters including mean, standard deviation, and coefficient of variation were assessed using the statistical computing software R (R Development Core Team 2012). The analysis of variance (ANOVA) was also performed to determine the variation of bulk density, and SOC according to soil depth and across vegetation types. The comparison with existing data was carried out to assess the deviation of the results from similar previous studies.

A mapping of spatial distribution of SOC according to vegetation type was developed using ArcGIS 10 and the most recent vegetation map of the Lama forest (Bonou *et al.* 2009). Mean SOC values were assigned to each vegetation type classes (Fig. 2).

In all vegetation types, the lowest bulk densities (BD) were found in the upper soil layer, 0–10 cm, and the highest values in the deep layers, 20–30 cm (Table 1) suggesting that BD increases with depth. The variation in BD was more pronounced (higher coefficient of variation) in the upper layers (0–10 cm) in the undisturbed forest than in the other vegetation types (Table 1). Analysis

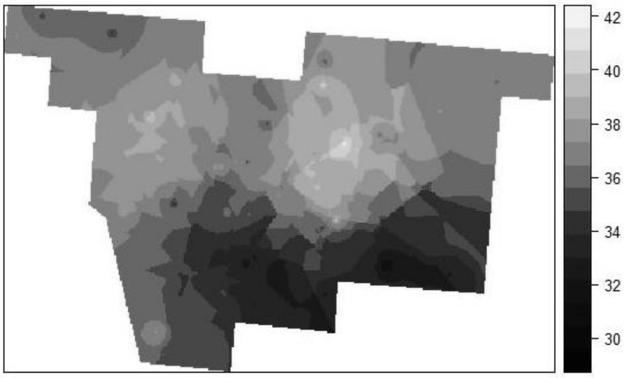

Fig. 2. Spatial distribution of SOC in lama forest reserve.

of variance ($F_{2,126}$=100.56, P < 0.001) revealed a significant variation of BD between depths (Table 1). There were no significant differences between the mean values of BD observed at the same horizon across vegetation types (F_2=0.05, P = 0.952). For example, the mean BD observed in 0–10 cm layer (1.15 g cm^{-3}) was identical for undisturbed forest, degraded forest and fallow and the mean BD in 10–20 cm in undisturbed forest were only 0.8–2.3% lower than in degraded forest and fallow.

For all vegetation types, the OM, carbon content (CC) and SOC showed a decreasing trend from the upper layer of soil to the 30 cm depth (Table 2, Figs. 3 and 4). The soil factors were significantly different by vegetation types ($F_{2,126}$=6.41, P = 0.002) and depth ($F_{2,126}$=109.81, P < 0.001) namely between undisturbed forest and fallow (Table 1). The highest values of OM content, carbon content and carbon stock were detected in undisturbed forest. However, low variation in these factors within and across vegetation types was observed (Table 2).

In undisturbed forest, the most distant points from each other were located in plots P_1 (2°4´50´´E, 6°58´35´´N) and P_{13} (2°09´54´´E, 6°5740´´N) and the closest points in plots P_{18} (2°07´59´´E, 6°57´30´´N) and P_{21} (2°07´47´´E, 6°57´37´´N). The assessment showed that OM content (g g^{-1}) in plot P_{13} was only 1.17 times higher than in plot P_1 and that in plot P_{21} it was 1.01 times higher than in plot P_{18}. Similar observations were made in the other vegetation types. Considering the plot P_{20} (2°08´02´´E, 6°57´06´´N) closest to the centre of the forest and located in undisturbed forest as reference point, we assessed the variation of OM content according to the distance for all other plots compared to the reference point. The OM in P_{20} is 0.57 to 0.99 higher than that in other plots. The variation indicated fairly homogeneous spatial distribution of OM. P_{20} has the highest value of OM and the observations indicated that OM decreases as the distance increases from the center to the periphery of the forest (Fig. 3). The estimated carbon stock in each layer 0–10, 10–20 and 20–30 cm in undisturbed forest was higher than in degraded forest which is also higher than in the fallow (Table 3, Figs. 3 and 4).

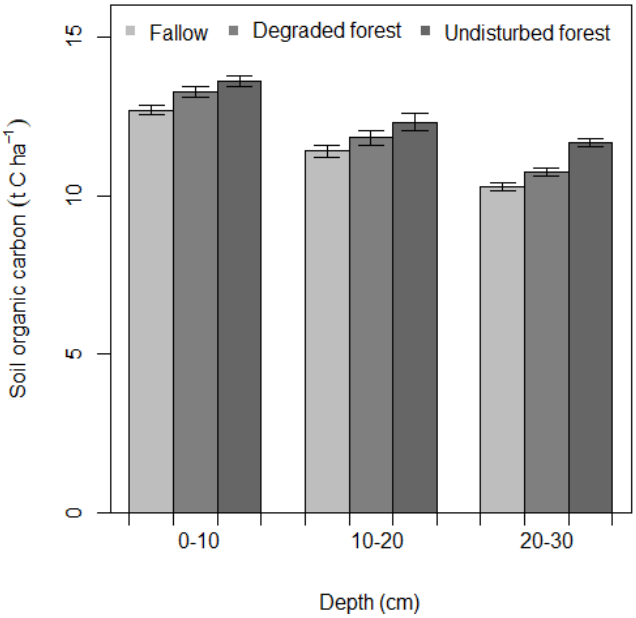

Fig. 3. Distribution of soil organic carbon according to vegetation type for soil depth 30 cm.

The bulk densities found in this study (Table 1) were within the range (1–2 g cm^{-3}) reported in other studies on vertisol in the tropics (Jewitt *et al.* 1979; Seyoum 2016; Virmani *et al.* 1982). The increasing trend in bulk density with soil depth was also in line with findings from Návar & Synnott (2000); Osborne *et al.* (2011); Dengiz *et al.* (2012) who reported soil compression and compaction due to overburden as causes of this trend. However, the black cotton soil in the Lama forest has not been subject to land use activities since the interruption of deforestation and agricultural activities in the year 1987. One possible explanation of this trend could be the higher water content in the upper layer of the soil. As indicated above, soil in the study area is characterized by a poor drainage and water hardly infiltrates in the deeper layers. The lack of significant effect of vegetation types on bulk density (low variation across vegetation) may be interpreted by the fact that black cotton soil properties have reached equilibrium

Table 2. Organic matter content (g g^{-1} soil), organic carbon content (g g^{-1} soil) and soil organic carbon stock (t C ha^{-1}) of soil depth across vegetation types. Organic matter content was derived from loss on ignition; carbon content was estimated using the conversion factor 0.58. Stand. dev. is Standard deviation and CV is the coefficient of variation.

Vegetation types		Undisturbed forest			Degraded forest			Fallow		
Soil depth (cm)		0–10	10–20	20–30	0–10	10–20	20–30	0–10	10–20	20–30
Water Content (g g^{-1})	Range	0.17–0.33	0.15–0.29	0.16–0.31	0.16–0.32	0.18–0.29	0.17–0.29	0.19–0.31	0.16–0.27	0.18–0.26
	Mean	0.27	0.24	0.23	0.27	0.24	0.23	0.24	0.23	0.22
	Stand. dev.	0.05	0.04	0.04	0.06	0.04	0.04	0.04	0.03	0.03
	CV (%)	18.10	15.92	15.85	21.15	16.23	16.14	17.58	14.58	12.28
Organic Matter (g g^{-1})	Range	0.14–0.25	0.12–0.21	0.10–0.18	0.17–0.23	0.14–0.18	0.10–0.17	0.17–0.22	0.10–0.18	0.08–0.16
	Mean	0.21	0.16	0.14	0.20	0.16	0.14	0.19	0.14	0.12
	Stand. dev.	0.03	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.02
	CV (%)	13.91	14.02	14.99	8.36	10.22	15.42	7.05	14.63	17.28
Carbon Content (g g^{-1})	Range	0.08–0.20	0.07–0.15	0.06–0.13	0.10–0.13	0.08–0.11	0.06–0.10	0.10–0.13	0.07–0.10	0.05–0.09
	Mean	0.12	0.10	0.09	0.12	0.09	0.08	0.11	0.09	0.07
	Stand. dev.	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01
	CV (%)	19.33	18.02	19.70	8.36	10.22	15.42	7.05	11.31	13.77
Soil organic carbon stock (t C ha^{-1})	Range	11.09–17.46	10.14–14.44	8.66–14.11	11.21–14.60	10.23–13.48	8.8–13.42	10.03–14.51	9.05–13.32	8.01–12.50
	Mean	13.61	12.32	11.66	13.27	11.82	10.74	12.68	11.41	10.27
	Stand. dev.	1.44	1.14	1.31	0.97	1.20	1.44	1.14	1.23	1.22
	CV (%)	10.59	9.24	11.25	7.32	10.12	13.38	9.01	10.74	11.91

Table 3. Distribution of total soil organic carbon stock across vegetation types for soil depth 30 cm.

Vegetation types	Carbon stock (t C ha^{-1})	Area (ha)	Total carbon stock (t C)
Undisturbed forest	37.59	2076.73	78 064.281
Degraded forest	35.83	1075.67	38 541.256
Fallow	34.36	1624.6	55 821.256
Total			172 426.793

as result of less perturbation over three decades (De Blécourt *et al.* 2013).

Table 4. Soil organic carbon stock (t C ha^{-1}) in Lama forest reserve and comparison with other published data.

Some studies on vertisol	Climate	Carbon stock t C ha^{-1}	Soil depth (cm)
This study	Tropical	36.12	0–30
Volkoff *et al.* (1999)	Tropical	59.00	0–20
Lal (2002)	Tropical	62.00	0–100
Tsai *et al.* (2010)	Tropical	88.60	0–30
Ngo *et al.* (2013)	Tropical	34.30	0–20
Brahim *et al.* (2014)	Tropical	45.60	0–30
Venkanna *et al.* (2014)	Tropical	49.63	0–60

The SOC stock reported in this study for the three vegetation types (Table 3) was in the lower end of the range 34.3–59 t C ha^{-1} in tropical climate (Table 4). Because the carbon stock of the undisturbed forest (37.59 t C ha^{-1}, Table 3) was derived for native vegetation, in this study it was considered as reference soil carbon stock in line with the IPCC Guidelines (IPCC 2006). However, data in Table 3 indicated large variation of SOC across the tropics. Because of this variation, it is difficult to identify the appropriate SOC stock determined elsewhere that could be applied as default in another region.

The decrease in OM content, C content and C stocks from upper soil layer was consistent with findings from Bessah *et al.* (2016), IPCC (2006), Morisada *et al.* (2004), Muñoz-Rojas *et al.* (2012), Su *et al.* (2006), Vanguelova *et al.* (2013). The first explanation of the decrease of these values with depth was the mineralization of organic matter (Kadlec *et al.* 2012). Lama forest, as semi-deciduous forest, loses large proportion of leaves in dry season to limit water requirement, this results in a large amount of litterfall between 6.2 and 9.0 tdm ha^{-1} yr^{-1} (Attignon *et al.* 2004; Djego 2006). As this litter comes from the aboveground biomass, its decomposition results in higher OM and C contents in upper horizons and could explain the decrease observed between the soil depths. In addition, Guendehou *et al.* (2014) reported that decomposition of litter chemical components (e.g. acid-hydrolysable) may be affected by the formation of stable complexes in black cotton soil. Such soil texture constitutes a physical barrier from to decomposed material deposit underground, as decomposers are limited in transporting of OM into deep soil leading to discrepancies with depth (Schmidt *et al.* 2011; Six & Paustian 2014).

The present study also suggests that vegetation types influenced spatial variation of soil factors as reported in Bessah *et al.* (2016) and Assefa *et al.* (2017). This finding suggest effects of plant species on carbon input as pointed out by Sariyildiz *et al.* (2015) and in the Lama forest, plant communities vary with vegetation types and explains the difference in soil patterns. This results in litter amount and the decomposition of litter (Attignon *et al.* 2004; Djego 2006) leading to modification of soil chemical properties and by the way OM and SOC (Guendehou *et al.* 2014; Guo *et al.* 2016).

The long-term changes in vegetation is known to affect SOC chemical composition and dynamics in forest chronosequence (Guo *et al.* 2016; Lawrence *et al.* 2015; Lv & Liang 2012; Wang *et al.* 2011; Xiao *et al.* 2016). Historical deforestation activities in the Lama forest converted 9000 ha of undisturbed forest to cropland between the years 1946 and 1987. The former croplands changed to degraded forest or fallow over three decades since 1987 onwards and no further changes in land-uses have occurred since the interruption of these activities so far. The low variation of OM, C contents and C stock per ha within each vegetation type and the fairly homogeneous spatial distribution of these soils factors across vegetation types confirmed that black cotton soils in degraded forest and fallow have reached equilibrium, if we consider undisturbed semi-deciduous forest as reference. The default time period assumed for carbon stocks to come to equilibrium was 20 years (IPCC 2006). The mechanism leading to SOC equilibrium after forest recovery was facilitated by the forest management activities especially enrichment by some tree species planting (*Terminalia superba, Khaya grandifoliola, Khaya senegalensis, Holoptelea grandis* and *Afzelia africana*) in former croplands (Djodjouwin *et al.* 2011, 2012). For instance, Hombegowda *et al.* (2016) demonstrated the rebound of SOC level back to undisturbed forest level when cropland was replaced by agroforestry systems. The study has also shown low value of carbon in periphery than forest interior (Fig. 4) suggesting an edge effect on SOC.

The study confirmed that black cotton soil properties decrease from the upper layer of soil and varies according to vegetation types suggesting the plant species effects. Additionally, absence of disturbance leads SOC to evolve at its normal rate after a given period. The data reported in this study are reference data for reporting soil carbon pool under international agreements such as REDD+ and greenhouse gas inventories for national communications and biennial update reports of the UNFCCC. It contributes to database on tropical soils.

Acknowledgements

This study was conducted as part of the project "Pilot site: quantification and modelling of forest carbon stocks in Benin" funded by the Global Climate Change Alliance and the European Union (N° 00009 CILSS/SE/UAM-AFC/2013). We thank the Permanent Interstates Committee for Drought Control in the Sahel (CILSS) and the Regional Centre AGRHYMET for the technical assistance provided during the implementation phase of the project. We thank the Editor and two anonymous reviewers for thoughtful comments that improved a previous version of our manuscript.

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(Received on 13.04.2017 and accepted after revisions, on 13.02.2018)