INNSPUB

International Journal of Biosciences | IJB |
ISSN: 2220-6655 (Print); 2222-5234 (Online)
Website: https://www.innspub.net
Email contact: info@innspub.net
Vol. 27, Issue: 01, p. 8-20, 2025

RESEARCH PAPER OPEN ACCESS

Importance of soils when estimating carbon storage in Central African swamp forests

Yannick Enock Bocko[1*], Greta Christina Dargie[2], Suspense Averti Ifo[3], Jean Joël Loumeto[1], Simon L. Lewis[2,4]

[1]*Laboratoire de Biodiversité, de Gestion des Ecosystèmes et de l'Environnement, Faculté des Sciences et Techniques, Université Marien NGOUABI, Brazzaville, Republic of Congo*

[2] *School of Geography, University of Leeds, Leeds, LS2 9JT, United Kingdom*

[3]*Laboratoire de Géomatique et d'Ecologie, Tropicale Appliquée, École Normale Supérieure, Université Marien Ngouabi, Brazzaville, Republic of the Congo*

[4] *Department of Geography, University College London, WC1E 6BT, United Kingdom*

Key words: Central Africa, Congolese cuvette, Swamp forest, Soil, Total carbon

DOI: https://dx.doi.org/10.12692/ijb/27.1.8-20 Published: July 02, 2025

ABSTRACT

The swamp forests of Central Africa, although little anthropised, could undergo major change in the future. Monitoring spatio-temporal variations in their carbon stocks requires the inclusion of key forest compartments, in particular the soil, which is rarely quantified. The aim of this study was to assess the soil's contribution to total carbon storage in the three forest types of the swamp forests of the Congolese Cuvette: flooded forest (FF), periodically flooded forest (PFF) and terra firma forest (TFF). Soil samples from the 0-15 cm horizon and measurements of trees (dead and alive) were taken in 41 permanent nested circular plots. Chemical analysis of the soils revealed that organic carbon, total nitrogen, organic matter, pH and C/N increased significantly from TFF to FI. Soil carbon content tended to double from TFF to PFF and from PFF to FF. The C/N ratio < 25 obtained under PFF and TFF indicates normal OM mineralization. A highly significant difference was observed between the total carbon including the soil compartment (400.84±12.12, 420.93±18.77 and 411.49±35.33 tC/ha for FF, PFF and TFF respectively) and that excluding it (313.47±12.42, 406.74±18.38 and 407.29±35.37 tC/ha for FF, PFF and TFF respectively). Including the soil compartment in the total carbon estimate added 4, 14 and 87 tons of carbon for TFF, PFF and FF, respectively. These results show the need to include the amount of soil carbon when estimating the carbon stock of the swamp forest of Central Africa.

***Corresponding author:** Yannick Enock Bocko ✉ byannickenock@gmail.com

INTRODUCTION

Present in all three tropical continents, swamp forests are forest formations that evolve under the principal dependence of the soil (Letouzey, 1982). In Africa, swamp forests are found in southern Cameroon, Gabon, the Republic of Congo (RC), the Democratic Republic of Congo (DRC), the Niger Delta (Bonhême *et al.*, 1998) and South soudan (Zaroug *et al.*, 2013). Occupying a vast area of the Congo Basin forests, there are three broad forest classifications (Betbeder *et al.*, 2014) each with very different floristic compositions (Bocko *et al.*, 2016): terra firma forest, periodically flooded forest and flooded forest, the two latter termed swamp forests. The swamp forests of the Cuvette Congolaise contain the most extensive tropical peat complex in the world (Crezee *et al.*, 2022) which provides a number of ecosystem services to the people of the Congo Basin forest sub-region. The swamp forests are a major carbon store, and likely contribute to climate change mitigation *through* carbon sequestration. They also contribute to biodiversity conservation, with the swamps being home to forest elephants, lowland gorillas and bonobos. The swamp forests provide fish for local people, alongside hunting and other foodstuffs, and so contribute to food security, and many of these products provide income to local people which reduced poverty (Crump, 2017). However, given the threats to their peatland forest (Dargie *et al.*, 2019), the interest in managing them sustainable requires data, including the carbon stocks in the vegetation and the soil. This will enable a better management policy to be put in place for the swamp forests of the Central Cuvette, as their deforestation and degradation can lead to significant CO_2 emissions. A good estimation of the amount of carbon in each forest compartment is therefore necessary (IPCC, 2008).

The study carried out by (Pearson *et al.*, 2005) on the estimation of carbon stocks identified four key forest compartments in tropical zones that contribute effectively to atmospheric CO_2 emissions in the face of deforestation and forest degradation. These are above-ground biomass, below-ground biomass, dead wood and soil. As the most important compartment of the forest ecosystem in the context of logging and climate change mitigation and adaptation, above-ground biomass carbon is the most frequently estimated of all forest compartments. This is also due to the fact that living trees are easily measurable and are more exposed to deforestation and forest degradation (Pearson *et al.*, 2005). However, it should be noted that above-ground biomass carbon tends to represent more than 60% of the total carbon in a forest ecosystem that is mainly dependent on climate (Jeyanny *et al.*, 2014; Lü *et al.*, 2010; Suwarna *et al.*, 2012). Hence the interest in estimating above-ground biomass carbon, which can also be used to deduct below-ground biomass carbon (Ekoungoulou *et al.*, 2015; Hubau *et al.*, 2020; Lewis *et al.*, 2009). Estimates of the carbon content of dead wood are less numerous and not very diversified worldwide. The literature review carried out by (Palace *et al.*, 2012) shows that this work has been carried out mainly in the Americas, followed by Asia and Europe. At present, Africa is still the continent where very few studies have been carried out on estimating biomass and carbon stocks in dead wood. What's more, the existing data has been collected more in terra firme forest ecosystems and not in swamp forest (Carlson *et al.*, 2017; Djomo *et al.*, 2011; Gautam and Pietsch, 2012; Ifo *et al.*, 2015). Soil organic carbon is the least valued forest compartment in the world. Yet their carbon storage capacity is very high and greater than that of other compartments in edaphic forest ecosystems (Crezee *et al.*, 2022; Dargie *et al.*, 2017; Donato *et al.*, 2011; Hribljan *et al.*, 2016; Pearson *et al.*, 2005). In addition, soil organic carbon is very sensitive to forest disturbance. Indeed, the quantity of organic carbon increases or decreases after forest degradation depending on the type of soil and precipitation (Ngo *et al.*, 2013; Powers *et al.*, 2011). For this reason, it is necessary to take the soil compartment into account when estimating the total carbon of a swamp forest in order to better assess its standing stock of carbon and to provide a baseline for future studies of the capacity to fix atmospheric carbon and changes in carbon stocks. At present, there is little ecological research that has taken into account all four key forest carbon compartments (Lü *et al*., 2010; Ngo *et al*., 2013; Suwarna *et al*., 2012; Yeboah *et al*., 2014). The aim of this study was to assess the contributions of each key forest compartment to total carbon storage in the swamp forest types within the Cuvette Centrale in the Congo Basin, in the Likouala region, Republic of the Congo. Specifically, the aim was to (i) characterize the soil and (ii) estimate the carbon in each forest compartment.

MATERIALS AND METHODS

Study area

This study was carried out in the north of the Republic of Congo, in the Likouala region, at three sites: Bondzale (1.91242N and 18.01296E), Ekolongouma (1.225955N and 17.911272E) and Itanga (1.205033N and 17.447833E). The average annual temperature is 26°C and rainfall is 1557 mm/year, with a relative humidity of 80% (ANAC, 2024). Vegetation in the study area was represented by three forest types (Betbeder *et al*., 2014; Bocko *et al*., 2016): flooded forest (IF), periodically flooded forest (PIF) and terra firma forest (FTF). Soil maps and other studies suggest the flooded forests are often peat forming (Crezee *et al*., 2022), the periodically flooded forests are often histosols (Lewis *et al*., 2009), and the terra firme forest is ferralitic type and highly desaturated. The topography was generally flat with an altitude of between 300 and 400 m.

Chemical characterisation of the soil

Collection of soil samples

In each study site, a transect crossing the three forest types characterizing a swamp forest in the Congolese Cuvette was carried out. A total of 41 permanent nested circular plots (Ekoungoulou *et al*., 2015) were installed in the study area (Table 1). The nested circular plots were composed of three nested sub–units of 6 m, 14 m and 20 m radius, where trees in the diameter ranges of 10-30 cm, 30-60 cm and > 60 cm respectively were measured.

Two soil samples were taken with a soil auger to a depth of 0-15 cm (Campbell *et al*., 2007), in each cardinal direction (north-south and east-west, 1 m from each end). There were a total of 4 samples per study plot. A total of 52 soil samples were collected at Itanga and 56 at each of the Ekolongouma and Bondzalé sites, giving a total of 164 samples for the three sites. The four samples collected one meter from each end of the cardinal directions of each permanent biomass sampling plots formed a composite sample. This gave a total of 41 composites samples derived from the 164 soil samples.

Physicochemical analysis of the soil

The soil samples were air-dried, then prepared for chemical analysis at the chemical analysis laboratory of the Institut de Recherche en Sciences Environnementale et Naturelle (IRSEN, formerly the laboratory of the Institut de Recherche pour le Développement (IRD)), located in Pointe-Noire (Congo). The physical analyses focused on the bulk density and organic matter of the soil. The apparent density of the soil was obtained by dividing the mass of the soil sample dried at 60°C in the oven to a constant weight. The organic matter content was calculated using the loss on ignition method. Chemical analyses were carried out for pH (H_2O), organic carbon (Walkley and Black method) and total nitrogen (Kjeldahl method).

Forest carbon compartments

Estimation of soil organic carbon in tonnes per hectare

By multiplying the depth of the horizon under consideration (0-15 cm) by the organic carbon content and bulk density of the soil, it was possible to estimate the soil carbon stock in tons per hectare (Kauffman and Donato, 2012).

Estimation of carbon in the biomass of living trees

Only trees with a diameter greater than or equal to 10 cm were sampled in the 41 permanent nested circular plots. The nested circular plots consisted of three sub-units with radii of 6 m, 14 m and 20 m, where trees with diameters of 10-30 cm, 30-60 cm and > 60 cm respectively were measured. Trees with stilt roots, buttresses and/or malformations on the trunk at 1.30 m above the ground were measured at 50 cm above them (Phillips *et al.*, 2021). The scientific and local names of the various trees sampled were determined. A herbarium was set up in the field in order to refine the identification and confirmation of the scientific names of the determined and undetermined species. This identification and confirmation of the scientific names of the species took place at the national herbarium in the Brazzaville region.

Biomass was quantified using an allometric equation. The allometric equation of (Chave *et al.*, 2014), which takes into account diameter, wood density and the environmental stress index *(E)*, was used to estimate above-ground biomass (AGB). The environmental stress index values for each plot were extracted from the climate map (Chave *et al.*, 2014), after converting the geographical coordinates (of each biomass sampling plot) into text format. This extraction of *(E)* was done in R software (version R.4.2) *via* the *extract-cbind* fonction of the "raster" package.

The specific wood densities of the various species sampled were taken from the *global wood density* database (Zanne *et al.*, 2009). Average wood densities for the genus, family or plot were used for species with unknown specific density (Chave *et al.*, 2008). Plot values were extrapolated to the hectare using an expansion factor that indicates the area represented by each plot (Walker *et al.*, 2016).

Thus, three different factors one for each size class of the nested plots were used. This standardization was necessary in order to make comparisons with other studies.

A ratio of 0.235 (AGB ≤ 62.5 t MS/ha) from (Mokany *et al.*, 2006) were used to quantify the belowground or root biomass (BGB) of each living tree. The biomass of a study plot then corresponded to the sum of the biomasses of all the individual trees sampled. By multiplying the quantity of biomass in each plot by 0.47, it was possible to estimate the quantities of carbon in the above-ground and below-ground biomass (Thomas and Martin, 2012)).

Estimating carbon in standing dead wood

Standing coarse woody debris was sampled in the same way as live trees in the forest ecosystem in the various live tree sampling plots. The dbh was measured using the same methods as for live trees, and the height was measured using a clinometer. The volume of standing deadwood was calculated using the formula in (Mund, 2004):

$$V = \pi * h * f * \left(\frac{d}{2}\right)^2 \qquad (1)$$

Where V is the Volume of standing coarse woody debris (m^3), d is the stem diameter (m), h is the height of standing deadwood (m) and f is the form factor (0.627). Biomass was estimated by multiplying the volume by the deadwood specific gravity of 0.47 (Carlson *et al.*, 2017). The amount of carbon was estimated by halving the dry mass obtained (Woldendorp *et al.*, 2002).

Estimation of carbon in dead wood lying on the ground

Coarse woody debris lying on the ground was measured using the line intersection method presented by (Harmon and Sexton, 1996). This involved drawing two lines, each 50 m long, in each cardinal direction (north-south and east-west) at right angles to the center of a sample plot of live trees.

The diameter of each piece of coarse woody debris crossing the sampling line was systematically measured. A piece of coarse woody debris was measured if and only if: (1) more than 50% of the coarse woody debris was above ground and (2) the sampling line crossed at least 50% of the diameter of the fallen piece of coarse woody debris (Walker *et al.*, 2016). The volume of dead wood *(Ø≥2.5* cm) accumulated on the ground was calculated using the formula in (Warren *et al.*, 2008):

$$v = \frac{\pi^2 \left(\sum di^2\right)}{8L} \quad (2)$$

Where V is the volume of coarse woody debris ($m^3.ha^{-1}$), *di* is the diameter of each coarse woody debris sampled (m) and L is the length of the transect, which was 100 m in the case of this study. The biomass and carbon values of each coarse woody debris lying on the ground were estimated in the same way as for standing coarse woody debris.

Statistical analysis of the data

The mean values of the various physical and chemical soil parameters, as well as those of biomass carbon, were accompanied by a standard error. The Kruskal-Wallis test was used to analyze the difference in carbon stocks between the forest types studied. Dunn's post hoc test *(*dunn.test) was used only when the difference in estimated values was found to be significant after using the Kruskal-Wallis test (Dinno, 2015). All statistical analyses were performed using R software (http://www.r-project.org); (R Core Team, 2020).

RESULTS

Spatial variability of soil properties

Mean values of organic carbon, total nitrogen and C/N ratio increased from upland forest to flooded forest (Table 2). The contents of the five chemical (SOC, N, C/N, OM and pH) and physical (Da) soil parameters showed very highly significant differences between the three forest types studied (Kruskal-Wallis. test, p-value < 0.0001). However, it should be noted that Dunn's test revealed that these very highly significant differences were firstly between the values obtained in flooded and periodically flooded forest, and secondly between those obtained in flooded and dryland forest (Table 2).

Organic matter content varied very significantly from one forest type to another, decreasing from flooded forest to dry forest (Table 2).

Table 1. Distribution of permanent study plots by site and forest type crossing each transect.

Study site	Transect length	Forest types	Plots number
Bondzale	6 km	FF	6
		PFF	4
		TFF	4
Ekolongouma	9 km	FF	6
		PFF	4
		TFF	4
Itanga	6 km	FF	6
		PFF	4
		TFF	3

On the other hand, soil acidity, which also decreased from flooded forest to upland forest, showed no significant difference between periodically flooded forest and upland forest.

Contribution of each carbon pool to total forest carbon storage

The mean quantities of carbon from the biomass of living trees (above and below ground) and from dead wood tended to increase from flooded forest to terra firme forest (Table 3). The Kruskal-Wallis test revealed no significant difference between the quantities of dead wood carbon in the three forest types studied (P= 0.93), Similary, the Dunn's test showed no significant difference between periodically flooded and dry land forest, for live tree carbon (Table 3). The results of the present study also show that soil organic carbon values, obtained in tonnes per hectare, increased from upland forest to flooded forest, with highly significant differences between the three forest types studied (Kruskal-Wallis, P < 0.0001) (Table 3).

As regards total carbon, including the four compartments (AGB, BGB, CWD and SC, Table 3) considered, no significant differences were observed between the three types of forest studied (Kruskal-Wallis, P-value = 0.778): FF (400.84±12.12[a]), PFF (420.93±18.77[a]) and TFF (411.49±35.33[a]). However, if the soil compartment was excluded during carbon estimation, then there are highly significant differences, were observed lower values in FF (313.47±12.42[a]) than wither PFF (406.74±18.38[b]) or TFF (407.29±35.37[b]) (Kruskal-Wallis, P-value = 0.001). The results also revealed that the amount of soil carbon in the three forest types tended to double from terra firma forest to periodically flooded forest, and then double again from periodically flooded forest to flooded forest (Fig. 1A). Live tree AGB is always the largest carbon pool, but in TFF almost three-quaters of the total carbon is stored in live AGB, but in PFF this reduces to two-thirds, and in FF only half the total carbon is in live AGB. With forest types, the amount of total forest carbon (including soil carbon) was significantly lower when excluding soil carbon in FF and PFF, but was not significantly lower in TFF (Fig. 1B).

Table 2. Physicochemical composition of the soils of the three forest types of the Likouala swamp forest.

Forest-types (number of plots)	**Chemical Parameters**					**Physical Parameter**
	SOC (%)	N (%)	C/N	pH (H_2O)	OM (%)	BD (g/cm³)
FF (18)	52,00±0,60[a]	1,33±0,13[a]	47,81±5,52[a]	3,80±0,01[a]	87,36±0,98[a]	0,18±0,01[a]
PFF (12)	6,18±0,98[b]	0,32±0,04[b]	20,89±3,52[b]	4,27±0,13[b]	14,19±1,86[b]	0,74±0,12[b]
TFF (11)	2,43±0,26[b]	0,21±0,03[b]	12,36±1,40[b]	4,23±0,03[b]	5,20±0,17[c]	0,93±0,06[b]

SOC: Soil organic carbon, N: Nitrogen, BD: Bulk density, OM: Organic matter, FF: Flooded forest, PFF: Periodical flooded forest and TFF: Terra firme forest. Values in parentheses represent number of samples. Les lettres a, b et c révèlent ou non la significativité de la différence entre les valeurs obtenues après usage du test de Dunn.

DISCUSSION

Spatial variability of soil properties

The results of the present study show that there is a significant difference between the three forest types studied in terms of concentrations of organic carbon, nitrogen, C/N ratio, OM, pH and Da (Kruskal-Wallis. test, p-value < 0.05). The chemical compounds of the three types of facies studied tended to increase from FTF to IF, except for pH, which showed the opposite pattern (IF to FTF). This latter observation was highlighted by (Dabin, 1985) when characterizing the physicochemistry of soils under tropical rainforests. Several factors can explain the differences and directions of change in the levels of different physical and chemical compounds in the facies studied, including: floristic composition and microbial activity (Chambers *et al.*, 2011; Dabin, 1985; Saint-Laurent *et al.*, 2017; Vashum *et al.*, 2016).

The high levels of chemical compounds in soils under FF indicate low activity on the part of decomposing micro-organisms. (Page *et al.*, 2011) point out that a soil contains peat when its organic matter (OM) content is greater than or equal to 65% in the first thirty centimetres of the soil. The OM content (87.36±0.98%) and highly acidic pH obtained under FF indicate that the soil is a peat bog. Other data and analyses indicate that the FF plots are peat lands of the top 30 cm soil depth (Crezee *et al.*, 2022b; Dargie *et al.*, 2017b). In other words, a soil with a reducing water regime where dissolved oxygen is low due to saturation by groundwater (FAO-UNESCO, 1975).

As a result, there is little mineralization of organic matter, which justifies the high nitrogen content (1.33±0.13%), high C/N ratio (47.81±5.52) and high organic carbon content (52.00±0.60%) under FF. For (Balloy *et al.*, 2017) the low rate of OM decomposition leads to an increase in soil organic carbon content. This was the case under the FF studied.

The soil under PFF (with seasonal flooding constraints) has a low carbon content (5.73±1.55%) compared with that under FF, but twice as high as that under PFF. The decrease in nitrogen content (0.31±0.12%) and C/N (20.37±11.84) and the increase in pH (4.23±0.5) indicate normal microbial activity under PFF. In fact, the C/N ratio < 25 obtained under PFF indicates normal mineralization of OM and leads to the release of nitrogen that can be used by plants (Balloy *et al.*, 2017). Competition between decomposer microorganisms and fine plant roots for nitrogen nutrition is very low. The soil under TFF (not exposed to flooding constraints) has a very low carbon content (2.43±0.83%) with a very low nitrogen content of 0.10% (compared with the soil under PFF). These results show that microbial activity follows an increasing gradient from soil under FF to soil under TFF. And the C/N ratio (12.59±4.74%) indicates that the rate of OM decomposition is very high under TFF. Although the soil pH under TFF is more or less the same as the soil under PFF ; OM mineralization is very advanced under TFF.

Table 3. Mean carbon values for four pools of the three forest types in the Likouala swamp forest.

Forest types	AGB (t/ha)	BGB (t/ha)	CWD (t/ha)	SC (t/ha)
FF	213,10±10,08[a]	44,43±2,19[a]	7,67±1,81[a]	139,89±4,31[a]
PFF	286,23±17,57[b]	63,04±3,97[b]	7,00±1,17[a]	65,27±22,86[b]
TFF	303,20±28,76[b]	67,72±6,52[b]	9,59±3,77[a]	33,89±8,02[c]

AGB: Above-ground biomass, BGB: Below ground biomass, CWD: Coarse woody debris and SC: Soil carbon

The results of this study were compared with those found in tropical zones. Carbon, nitrogen, C/N ratio and OM contents show great spatial variability in tropical forests (Jeyanny *et al.*, 2014). They differ from one forest type to another, from one region to another and from one country to another. The results obtained under flooded forest (FF) in our study area are very similar to those found by (Dargie *et al.*, 2017) under FF in swamp forests in the Likouala region. The organic carbon content under FF is typical of *peatland* forests, being well above 50% (Beilman *et al.*, 2009; Dargie *et al.*, 2017; Vitt *et al.*, 2000). The carbon content of the present study (52%) is slightly lower than that found by (Dargie *et al.*, 2017) in the central cuvette of the Congo Basin (59±3%) and by (Dommain *et al.*, 2011) in central Kalimantan of Asia (57.88±1.64%). However, it is slightly higher than that found in Amazonia (47.6%) by (Draper *et al.*, 2014).

The results obtained under periodically flooded forest (PFF) in our study area are lower than those found by (Ifo *et al.*, 2017) under PFF dominated by *Guibourtia demeusei* (116,16 tC.h-1) and much higher than those found by the same author in the same region under PFF dominated by *Lophira alata* (17,21 tC.h-1). Soils under terra firme forest (TFF) in our study area have carbon contents that are slightly higher than those found by (Ifo *et al.*, 2017) under secondary TFF with *Musanga cecropioides*, in the Likouala region (northern Congo). They are also higher than those obtained by (Peh *et al.*, 2011) under mixed TFF and under TFF dominated by *Gilbertiodendron dewevrei*, in the Dja Reserve in Cameroon. (Yadav *et al.*, 2015) also found a carbon content lower than ours under TFF in the Narmada forest division in Gujarat, India. However, the carbon content obtained by (Amlin *et al.*, 2014) under secondary TFF in Malaysia is higher than that found in the present study.

The differences in soil organic carbon content noted between those of this study and those found by other authors in tropical forests can be explained by soil types and the specific compositions of forest type. Soil types and floristic composition influence carbon accumulation in tropical forests in several ways. In fact, the type of litter provided by the plants and the soil's water regime affect the pH, which can become very acidic, acidic or weakly acidic. This results in an increase in soil carbon content in relation to the decrease in pH and water saturation, which reduces microbial activity (FAO-UNESCO, 1975; Saint-Laurent *et al.*, 2017; Vashum *et al.*, 2016). This is why soil organic carbon stocks are higher in edaphic forest ecosystems (Dargie *et al.*, 2017; Donato *et al.*, 2011; Hribljan *et al.*, 2016; Pearson *et al.*, 2005).

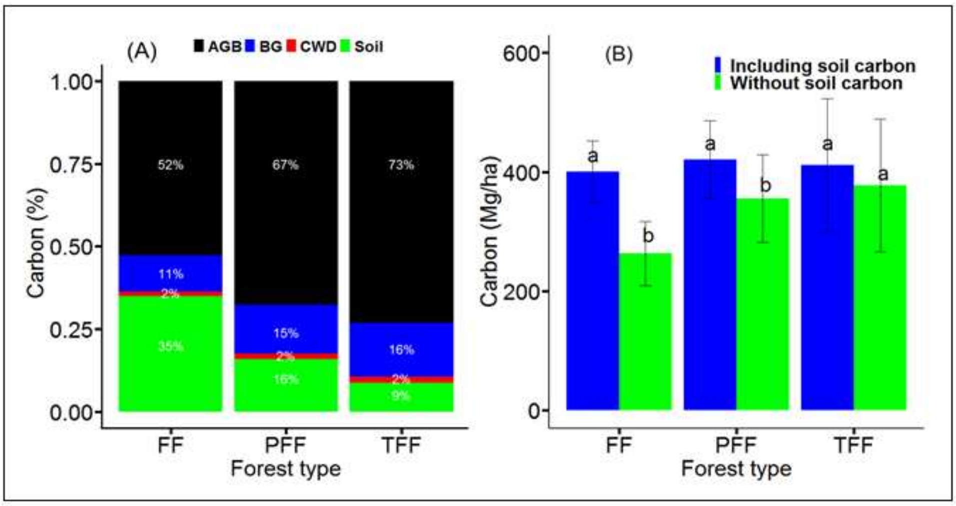

Fig. 1. Contribution of the different forest pools to carbon storage in the three forest types of the swamp forest of the Likouala département (A): proportion of carbon in the four carbon pools studied and (B): influence of soil carbon in the total estimate of forest carbon.

Contribution of carbon pools to total forest carbon storage

The percentage contribution of each carbon pool of the three forest types studied falls well within the range of values found in tropical zones. For example, forest compartments such as BG (11 to 16%) and CWD (2%) have contributions that oscillate between the values of 1 and 20% of the total carbon stock mentioned by Sierra *et al.* (2012). As for above-ground biomass, it tends to account for more than 60% of the total carbon in a forest ecosystem that is mainly dependent on climate (Jeyanny *et al.*, 2014; Lü *et al.*, 2010; Pearson *et al.*, 2005; Suwarna *et al.*, 2012).

The results of the present study revealed a significant contribution of the soil compartment in the estimation of the total carbon of the flooded forest and the periodically flooded forest. Therefore there is a highly significant difference between the total carbon of the swamp forest studied when including the soil compartment and excluding it. Soil organic carbon thus represents a significant fraction of the total carbon of a swamp forest in the Congo Basin. In fact, taking into account only the 0-15 cm horizon of the soil compartment when estimating the total carbon of the three forest types of the Likouala swamp forest resulted in gains of around 87, 14 and 4 tonnes of carbon, respectively for the FF, PFF and TFF. For this reason, consideration of the 0-100 cm horizon of the soil compartment would lead us to improve its percentage contribution, which could reach or exceed 50% of the total carbon of each forest type studied. In fact, it is accepted that the 0-100 cm horizon of a tropical soil contributes 50% of the carbon storage of a forest ecosystem (Dixon *et al.*, 1994). However, it should be noted that this contribution can exceed 50% in ecosystems that depend mainly on the soil, such as mangroves and peatlands (Dargie *et al.*, 2017; Kauffman and Bhomia, 2017). This is the case for the contribution of the soil compartment of the flooded (with peat) forest studied. Thus, the exclusion of below-ground biomass (large and fine roots), necromass (coarse woody debris and litter) and soil organic carbon leads to a considerable underestimate of the total carbon of a given forest ecosystem.

CONCLUSION

The present study shows that soil properties vary from one forest type to another, with levels of chemical parameters increasing from upland forest to flooded forest. This finding reveals that the activity of decomposing micro-organisms increases from flooded forest (low) to terra firme forest (high). The contributions of the 4 key compartments studied differ between them and between forest types.

Taking into account the organic carbon of the 0-15 cm soil horizon when estimating the total carbon of each forest type revealed a highly significant difference between the total carbon including the soil compartment and that excluding it. It would therefore be prudent to estimate the total carbon stock of a swamp forest ecosystem while neglecting soil organic carbon stocks.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

AUTHORS CONTRIBUTIONS

YEB, JJL and SLL conceived the idea for the study. YEB, GCD and SLL collected the data. YEB led the aggregation of the data and performed the analyses. YEB wrote the first draft of the manuscript, with all authors providing editorial input.

ACKNOWLEDGEMENTS

We thank the villages of Bolembe, Ekolongouma, Bondzalé and Itanga, for their assistance during the field data collection period. Thanks to the Ministry of Forestry Economy and the Ministry of Higher Education, Scientific Research and Technological Innovation, Republic of the Congo, Marien Ngouabi University and the Likouala Department governor for the the facilitation. We thank the fieldworker team. At the end of this work, we would also like to thank WCS Epéna team for the logistical.

REFERENCES

Amlin G, Suratman MN, Isa NNM. 2014. Soil Chemical Analysis of Secondary Forest 30 Years after Logging Activities at Krau Wildlife Reserve, Pahang, Malaysia. APCBEE Procedia **9,** 75–81. https://doi.org/10.1016/j.apcbee.2014.01.014

ANAC. 2024. Données Météorologique de la région de la Likouala-Données météorologiques du district d'Impfondo pour les 50 dernières années. Base de données annuelles de l'agence nationale de l'aviation civile (ANAC), Ministère de transport et de l'aviation civile, Brazzaville, Congo.

Balloy B, Bispo A, Bouthier A, Chenu C, Cluzeau D, Degan F, Metzger L. 2017. Tour d'horizon des indicateurs relatifs à l'état organique et biologique des sols, 1-61. hal-02788601

Beilman DW, MacDonald GM, Smith LC, Reimer PJ. 2009. Carbon accumulation in peatlands of West Siberia over the last 2000 years. Global Biogeochemical Cycles 23, 2007GB003112. https://doi.org/10.1029/2007GB003112

Betbeder J, Gond V, Frappart F, Baghdadi NN, Briant G, Bartholome E. 2014. Mapping of Central Africa Forested Wetlands Using Remote Sensing, IEEE. J. Sel. Top. Appl. Earth Observations Remote Sensing **7,** 531–542. https://doi.org/10.1109/JSTARS.2013.2269733

Bocko YE, Dargie G, Ifo AS, Yoka J, Loumeto JJ. 2016. Répartition spatiale de la richesse floristique des forêts marécageuses de la Likouala, Nord-Congo. Afrique SCIENCE **12(4),** 200-212.

Bonhême I, Rousteau A, Imbert D, Saur E. 1998. Forêt marécageuse à Pterocarpus officinalis : sa situation en gouadeloupe. Bois et Forêts des Tropiques, N°258 **(4),** 59-68.

Campbell CA, VandenBygaart AJ, Grant B, Zentner RP, McConkey BG, Lemke R, Gregorich EG, Fernandez M. 2007. Quantifying carbon sequestration in a conventionally tilled crop rotation study in southwestern Saskatchewan. Canadian Journal of Soil Science 87, 23-38. https://doi.org/10.4141/S06-015

Carlson BS, Koerner SE, Medjibe VP, White LJT, Poulsen JR. 2017. Deadwood stocks increase with selective logging and large tree frequency in Gabon. Global Change Biology **23,** 1648-1660. https://doi.org/10.1111/gcb.13453

Chambers FM, Beilman DW, Yu Z. 2011. Methods for determining peat humification and for quantifying peat bulk density, organic matter and carbon content for palaeostudies of climate and peatland carbon dynamics.

Chave J, Olivier J, Bongers F, Châtelet P, Forget P-M, Van Der Meer P, Norden N, Riéra B, Charles-Dominique P. 2008. Above-ground biomass and productivity in a rain forest of eastern South America. Journal of Tropical Ecology **24,** 355-366. https://doi.org/10.1017/S0266467408005075

Chave J, Réjou-Méchain M, Búrquez A, Chidumayo E, Colgan MS, Delitti WBC, Duque A, Eid T, Fearnside PM, Goodman RC, Henry M, Martínez-Yrízar A, Mugasha WA, Muller-Landau HC, Mencuccini M, Nelson BW, Ngomanda A, Nogueira EM, Ortiz-Malavassi E, Pélissier R, Ploton P, Ryan CM, Saldarriaga JG, Vieilledent G. 2014. Improved allometric models to estimate the aboveground biomass of tropical trees. Global Change Biology **20,** 3177–3190. https://doi.org/10.1111/gcb.12629

Crezee B, Dargie GC, Ewango CEN, Mitchard ETA, Emba BO, Kanyama TJ, Bola P, Ndjango J-BN, Girkin NT, Bocko YE, Ifo SA, Hubau W, Seidensticker D, Batumike R, Imani, G, Cuní-Sanchez A, Kiahtipes CA, Lebamba J, Wotzka H-P, Bean H, Baker TR, Baird AJ, Boom A, Morris PJ, Page SE, Lawson IT, Lewis SL. 2022a. Mapping peat thickness and carbon stocks of the central Congo Basin using field data. Nat. Geosci. **15,** 639-644. https://doi.org/10.1038/s41561-022-00966-7

Crump J (Dir.). 2017. De la fumée sur l'eau – lutter contre les menaces mondiales liées à la destruction et à la dégradation des tourbières. Évaluation du PNUE en vue d'une intervention rapide. Programme des Nations Unies pour l'environnement et GRID-Arendal, Nairobi et Arendal, www.grida.no, 1-76.

Dabin B. 1985. Les sols tropicaux acides. Cah.ORSTOM, sér.Pedol., **21(1),** 1984-1985.

Dargie GC, Lawson IT, Rayden TJ, Miles L, Mitchard ETA, Page SE, Bocko YE, Ifo SA, Lewis SL. 2019. Congo Basin peatlands: threats and conservation priorities. Mitig Adapt Strateg Glob Change **24,** 669–686. https://doi.org/10.1007/s11027-017-9774-8

Dargie GC, Lewis SL, Lawson IT, Mitchard ETA, Page SE, Bocko YE, Ifo SA. 2017. Age, extent and carbon storage of the central Congo Basin peatland complex. Nature **542,** 86–90. https://doi.org/10.1038/nature21048

Dinno A. 2015. Nonparametric Pairwise Multiple Comparisons in Independent Groups using Dunn's Test. The Stata Journal **15,** 292-300. https://doi.org/10.1177/1536867X1501500117

Dixon RK, Solomon AM, Brown S, Houghton RA, Trexier MC, Wisniewski J. 1994. Carbon Pools and Flux of Global Forest Ecosystems. Science **263,** 185–190. https://doi.org/10.1126/science.263.5144.185

Djomo AN, Knohl A, Gravenhorst G. 2011. Estimations of total ecosystem carbon pools distribution and carbon biomass current annual increment of a moist tropical forest. Forest Ecology and Management **261,** 1448–1459. https://doi.org/10.1016/j.foreco.2011.01.031

Dommain R, Couwenberg J, Joosten H. 2011. Development and carbon sequestration of tropical peat domes in south-east Asia: links to post-glacial sea-level changes and Holocene climate variability. Quaternary Science Reviews **30,** 999-1010. https://doi.org/10.1016/j.quascirev.2011.01.018

Donato DC, Kauffman JB, Murdiyarso D, Kurnianto S, Stidham M, Kanninen M. 2011. Mangroves among the most carbon-rich forests in the tropics. Nature Geosci **4,** 293–297. https://doi.org/10.1038/ngeo1123

Draper FC, Roucoux KH, Lawson IT, Mitchard ETA, Honorio Coronado EN, Lähteenoja O, Torres Montenegro L, Valderrama Sandoval E, Zaráte R, Baker TR. 2014. The distribution and amount of carbon in the largest peatland complex in Amazonia. Environ. Res. Lett. **9,** 124017. https://doi.org/10.1088/1748-9326/9/12/124017

Ekoungoulou R, Niu S, Loumeto JJ, Ifo AS, Bocko YE, Mikieleko KEF, Guiekisse MDE, Senou H, Liu X. 2015. Evaluating the Carbon Stock in Above-and Below- Ground Biomass in a Moist Central African Forest. Applied Ecology and Environmental Sciences **3(2),** 51-59. https://doi.org/10.12691/aees-3-2-4.

FAO-UNESCO. 1975. Carte mondiale des sols (1/5000000). Volume I, Unesco- Paris, 68.

Gautam S, Pietsch SA. 2012. Carbon pools of an intact forest in G abon. African Journal of Ecology **50,** 414–427. https://doi.org/10.1111/j.1365-2028.2012.01337.x

Harmon ME, Sexton J. 1996. Guidelines for Measurements of Woody Detritus in Forest Ecosystems. Publication No. 20. U.S. LTER. Network Office: University of Washington, Seatle, WA, USA, p 73.

Hribljan JA, Suárez E, Heckman KA, Lilleskov EA, Chimner RA. 2016. Peatland carbon stocks and accumulation rates in the Ecuadorian páramo. Wetlands Ecol Manage **24,** 113–127. https://doi.org/10.1007/s11273-016-9482-2

Hubau W, Lewis SL, Phillips OL, Affum-Baffoe K, Beeckman H, Cuní-Sanchez A, Daniels AK, Ewango CEN, Fauset S, Mukinzi JM, Sheil D, Sonké B, Sullivan MJP, Sunderland TCH, Taedoumg H, Thomas SC, White LJT, Abernethy KA, Adu-Bredu S, Amani CA, Baker TR, Banin LF, Baya F, Begne SK, Bennett AC, Benedet F, Bitariho R, Bocko YE, Boeckx P, Boundja P, Brienen RJW, Brncic T, Chezeaux E, Chuyong GB, Clark CJ, Collins M, Comiskey JA, Coomes DA, Dargie GC, De Haulleville T, Kamdem MND, Doucet J-L, Esquivel-Muelbert A, Feldpausch TR, Fofanah A, Foli EG, Gilpin M, Gloor E, Gonmadje C, Gourlet-Fleury S, Hall JS, Hamilton AC, Harris DJ, Hart TB, Hockemba MBN, Hladik A, Ifo SA, Jeffery KJ, Jucker T, Yakusu EK, Kearsley E, Kenfack D, Koch A, Leal ME, Levesley A, Lindsell JA, Lisingo J, Lopez-Gonzalez G, Lovett JC, Makana J-R, Malhi Y, Marshall AR, Martin J, Martin EH, Mbayu FM, Medjibe VP, Mihindou V, Mitchard ETA, Moore S, Munishi PKT, Bengone NN, Ojo L, Ondo FE, Peh KS-H, Pickavance GC, Poulsen AD, Poulsen JR, Qie L, Reitsma J, Rovero F, Swaine MD, Talbot J, Taplin J, Taylor DM, Thomas DW, Toirambe B, Mukendi JT, Tuagben D, Umunay PM, Van Der Heijden GMF, Verbeeck H, Vleminckx J, Willcock S, Wöll H, Woods JT, Zemagho L. 2020. Asynchronous carbon sink saturation in African and Amazonian tropical forests. Nature **579,** 80–87. https://doi.org/10.1038/s41586-020-2035-0

Ifo AS, Koubouana F, Jourdain C, Nganga D. 2015. Stock and Flow of Carbon in Plant Woody Debris in Two Different Types of Natural Forests in Bateke Plateau, Central Africa. OJF **05,** 38–47. https://doi.org/10.4236/ojf.2015.51005

Ifo SA, Koubouana F, Binsangou S, Parfait A, Marcelle B. 2017. Amount of Soil Carbon Stock within Primary and Secondary Forest in the North of the Republic of Congo. SE **2,** 159. https://doi.org/10.22158/se.v2n2p159

IPCC. 2008. 2006 IPCC Guidelines for National Greenhouse Gas Inventories- A primer, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Miwa K., Srivastava N. and Tanabe K. (eds). Published: IGES, Japan. p 20.

Jeyanny V, Husni M, Rasidah KW, Kumar BS, Arifin A, Hisham MK. 2014. Carbon stocks in different carbon pools of a tropical lowland forest and a montane forest with varying topography. Journal of Tropical Forest Science **26(4),** 560-571.

Kauffman JB, Bhomia RK. 2017. Ecosystem carbon stocks of mangroves across broad environmental gradients in West-Central Africa: Global and regional comparisons. PLoS ONE **12(11), 1-17,** e0187749. https://doi.org/10.1371/journal.pone.0187749

Kauffman JB, Donato D. 2012. Protocols for the measurement, monitoring and reporting of structure, biomass and carbon stocks in mangrove forests. Working Paper 86. Center for International Forestry Research (CIFOR), Bogor, Indonesia. https://doi.org/10.17528/cifor/003749

Letouzey R. 1982. Manuel de botanique forestière d'Afrique Tropicale. Livre : Botanique Générale, Tome 1. Centre Technique Forestier Tropical, 2ème édition. France, 1-648.

Lewis SL, Lopez-Gonzalez G, Sonké B, Affum-Baffoe K, Baker TR, Ojo LO, Phillips OL, Reitsma JM, White L, Comiskey JA, Marie-Noël DK, Ewango CEN, Feldpausch TR, Hamilton AC, Gloor M, Hart T, Hladik A, Lloyd J, Lovett JC, Makana J-R, Malhi Y, Mbago FM, Ndangalasi HJ, Peacock J, Peh KS-H, Sheil D, Sunderland T, Swaine MD, Taplin J, Taylor D, Thomas SC, Votere R, Wöll H. 2009. Increasing carbon storage in intact African tropical forests. Nature **457,** 1003–1006. https://doi.org/10.1038/nature07771

Lü X-T, Yin J-X, Jepsen MR, Tang J-W. 2010. Ecosystem carbon storage and partitioning in a tropical seasonal forest in Southwestern China. Forest Ecology and Management **260,** 1798–1803. https://doi.org/10.1016/j.foreco.2010.08.024

Mokany K, Raison RJ, Prokushkin AS. 2006. Critical analysis of root : shoot ratios in terrestrial biomes. Global Change Biology **12,** 84–96. https://doi.org/10.1111/j.1365-2486.2005.001043.x

Mund M. 2004. Carbon pools of European beech forests ( ) under different silvicultural management. Dissertation, zur Erlangung des Doktorgrades der Fakultät für Forstwissenschaften und Waldökologie der Georg-August-Universität Göttingen. Berichte des Forschungszentrums Waldökosysteme, Reihe A, Band **189,** 256 p.

Ngo KM, Turner BL, Muller-Landau HC, Davies SJ, Larjavaara M, Nik Hassan NFB, Lum S. 2013. Carbon stocks in primary and secondary tropical forests in Singapore. Forest Ecology and Management **296,** 81–89. https://doi.org/10.1016/j.foreco.2013.02.004

Page SE, Rieley JO, Banks CJ. 2011. Global and regional importance of the tropical peatland carbon pool. Global Change Biology.

Palace M, Keller M, Hurtt G, Frolking S. 2012. A Review of Above Ground Necromass in Tropical Forests, in: Sudarshana, P. (Ed.), Tropical Forests. InTech. https://doi.org/10.5772/33085

Pearson T, Harris N, Shoch D, Brown S. 2005. A sourcebook of methods and procedures for monitoring and reporting anthropogenic greenhouse gas emissions and removals associated with deforestation, gains and losses of carbon stock in forests remaining forests, and forestation, 47-70.

Peh KS-H, Sonké B, Lloyd J, Quesada CA, Lewis SL. 2011. Soil Does Not Explain Monodominance in a Central African Tropical Forest. PLoS ONE 6, e16996. https://doi.org/10.1371/journal.pone.0016996

Phillips O, Baker T, Feldpausch T, Brienen R. 2021. RAINFOR Field Manual for Plot Establishment and Remeasurement.

Powers JS, Corre MD, Twine TE, Veldkamp E. 2011. Geographic bias of field observations of soil carbon stocks with tropical land-use changes precludes spatial extrapolation. Proceedings of the National Academy of Sciences of the United States of America U.S.A. **108,** 6318-6322. https://doi.org/10.1073/pnas.1016774108

R Core Team. 2020. R : Un langage et un environnement pour le calcul statistique | BibSonomy [WWW Document]. URL (accessed 7.29.24). https://www.bibsonomy.org/bibtex/7469ffee3b07f9167cf47e7555041ee7

Saint-Laurent D, Gervais-Beaulac V, Paradis R, Arsenault-Boucher L, Demers S. 2017. Distribution of Soil Organic Carbon in Riparian Forest Soils Affected by Frequent Floods (Southern Québec, Canada). Forests **8,** 124. https://doi.org/10.3390/f8040124

Suwarna U, Elias E, Darusman D, Istomo I. 2012. Estimation of Total Carbon Stocks in Soil and Vegetation of Tropical Peat Forest in Indonesia. jtfm **18,** 118–128. https://doi.org/10.7226/jtfm.18.2.118

Thomas SC, Martin AR. 2012. Carbon Content of Tree Tissues: A Synthesis. Forests **3,** 332–352. https://doi.org/10.3390/f3020332

Vashum KT, Kasomwoshi T, Jayakumar S. 2016. Soil organic carbon sequestration potential of primary and secondary forests in Northeast India. Proceedings of the International Academy of Ecology and Environmental Sciences **6(3),** 67-74.

Vitt DH, Halsey LA, Bauer IE, Campbell C. 2000. Spatial and temporal trends in carbon storage of peatlands of continental western Canada through the Holocene. Canadian Journal of Earth Sciences **37,** 683–693.
https://doi.org/10.1139/e99-097

Walker SM, Murray L, Tepe T. 2016. Allometric Equation Evaluation Guidance Document. Winrock International. 75 p.

Warren DR, Keeton WS, Kraft CE. 2008. A comparison of line-intercept and census techniques for assessing large wood volume in streams. Hydrobiologia **598,** 123–130.
https://doi.org/10.1007/s10750-007-9144-8

Woldendorp G, Keenan RJ, Ryan MF. 2002. Coarse Woody Debris in Australian Forest Ecosystems. A Report for the National Greenhouse Strategy, Module 6.6 (Criteria and Indicators of Sustainable Forest Management), 1-75.

Yadav RS, Pandya IY, Jangid MS. 2015. Estimating Status of Soil Organic Carbon in Tropical Forests of Narmada Forest Division, Gujarat, India. Int. Res. J. Environment **4(1),** 19-23.

Yeboah D, Burton AJ, Storer AJ, Opuni-Frimpong E. 2014. Variation in wood density and carbon content of tropical plantation tree species from Ghana. New Forests **45,** 35–52.
https://doi.org/10.1007/s11056-013-9390-8

Zanne AE, Lopez-Gonzalez G, Coomes DA, Ilic J, Jansen S, Lewis SL, Miller RB, Swenson NG, Wiemann MC, Chave J. 2009. Data from: Towards a worldwide wood economics spectrum.
https://doi.org/10.5061/DRYAD.234

Zaroug MAH, Sylla MB, Giorgi F, Eltahir EAB, Aggarwal PK. 2013. A sensitivity study on the role of the swamps of southern Sudan in the summer climate of North Africa using a regional climate model. Theor Appl Climatol **113,** 63–81.
https://doi.org/10.1007/s00704-012-0751-6