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Soil organic carbon stock under semi-deciduous tropical forests: case of the Téné protected forest (Oumé, Côte d'Ivoire)

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Abstract

Soil organic carbon stocks (SOCS) estimated from international databases are generally subject to uncertainties. These errors are more significant in developing countries where field studies are rare. To overcome this shortcoming, soil samples were collected in the experimental set-up of Téné protected forest (ES-TPF), located in central-western Côte d'Ivoire, to identify the soil types and the corresponding actual SOCS. The FAO soil classification guide was used to identify soil types. SOCS were determined from the carbon concentrations, bulk densities, and proportions of fine elements, in 0-30 cm, 30-60 cm and 60-100 cm thicknesses. The results showed three soil types, namely Plinthosols at top slope, Ferralsols at top and middle slope and Fluvisols at bottom slope. In the reference thicknesses 0-30 cm and 0-100 cm, the respective SOCS are on average 44.89±25% $tC.ha^{-1}$ and 61.56±23% $tC.ha^{-1}$ in Plinthosols; 49.16±26% $tC.ha^{-1}$ and 93.40±16% $tC.ha^{-1}$ in Ferralsols; 41.18±32% $tC.ha^{-1}$ and 68.54±22% $tC.ha^{-1}$ in Fluvisols. Almost all these values differed from those in the international databases, especially in the depths. Therefore, the results obtained are recommended for a better accounting and management of SOCS in the semi-deciduous tropical forests of West Africa.

Keywords: SOCS; Semi-deciduous tropical forests; Plinthosols; Ferralsols; Fluvisols; Côte d'Ivoire

1. Introduction

Soils are a biggest continental carbon sink, storing 1,500 giga tonnes of carbon (GtC) in 0-100 cm thickness, which is about twice as much as atmospheric carbon (805 GtC) and three times as much as vegetation (550 GtC) [1]. In sub-Saharan Africa, 68% of terrestrial carbon is estimated to be stored in soils [2]. Proper management of this important reservoir could significantly reduce and mitigate greenhouse gases emission and improve soil quality [3].

However, current estimates of soil organic carbon stocks (SOCS) are based on international databases, which explains the uncertainties observed from one author to another [3]. This situation does not allow for effective management of SOCS, hence the need to encourage field studies to obtain actual SOCS at local level [4]. In Africa, where tropical forest areas continue to decrease, carbon losses in forest soils, estimated between 20 and 50% by 2050, are quite worrying [5,

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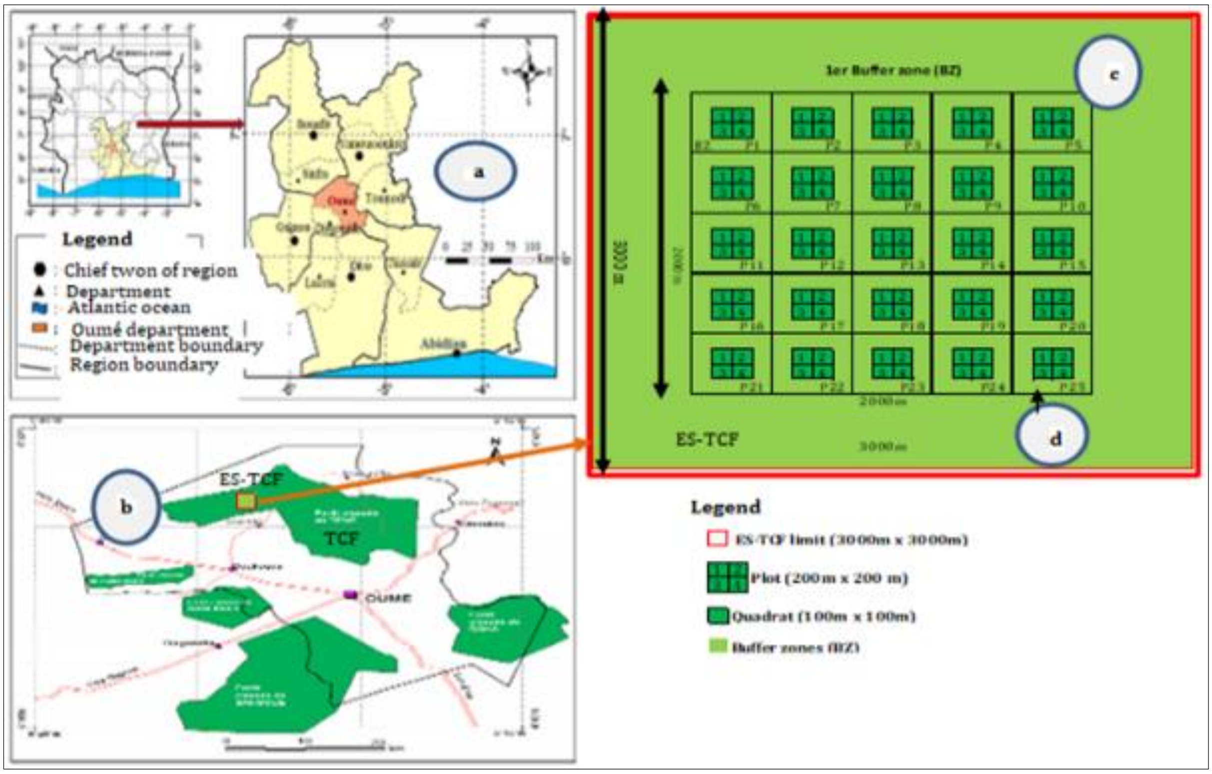
6, 7]. To limit these losses in these specific environments, new studies at local level are increasingly encouraged to clearly identify soil types and corresponding actual SOCS. However, given the recurrent disturbances in tropical forest ecosystems, such studies must be conducted in permanent forest plots. For this reason, the present study was carried out in the experimental set-up of the Téné protected forest (ES-TPF), installed by Société de Développement des Forêts (SODEFOR) in 1977. This site has benefited from a rigorous collection and monitoring plan since 1977 concerning tree biodiversity ang growth.

The interest of this work is to assess carbon stocks and its variability in different types of soils encountered under semi-deciduous tropical forests, with a view to better management and accounting of SOCS [8] in national greenhouse gas emission reduction initiatives [9 ,10].

2. Material and methods

2.1. Study site

Samples were collected in 2020 in ES-TCF, one of three SODEFOR research experiments carried out in 1977. This forest, with 29,700 ha, was in Oumé Department, in central-western Côte d'Ivoire, between 6°27' and 6°37'N and 5°20' and 5°40'W (Figure 1a). The TPF belongs to the mesophilic sector of the Guinean domain, characterized by a dense semi-deciduous open canopy rainforest vegetation [11]. The ES-TPF occupied a total area of 900 ha and was composed of 500 ha of buffer zone and 400 ha of experimentation (Figure 1c). It was gridded by layons 400 m apart, which delimited 25 units of 16 ha each. A second buffer zone of 100 m surrounded the 4 ha measurement plots. Each plot was subdivided into 4 sub-plots or quadrats of 1 ha each, for a total of 100 quadrats installed in the ES-TPF. The mean annual rainfall and temperature of the study area were 1400 mm and 26°C respectively [12].



(a) Location of TPF experimental set-up. (b) Boundary of TPF and location of the study area. (c) Plan of experimental set-up, comprising 25 plots of 4 ha spread over an area of 400 ha. (d) Subdivision of a plot into 4 sub-plots or quadrat of 1 ha

Figure 1 Presentation of the study site

2.2. Method of soils type classification

The soil types of ES-TPF were identified based on the FAO soil classification guide [13]. The horizons, properties and diagnostic materials of morphological units were first characterized. Then, each morphological unit was classified into a Reference Soil Group. Finally, the specific characteristics of the soils were used to name them. Identification of morphological units was carried out by a pedological survey of the site, using the topo-sequence method [14], by systematic approach [15]. For the application of the topo-sequence method, a Digital Terrain Model (DTM) of the site was acquired using software Global Mapper (24.0 version) and Surfer (23.4 version). The three-dimensional map produced highlighted the topography of the area and 10 topo-sequences were drawn up (Figure 2a). Points at different topographic levels were observed by taking core samples with an auger. In this way, the distribution of soils along the topo-sequences and possible morpho-pedological landscapes were described. In practical terms, this approach consisted of creating a grid of the site (Figure 2b), at a scale of 1:5000, i.e., one point every 50 meters, using Qgis software (2.18 version).

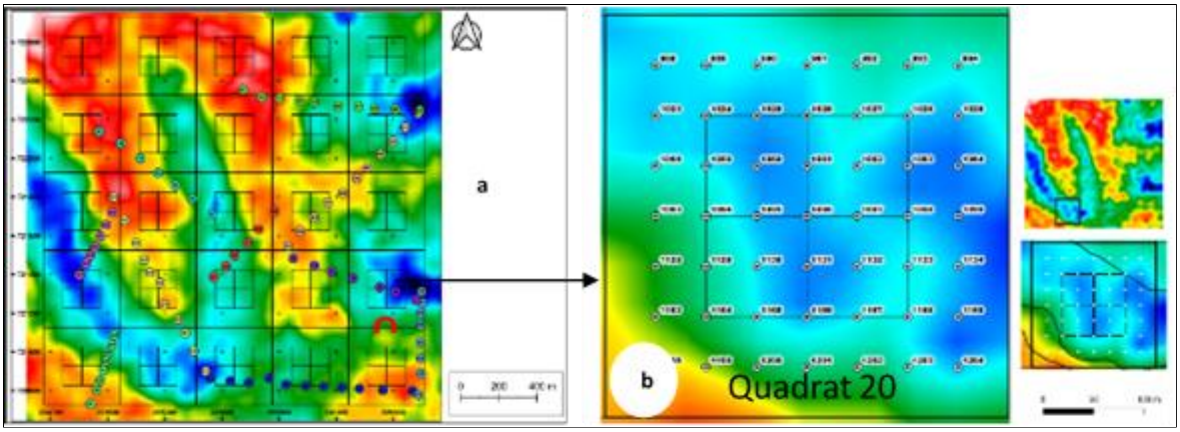
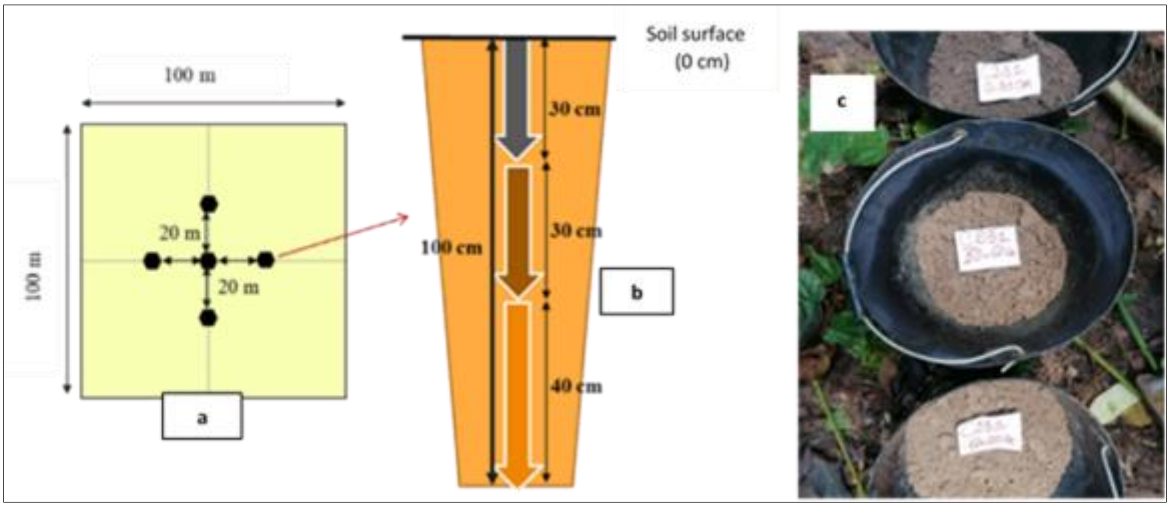


Figure 2 (a) Identification of the topo-sequences; (b) sounding points in plot 20 of the ES-TPF

After morpho-pedological landscapes identification, four pits were installed per morpho-pedological unit, to characterize the horizons, properties, and diagnostic materials. In each horizon, about 500g of soil were collected to determine texture, bulk density (clay, lemon, and sand), carbon concentration and percentage of coarse elements, at the Laboratoire d'Analyse des Végétaux et des Sols (LAVESO) of Institut National Félix Houphouët-Boigny de Yamoussoukro (INP-HB) in Côte d'Ivoire, and at the Laboratoire des Moyens Analytiques of IRD at Dakar (Senegal). Data were analyzed following van Reeuwijk procedures [16]. Field observations and laboratory results allowed to identify ES-TPF soil types.

2.3. Soil organic carbon stock estimation

2.3.1. Soil sample device



(**a**) Position of the 5 sampling points per thickness in a quadrat. (**b**) soil sample collection thicknesses: 0-30 cm (100 samples); 30-60 cm (100 samples); 60-100 cm (26 samples). (**c**) soil samples collected in quadrat 1 of plot 23, in thicknesses of 0-30 cm, 30-60 cm and, 60-100 cm

Figure 3 Auger soil sample collection device

SOCS were estimated in 0-30 cm,30-60cm and, 60-100 cm thicknesses of the ES-TPF. In the first two thicknesses, samples were taken from all 100 quadrats of the ES. However, in the 60-100 cm layer, due to presence of a stone layer, only 26 plots were sampled. Each sample is a composite of 5 samples taken at the midpoint and at 4 lateral points, placed at 20 meters from the midpoint (Figure 3).

2.3.2. SOCS determination

Equation 1 (Éq1) was used to estimate SOCS [17].

$$\text{Éq1 : } \mathbf{SOCS=Bd*E*C_{tot}*(1\text{-}\%CE)}.$$

SOCS was the organic carbon stock (expressed in $kgC.m^{-2}$), Bd, bulk density ($kg.m^{-3}$), E was the sample thickness (m), C_{tot} was total carbon content ($gC.kg^{-1}$) and %CE is percentage of coarse soil elements.

The bulk density (Bd) was measured by the cylinder method. For each soil type, three different quadrats were identified. On these particular quadrats, Bd was measured in the 5 depth level: 0-10 cm; 10-20 cm; 20-30 cm; 40-50 cm and 70-80 cm. The mean of Bd measured on the three quadrats for each type of soil was calculated for each layer. Total carbon was determined on each all soil samples by Walkley and Black method [18], which consists of estimating the carbon dioxide (CO_2) corresponding to the combustion of organic matter [19]. For %EC, air-dried soil samples were sieved and washed and particles larger than 2 mm in diameter were air dried and weighed. The proportion of coarse material was determined by the equation: %CE=p(CE)/Pt, where %CE is the proportion of coarse material, p(CE) is the weight of coarse material (g) and Pt is the total weight of the sample (g). These parameters were determined at LAVESO in Yamoussoukro (Côte d'Ivoire).

2.3.3. Maximum carbon storage capacity determination

To estimate maximum capacity of soil organic carbon stock (CapSOCS), the maximum soil carbon concentration [CmSOC] was first determined. It was calculated in this study with the formula:

$$\mathbf{[CmSOC]=4.09 +0.37*(\%mineral\ fraction\leq 20\ \mu m)}\ [20],$$

Where [CmSOC] expressed in $gC.kg^{-1}$). This formula is derived from the principle that SOC stabilization is limited by the specific surface areas of interaction of silts and clays with soil organic matter [21]. As this equation is only valid for the 0-10 cm thickness and is adapted according to the clay type [20], soils with a clay percentage higher than 30% were considered.

2.4. Statistical analysis

Statistical analyses were carried out with R software. The mean SOCS of the different soil types were compared with each other using the Kruskal-Wallis and Mann-Whitney tests at the 0.05 significance level. The Wilcoxon-Mann-Whitney test was used to compare the average SOCS obtained in the different soil types with recent estimates of SOCS from international databases, i.e., Harmonized World Soil Database (HWSD) and Intergovernmental Panel on Climate Change (IPCC) soil database.

3. Results and discussion

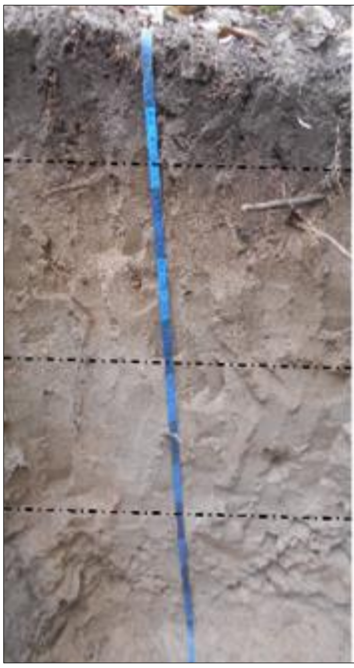
3.1. Soil types identified in ES-TPF

In the experimental set-up of the Téné protected forest, three main soil types are observed: Fluvisols, Ferralsols and Plinthosols (Figure 8).

3.1.1. Fluvisols of bottom slopes

Fluvisols soil were found on the lower slopes of a concave topo-sequence, on a gentle slope (6%). The vegetation encountered was essentially woody. The characteristics of the 4 horizons generally observed in the 0-120 cm thickness of this soil were presented in figure 4. It had a moderate drainage, a heterogeneous texture with a brutal transition. The presence of patches characterizing a periodic flooding was observed. Also, the percentage of organic carbon (0.58%) was greater than 0.2%. All these characteristics refered to a fluvial material [13], which was found at a depth of less than 25 cm on a thickness of 25 cm, typical of there a Fluvisol. The gleyic properties and its silty texture, refered respectively to the main qualifier gleyic and the additional qualifier siltic, hence the name Gleyic fluvisol was retained (siltic) [13]. However, in some places in this soil type, deposits of fluvial material and a sandy-silty texture were observed. In this case, the main and additional qualifiers are fluvic and loamic respectively, which refers to the name Fluvic fluvisol (loamic) [13]. Fluvisols occupied about 20% of the total area of the ES-TPF.

Several authors had observed this type of soil in different tropical regions including the lowland areas of West-central Côte d'Ivoire [22 ; 23]. Fluvisols identified in the ES-FCT were characterized as hydromorphic soils in 1992 [24]. However, this description was based on simple field observation, which therefore did not have a solid basis for soil classification. Furthermore, according to the IPCC soil type classification, Fluvisols contained very active clay soils [25]. This correspondence did not reflect Fluvisols identified in the ES-TPF, which had an average clay percentage of 8% with a high sand content (81%), in 0-120 cm layer. However, they cannot be described as Arenosols even though these soils are predominantly sandy.



Horizon 0-11/17 cm (A): very dark gray (2.5Y 3/1) when fresh; no coarse elements; sandy-silty texture; sparsely porous with fine interstitial pores; very many coarses, randomly oriented roots; fragmental structure with moderately aggregated, very friable structural elements; normal clear, irregular transition drainage.

Horizon 11/17-47 cm (E): light yellowish brown (2.5Y 6/3) when fresh; no coarse elements; sandy texture; sparsely porous with fine interstitial pores; numerous obliquely oriented, medium-sized roots; particulate structure with loosely aggregated structural elements; loose; normal smooth gradual transition drainage.

Horizon 47-82 cm (Eg): Light gray (2.5Y 7/2) when fresh; a few gray patches (10YR 7/2); no coarse elements; sandy texture; very poorly porous with fine interstitial pores; a few randomly oriented, fine-sized roots; particulate structure with weakly aggregated structural elements; loose; normal drainage of clear and distinct transition.

Horizon 82-120 cm (C): Light gray (2.5Y 7/2) when fresh; 20.5% coarse elements; sandy texture; very poorly porous with interstitial pores; numerous randomly oriented, fine-sized roots; particulate structure with loosely aggregated, fine-sized structural elements; normal drainage.

Figure 4 Characteristics of Fluvisol horizons of ES-TPF

3.1.2. Ferralsols and Plinthosols at the top slopes

These soils, located at 220 m elevation, were deep and were positioned at the top of a concave topo-sequence with a gentle slope (2-6%), under essentially woody vegetation. The average percentages of organic carbon (2.6%) and clay (38%) (in 0-120 layer) were respectively higher than 1.4 and 10. The boundaries between horizons were well distinguished and the coarse element load was less than 80%. All these characteristics summarized in Figure 5 confirm the presence of a ferral horizon. This horizon began at less than 150 cm depth and had a soil organic carbon content ≥ 1.4%. It was a Ferralsol. The dark red coloration and clay-sandy texture observed, lead back to the main qualifier Umbric and additional siltic, hence the name Umbric Ferralsol (siltic).

Ferralsols were the most represented soils in the West-Central region of Côte d'Ivoire [26]. Their strong presence in the study area (75%) of ES-TCF would therefore be justified. Top slopes Ferralsols were considered as moderately desaturated Ferralitic soils [24]. IPCC classifications refered to Ferralsols as poorly active clay soils [25].

In the area of occupation of these Ferralsols, soils limited to a depth of 60 cm by an induration of cuirass were noted in places (Figure 6). These soils had a continuous surface layer, apparently rich in iron oxides, characteristic of a plinthic horizon, which began at an average depth of 60 cm. These soil types were Plinthosols. The induration between 60 and 100 cm suggested the main qualifier Endopetric and the clayey-sandy texture of the useful horizon suggests the additional qualifier Siltic. This refered to the name Endopetric Plinthosols (Siltic). We noticed some profiles where the induration started at less than 50 cm, characteristic of Epipetric, which could be named Epipetric Plinthosols (Siltic).

Plinthosols occupied 5% of the total area of the system. This soil type, although not included in the map drawn by Bertault [24], was described in the central west of Côte d'Ivoire, at the top of the slopes [27], which corroborated our results. In international classifications, Plinthosols corresponded to Petroferric (FAO 1974 classification) or low-active clay soils according to the IPCC [3]. The IPCC classification therefore did not distinguish between Plinthosols and Ferralsols in the ES-TCF.

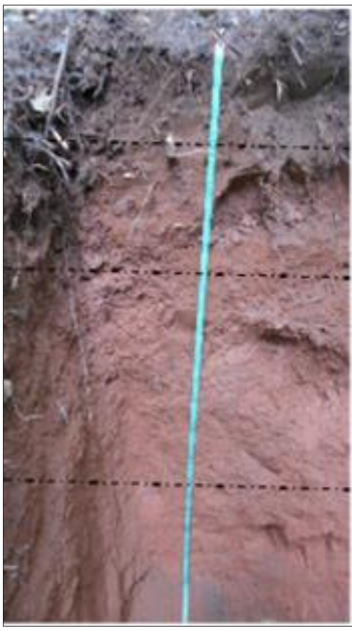


Figure 5 Characteristics of Ferralsols of top slopes

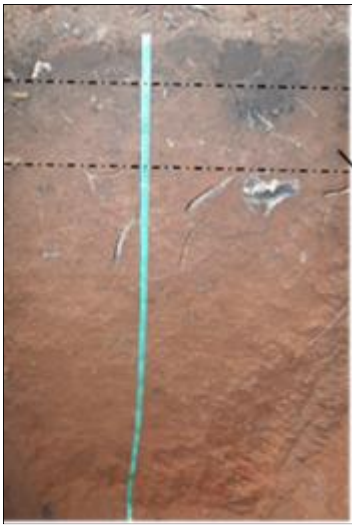
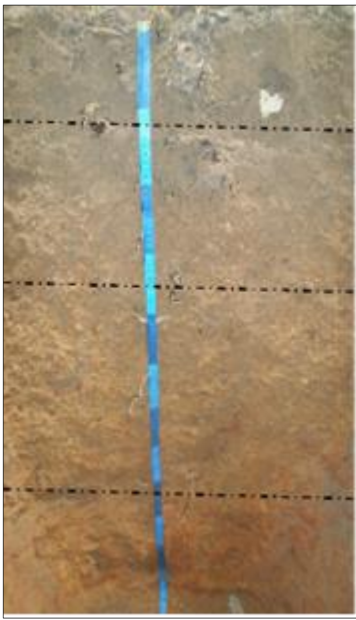


Figure 6 Characteristics of Plinthosols of top slopes

3.1.3. Ferralsols of middle slopes

These soils were intermediate between Fluvisols found on the lower slopes and Ferralsols found on the upper slopes. They were located at an average altitude of 195 m, on a concave topo-sequence of moderate slope (10-13%). Its vegetation is essentially woody. Overall, the profile was yellowish red in color and had four horizons (Figure 7). It wasdeep and patchy. Coarse material could be seen from the third horizon (17 cm) onwards.

The high organic matter content and the yellowish red colour suggested the main qualifiers pretic and umbric respectively. The reddish patches and the sandy-silty texture give the additional qualifiers ferric and loamic respectively. These soil types were referred to as Pretic umbric Ferralsol (ferric, loamic) [13]. At the same altitude, strongly cemented, dark-coloured concretions were observed, which refered to the main qualifiers pisoplinthic and umbric. Also, in places, the reddish spots, the induration layer observed at a depth of about 50 cm and the silty-sandy texture refered respectively to the supplements ferric, technic and loamic, which could be called Pisoplinthic umbric Ferralsol (ferric, loamic, technic) [13].



Horizon 0-12 cm (A): Dark brown (7.5YR 3/2) when fresh; 2% coarse; silty-sandy texture; poorly porous with medium-sized interstitial pores; numerous medium-sized horizontal roots; fragmentary structure with moderately aggregated medium-sized structural elements; very friable; normal drainage with distinct transition.

Horizon 12-35 cm (Btc1): Brown (7.5YR 4/4) in fresh state; abundant load of coarse elements 30%; silty-sandy texture; few interstitial pores of fine size; few roots of any orientation, medium size; fragmentary structure with strongly aggregated elements of medium size and friable; normal drainage of gradual transition.

Horizon 35-80 cm (Btc2) : Dark brown (7.5YR 4/6) when fresh; 45% coarse; silty texture; sparsely porous with fine interstitial pores; very few medium-sized, randomly oriented roots; fragmentary structure with strongly aggregated structural elements; firm; normal drainage with distinct transition.

Horizon 80-120 cm (Btg) : Dark brown (7.5YR 5/6) when fresh; some red spots (10R 4/6) of oxidation; 10.4% coarse elements; silty texture; poorly porous with fine interstitial pores; very few medium-sized, randomly oriented roots; fragmentary structure with medium-sized, highly aggregated structural elements; moderate drainage.

Figure 7 Characteristics of mid-slope soils

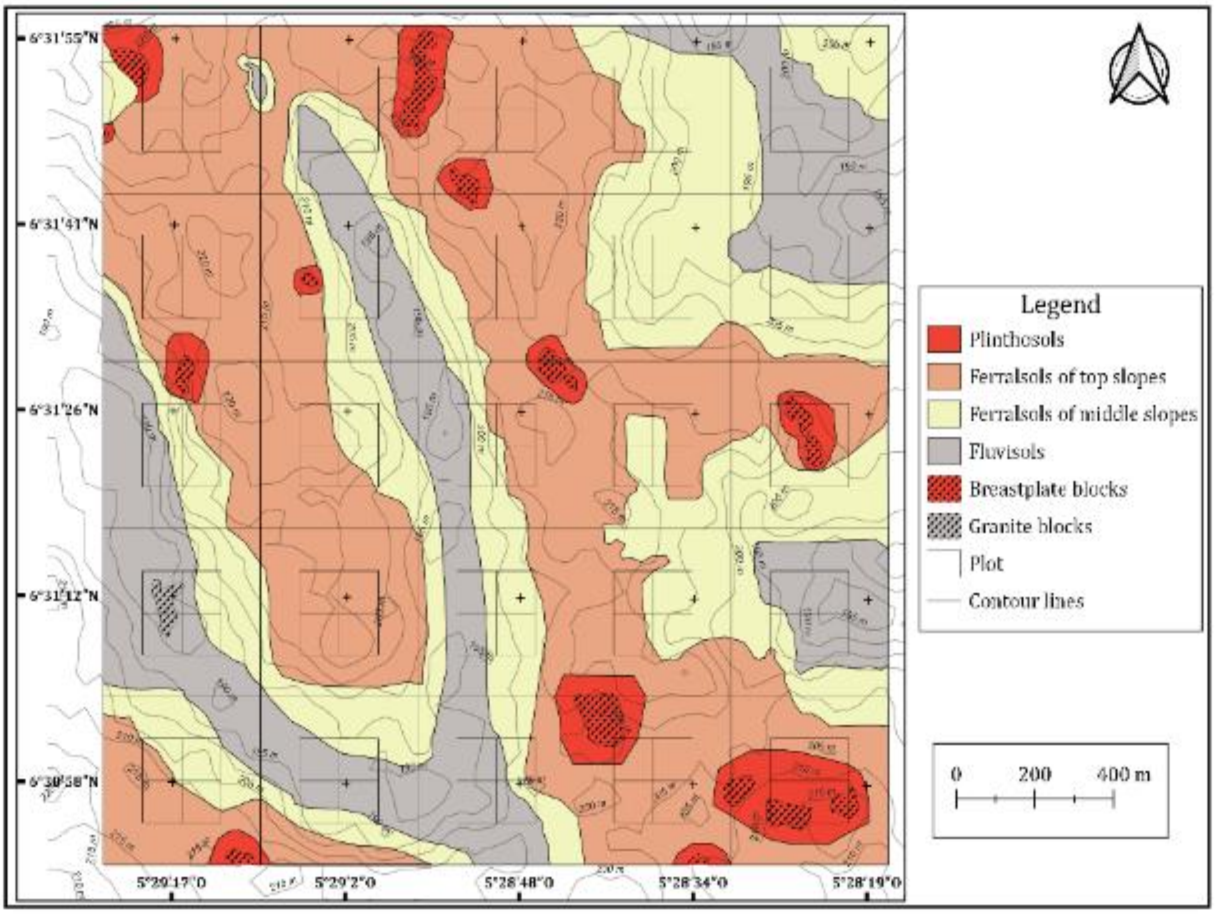


Figure 8 Soils map of experimental set up of TPF

3.2. Soil organic carbon stock

3.2.1. Total Carbon concentration

Total carbon concentrations (C) determined in the different soil types are presented in Figure 9. Regardless of the soil type, the C decreased with depth. In fact, the average C recorded in all the soils, in the thicknesses 0-30 cm; 30-60 and 60-100 cm was respectively 1.44±31% gC.kg^{-1}, 0.5±43% gC.kg^{-1} and 0.40±20% gC.kg^{-1}. In the 0-60 cm thickness, the highest C were observed in Plinthosols (top of slope) followed successively by Red Ferralsols (top of slope), Yellow Ferralsols (mid-slope) and Fluvisols (bottom of slope), which showed that the C increases with altitude. However, the Kruskall-Wallis test showed that in both types of Ferralsols there was no significant difference concerning C.

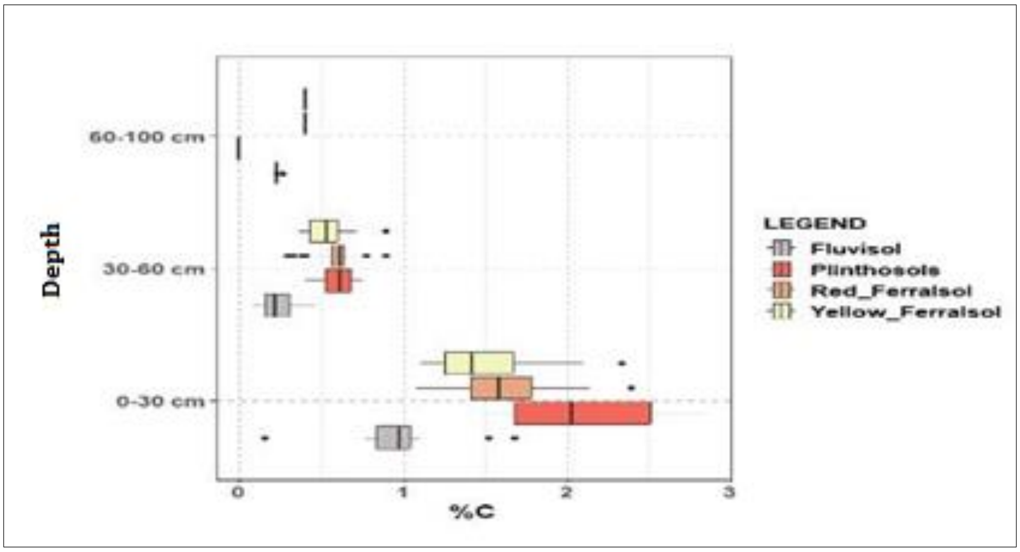


Figure 9 Soil carbon content (gC.kg^{-1}) in the different types of soils of ES-TCF for three sampling depths (0-30cm, 30-60cm, 60-100cm)

3.2.2. Bulk density

The bulk densities of the soils were shown in Figure 10. The average bulk density of the Fluvisol soils was 1.58 g.cm^3 with very little variation with depth. The other soils had approximately equivalent bulk densities at all depths. In these soils, bulk density was significantly lower (1.18g.cm^3) in the surface horizon (0-10cm), increased up to 30 cm depth and tended to decrease slightly between 30 and 100 cm. The Kruskal-Wallis comparison test at the 5% significance level showed that for each thickness, Bd of Fluvisols (1.58 g.cm^3) are higher than that of Ferralsols and Plinthosols (1.46 g.cm^3.

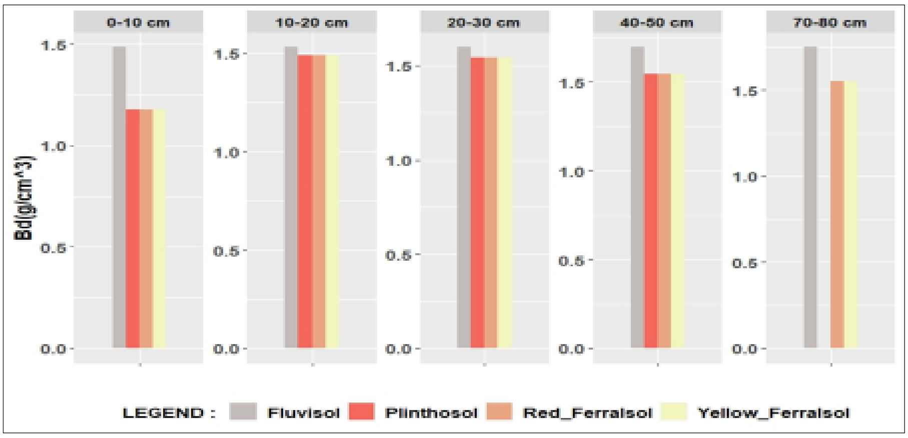


Figure 10 Bulk densities (g.cm^{-3}) in the different types of soils of ES-TCF for five sampling depths (0-10cm, 10-20cm, 20-30cm, 40-50cm and 70-80cm)

Coarse elements

The percentages (%) of coarse elements (CE) were shown in Figure 11. Plinthosols recorded the highest %CE (on average 45% CE in the 0-60 cm horizon), followed by Ferralsols (on average 20% CE in the 0-60 cm horizon) and Fluvisols (on average 3.5% CEM in the 0-60 cm horizon). Regardless of soil type, the %CE decreased with soil depth. The Kruskall-Wallis test showed that both types of Ferralsols had comparable %GE, but higher than the %CE in Fluvisols which are very low in CE (less than 4% CE on average in the 0-100cm thickness).

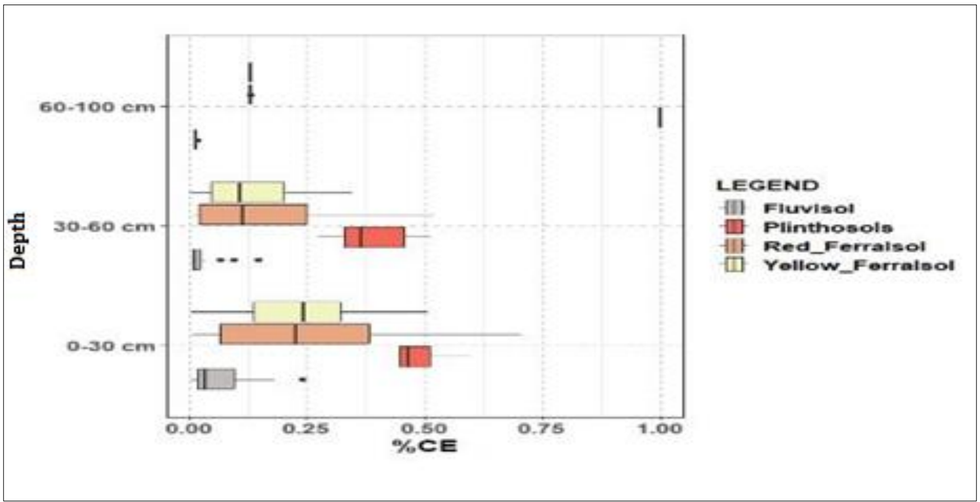


Figure 11 Percentage Bulk of Coarse elements (%CE) in the different types of soils of ES-TCF for tree sampling depths (0-30cm, 30-60cm and 60-100cm)

3.2.3. Soil organic carbon stock

SOCS calculated by soil type and thickness were recorded in Table 1.

Table 1 SOCS ($tC.ha^{-1}$) in the different types of soils of ES-TCF for thicknesses (0-30cm, 30-60cm, 60-100cm and 0-100cm)

SOIL TYPES	Tichnesses (cm)	n	Min $tC.ha^{-1}$	Max $tC.ha^{-1}$	Mean $tC.ha^{-1}$	Variation Coefficient
Plinthosols	0-30cm	5	30.52	64.45	44.89	25.12%
	30-60	5	13.70	23.46	16.67	20.74%
	60-100	5				
	0-100	5	46.12	87.91	61.56	22.93%
Reddish Ferralsols	0-30cm	29	24.22	100.17	50.45	31.08%
	30-60	29	11.61	32.98	22.82	23.52%
	60-100	29	21.80	21.80	21.80	0.00%
	0-100	29	66.41	140.69	95.08	18.85%
yellowish Ferralsols	0-30cm	18	38.36	77.73	47.88	21%
	30-60	18	12.04	41.04	22.03	27%
	60-100	18	21.80	21.80	21.80	0%
	0-100	18	75.17	123.51	91.71	14%
Fluvisols	0-30cm	18	6.66	68.31	41.18	32.15%
	30-60	18	3.90	22.71	11.25	43.86%
	60-100	18	15.82	17.61	16.12	4.15%
	0-100	18	29.19	98.82	68.54	21.65%

The results showed a decrease in SOCS as a function of altitude. Indeed, the soils sampled at the top of the slope (Reddish Ferralsols and Plinthosols) stored more carbon than the soils down the slope (Fluvisols). These results corroborated those obtained in natural formations while in more anthropized land use patterns (plantations, fallows and fields), the SOC stock tended to decrease with the slope [28].

Furthermore, the results showed a decrease in SOCS with depth, with an average of 58% of the 0-100cm SOCS in the 0-30cm thickness. This trend was in line with the results available in the literature, which generally admit that about 50% of the carbon stock of the 0-100cm thickness was stored in the first 30 cm of the soil [29].

The main objective of this study was to estimate the actual SOCS in different soil types in ES-TCF, to avoid the use of SOCS with uncertainties, determined using international databases. Recent SCOS estimates were made for the West African zone [3]. The first estimate uses the Harmonized World Soil Database (HWSD) [30]; the second estimate used more recent and improved mapping [31] and soil properties from HWSD. This new mapping was done at the same scale as the previous one but used the classification system of the World Soil Resources Database (WRB) [32]; the third estimate was based on an adaptation of the HWSD map by grouping soil types into broad soil classes, as defined by the IPCC and ecological zones as defined by FAO [33], and using the default SOC values proposed by the Intergovernmental Panel on Climate Change [25]. Apart from this estimate, which was specific to the West African zone, a global soil information system called "SoilGrids" provides SOCS to 30 cm depth (SOCS_SG).

Using HWSD database, SOCS in Plinthosols, Ferralsols and Fluvisols were, on average, 32.1 $tC.ha^{-1}$; 47.9 $tC.ha^{-1}$ and 48.9 $tC.ha^{-1}$, respectively, in the 0-30 cm thickness and 62.3 $tC.ha^{-1}$; 133.1 $tC.ha^{-1}$ and 157.5.9 $tC.ha^{-1}$ in the 0-100 cm horizon [3]. With these data, in the surface thickness (0-30 cm), HWSD values underestimated the average SOCS in Plinthosols and Ferralsols and overestimated the SOCS in Fluvisols. In contrast, in the deeper horizons, the HWSD value assessment significantly overestimated the SOCS of the soils. This trend was not observed by some authors who mentioned that using HWSD database underestimated the actual values of SCOS [29].

SOCS obtained using the JRC map remind even more contrasted than using the HWSD map [3]. Indeed, the JRC map only considered the dominant HWSD soil classes in each soil unit, which justified the differences observed between our estimates and the SOCS from the JRC map.

Using IPCC data, SOCS were estimated by agroecological zone. Within the IPCC broad ecological zones, the zone of the present study is the deciduous, tropical, and humid forests [25]. Within these vegetation types, Ferralsols and Plinthosols corresponded to low-active clay mineral soils (LAC). These soil types under semi-deciduous forests are estimated to store on average 47 $tC.ha^{-1}$ in the 0-30 cm thickness [3]. This estimate was comparable to the average SOCS obtained in the Plinthosols and Ferralsols of the study site (47.74 $tC.ha^{-1}$). Fluvisols were classified by the IPCC as highly active clay soils (HAC). These HAC under semi-deciduous forests would store an average of 65 $tC.ha^{-1}$ in the 0-30 cm thickness [3]. This estimate greatly overestimated the average SOCS obtained in Fluvisols of the study site (41.18 $tC.ha^{-1}$).

Furthermore, Mann-Whitney test showed that for the thickness 0-30 cm, the SOCS of SoilGril250m (SOCS-SG) was lower than SOCS in the present work (p-value < 0.0001, alpha = 0.05) (Tables 2).

Table 2 SOCS obtained against SOCS provided by SoilGrild 250 m

Variable	Minimum	Maximum	Moyenne	Ecart-type
SOCS_0-30 cm	6.664	100.168	46.465	14.019
SOCS-SG 0-30 cm	36.000	42.000	39.260	1.244

3.2.4. Carbon storage capacity and loss in semi-deciduous forest soils

The SOCS, SOCS storage capacities and carbon losses in 0-10 cm thickness of Ferralsols and Plinthosols were given in Table 3. The values obtained showed carbon losses of 67% on average in the 0-10 cm soil thickness. These losses could be explained by the disturbances recorded in the study site. Indeed, the site had experienced silvicultural treatments in 1977-1978, as well as two fires in 1983 and 2016. These disturbances, which modified the vegetation pattern [34], would be the main cause of the carbon losses observed in the ES-TCF. Indeed, depending on the frequency and intensity of fires, the floristic diversity, as well as the plant mass that falls on the ground, could be modified impacting negatively on the SOCS [35]. At the same time, fires in forest were a significant disruption that can affect SOCS [36].

Table 3 Carbon storage capacity and loss in the 0-10 cm horizon of Ferralsols and Plinthosols

Quadrat	Soil Type	(C+Sf) (%)	CE (%)	Bd (g.cm^{-3})	Ctot (%)	SOCS (tCc.ha^{-1}	CapCtot (%)	CapSOCS (tC/ha)	LSOCS (tC/ha)	LSOCS (%)
C042	Fy	36.63	15.00	1.19	2.40	24.28	4.23	42.74	18.47	76%
C104	Fy	35.12	10.00	1.15	2.36	24.43	4.22	43.68	19.25	79%
C212	Fy	37.20	15.00	1.16	2.55	25.14	4.23	41.68	16.54	66%
C033	Fr	36.50	5.00	0.96	2.40	21.89	4.23	38.53	16.64	76%
C171	Fr	36.80	8.00	1.33	2.70	33.04	4.23	51.71	18.67	57%
C243	Fr	38.90	0.00	1.11	2.60	28.86	4.23	47.00	18.14	63%
C151	Pl	40.10	42.00	1.12	2.80	18.19	4.24	27.53	9.34	51%
C253	Pl	37.40	31.00	1.10	2.60	19.73	4.23	32.09	12.36	63%
C254	Pl	42.60	35.00	1.12	2.50	18.20	4.25	30.92	12.72	70%
Mean		37.92	17.89	1.14	2.55	23.75	4.23	39.54	15.79	67%

(Fy) : yellowish Ferralsols; (Fr) : reddish Ferralsols; (Pl) : Plinthosols; (C) : Clay; (Sf) : fine Silt; (CE) : Coarse elements; (Bd) : Bulk densities; (C_{tot}) : total soil organic carbon; (SOCS) : Soil organic carbon stock; ($CapC_{tot}$) : Soil capacity in total Carbon ; (CapSCOS) Soil capacity in SOCS; (LSOCS) : loss of soil organic carbon stock

4. Conclusion

The main objective of this study was to estimate the actual SOCS in soils of semi-deciduous tropical forests, to correct SOCS values from international databases. The soil survey and analysis of soil samples collected in the ES-TCF allowed the identification of soils following the FAO soil classification guide. As a result of the analyses, Ferralsols, Fluvisols and Plinthosols, respectively with 75%, 20% and 5% of the soils, were identified in ES-TCF. In these respective soils, the average SOCS were 49.16 tC.ha^{-1}, 41.18 tC.ha^{-1} and 44.89 tC.ha^{-1} in the 0-30 cm thickness, and 93.40 tC.ha^{-1}, 68.54 and 61.56 tC.ha^{-1} in the 0-100 cm thickness.

These values were different from those presently produced by international databases. This difference justified the soil carbon measurement at the local level to better estimate the potential content of soil carbon and to improve these international databases. The values obtained can be used as SOCS reference values for Ferralsols, Plinthosols and Fluvisols, which occur in semi-deciduous tropical forests disturbed by logging and fire.

Although measured directly at the local level, significant variation in SOCS was observed between sites by soil type. This variation in SOCS could be attributed to site disturbances created by logging and the 1983 and 2016 fires. The flora present should be better written down to understand the variation in SOCS on each soil type, with the aim of better consideration and management of SOCS in West African semi-deciduous tropical forest carbon balance.

Compliance with ethical standards

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Disclosure of conflict of interest

There is no conflict of interest between the authors in respect of this manuscript.

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