Sustainability in Environment
ISSN 2470-637X (Print) ISSN 2470-6388 (Online)
Vol. 3, No. 2, 2018
www.scholink.org/ojs/index.php/se

Original Paper

Carbon Stocks of Coarse Woody Debris in Central African Tropical Forests

Romeo Ekoungoulou[1], Shukui Niu[1*], Fousseni Folega[2], Donatien Nzala[3] & Xiaodong Liu[1]

[1] Laboratory of Ecosystems Management and Planning, College of Forestry, Beijing Forestry University, Beijing 100083, China

[2] Unité de Recherche en Ecologie et Géomatique Appliquée, Laboratoire de Botanique et Ecologie Végétale, Faculté des Sciences, Université de Lomé BP 1515, Lomé, Togo

[3] Département des Techniques Forestières, Ecole Nationale Supérieure d'Agronomie et de Foresterie, Université Marien Ngouabi, BP69 Brazzaville, Republic of Congo

[*] Shukui Niu, E-mail: Unité de Recherche en Ecologie et Géomatique Appliquée, Laboratoire de Botanique et Ecologie Végétale, Faculté des Sciences, Université de Lomé BP 1515, Lomé, Togo

Received: November 8, 2017 Accepted: March 23, 2018 Online Published: April 8, 2018
doi:10.22158/se.v3n2p142 URL: http://dx.doi.org/10.22158/se.v3n2p142

Abstract

Coarse Woody Debris (CWD; defined here as fallen and standing dead trees and tree branches) is a critical-structural and functional component of forest ecosystems that typically comprises a large proportion of total aboveground carbon storage. Coarse woody debris estimation for the tropics is uncommon, and little is known about how carbon storage in CWD will respond to climate change. Given the predominant role that tropical forests play in global carbon cycling, this information gap compromises efforts to forecast climate change impacts on terrestrial carbon balance. In this study, we aimed to identify the variation in Coarse Woody Debris (CWD) stocks between forest types (Old-growth and selective logging forests) and among the plots in Ipendja mixed lowland terra firme tropical rainforest (central Africa), and we examined the consequence for CWD carbon stocks estimation. The study area is located at Ipendja forest management unit (UFA), close to Dongou district (Likouala Department), in Northern Republic of Congo. Data collection were done with eight rectangular plots, each 25 x 200 m (0.5 ha). The method of line intercepts sampling has been used in each studied site. A total number of 135 CWD samples of diameter ≥ 10 cm in the studied plots have been recorded. It was obvious that stock of coarse woody debris in Mokelimwaekili site (mean: 19.96 Mg ha^{-1}; sum: 79.84 Mg ha^{-1}) were higher than those of Sombo site (mean: 8.9 Mg ha^{-1}; sum: 35 Mg ha^{-1}). There was a significance difference in Ipendja evergreen forest about CWD stocks across two forest types and plots.

This finding suggests that values vary among forest types and that separate reference values should be adopted for estimates of undisturbed forest carbon stocks in the different ecosystems in Congo basin. Different reference values represent the variability of CWD among forest types and contribute to reducing uncertainties in current estimates of carbon stock in central African forest ecosystems.

Keywords

cwd, ipendja forest, mokelimwaekili, old-growth, selective logging, sombo

1. Introduction

Coarse Woody Debris (CWD) is an important component of carbon storage in tropical forests (Chambers et al., 2000; Rice et al., 2004; Palace et al., 2012; Osone et al., 2016). In undisturbed moist forests, it may account for approximately 10% of the total carbon storage (Pregitzer & Euskirchen, 2004) and can constitute up to 33% of the forests' Above Ground Biomass (AGB) (Baker et al., 2007). A disturbance event usually causes large changes in Coarse Woody Debris (CWD) stocks and fluxes (Osone et al., 2016). Increased mortality due to disturbance promotes carbon flux from the living mass to the Coarse Woody Debris (CWD) pool (Rice et al., 2004), and the subsequent decomposition of the dead trees increases the total carbon emission of the stand. Therefore, quantifying the stocks and fluxes of coarse woody debris helps our understanding of the carbon balance of the disturbed forests. Undisturbed tropical rainforests are generally highly resistant to fires because of the moist microclimate and low fuel loads that create low-flammability conditions (Osone et al., 2016).

The Kyoto protocol has led to increased attention to the potential of carbon sequestration in forests in order to mitigate rising levels of atmospheric CO_2. In the past decades, forests have absorbed about 30% of worldwide anthropogenic CO_2 emissions annually (Schulze et al., 2000). However, much uncertainty remains about forest carbon sink-source dynamics, especially the effects of forest management (Bellassen & Luyssaert, 2014; Ekoungoulou et al., 2014c). Naudts et al. (2016) founded that despite increases in forest area and in forest management in Europe in the past 250 years, European forests have failed to achieve a net removal of CO_2 from the atmosphere. This was attributed to increased wood extraction which has resulted in a removal of CO_2 from biomass, dead wood and forest soils. Thus, Naudts et al. (2016) demonstrated that not all aspects of forest management will mitigate climate change.

Globally, Coarse Woody Debris (CWD) contains about 36-72 Pg. of carbon (but see Russell et al., 2015 for factors that greatly affect such estimation), and the fate of this carbon will affect forest carbon dynamics (Cornwell et al., 2009) as well as global surface carbon stocks with feedback to climate (Brovkin et al., 2012).

In recent literature it has been proposed that leaving dead wood in the form of CWD in forests rather than clearing it, contributes to the system's carbon sequestration (Luyssaert et al., 2007; Gough et al., 2007; Nave et al., 2010; Cornelissen et al., 2012; Wiebe et al., 2014). Apart from carbon sequestration, coarse woody debris may also provide other ecosystem services such as a habitat, food and nutrients for numerous organisms. For instance, many saprophytic organisms are threatened by extinction due to the global decrease in the presence of coarse woody debris (Grove, 2002; Magnusson et al., 2016).

Coarse Woody Debris (CWD) is an important carbon pool in forests. Residence times of coarse woody debris vary widely based on their size, species and local environment. Half-lives of up to 230 years have been found (Harmon et al., 1986), and Kueppers et al. (2004) reported average residence times of up to 800 years for coniferous species in a subalpine setting. Locally, especially in cases of buried Coarse Woody Debris (CWD) on paludified sites, CWD may persist for over centuries (McFee & Stone, 1966; Triska & Cromack, 1980; Moroni et al., 2015). Although exact definitions may vary, Coarse Woody Debris (CWD) is usually defined as wood fragments with minimum diameters of between 2.5 and 10 cm (Harmon et al., 1986). Distinctions can be made between fine woody debris and intact stems and branches, the latter of which may be downed or still standing. We adhere to the classification proposed by Harmon and Sexton (1996). Fragments smaller than 10 cm in diameter and 1.5 m in length are fine woody debris (Magnusson et al., 2016). Larger fragments can be present as snags (vertical standing fragments resulting from natural processes), stumps (short vertical elements resulting from cutting) and logs (i.e., downed woody debris, DWD).

A common distinction between DWD and snags is a lean angle of 45°, larger angles representing snags and lower angles representing DWD. We adhere to Harmon and Sexton's (1996) proposal that also short elements at lean angles > 45° be defined as either snags (in case they result come from natural processes) or stumps (in case they result come from cutting). Belowground elements can be divided into buried wood and coarse roots (Harmon & Sexton, 1996). Although most studies focus on snags and logs, roots and stumps are important constituents of coarse woody debris (Palviainen & Finer, 2015), and are included in our definition of CWD.

However, most studies on Coarse Woody Debris (CWD) have focused on the aboveground CWD-pool and respiration fluxes of carbon from CWD, using eddy-covariance and respiration chamber methods (Gough et al., 2007; Luyssaert et al., 2007; Ohtsuka et al., 2014; Kahl et al., 2015), rather than incorporating the effect of CWD on soil carbon pools. This in spite of the fact CWD may yield a larger Dissolved Organic Carbon (DOC) flux to the forest soil per unit mass than foliar litter (Hafner et al., 2005). Secondly, CWD buried in the soil or covered by thick vegetation layers (most notably mosses) is not usually quantified. However, this pool of buried dead wood can be a significant forest ecosystem carbon pool with a very low turnover rate (McFee & Stone, 1966; Harmon & Sexton, 1996; Moroni et al., 2015). Despite its importance, this pool is not accounted for in forest carbon models (Moroni et al., 2015) and is often purposefully removed from soil or litter sampling efforts (McFee & Stone, 1966; Harmon & Sexton, 1996; Moroni et al., 2015), causing it to be a "missing carbon pool" in present day forest carbon cycle research (Magnusson et al., 2016). Failure to incorporate belowground processes in research into carbon dynamics of CWD results in a compromised vision at best. Decomposition of CWD continues as it is gradually transformed into soil organic matter, making it hard to determine endpoints of decomposition and effects on forest carbon pools in studies that focus merely on the aboveground pools of CWD (Mcfee & Stone, 1966; Magnusson et al., 2016).

The present study about the carbon stocks of Coarse Woody Debris (CWD) in Ipendja forest, will allow us to estimate the carbon stocks in forest ecosystems of the Likouala Department (Northern Republic of Congo) using Allometric equations. The results of this study will be useful to the Republic of Congo's national forest carbon quantification program, managed by the CN-REDD + Congo Project, and the Republic of Congo's Ministry of Forest Economy and Sustainable Development.

The objectives of this study were to: (i) quantify the Coarse Woody Debris (CWD) stocks including standing dead trees (snags) and fallen dead trees and branches (logs) in Ipendja mixed tropical forest using algometric equations; (ii) identify the drivers of coarse woody debris variation between two forests types (Old-growth and selective logging forests) of Ipendja lowland evergreen terra firme tropical forest.

2. Materials and Methods

2.1 Study Area

The area in which the present study was conducted is located in Republic of Congo's northern part, specifically in Ipendja (Figure 1) forest management unit (UFA), located at Dongou district (Likouala Department). Ipendja (2°32'N, 17°20'E) forest management unit (UFA) is managed by Thanry-Congo logging company according to them agreement allowed by Republic of Congo's Ministry of forest economy and sustainable development. The Department of Likouala covers an area that is around 150,000 hectares (STC, 2016). This Department extends 230 km from East to West and about 550 km from North to South. Likouala Department is limited at the North by the Central African Republic, at the South by the Department of Cuvette-Centrale, at the East by the Democratic Republic of Congo, at the West by Sangha Department (STC, 2016).

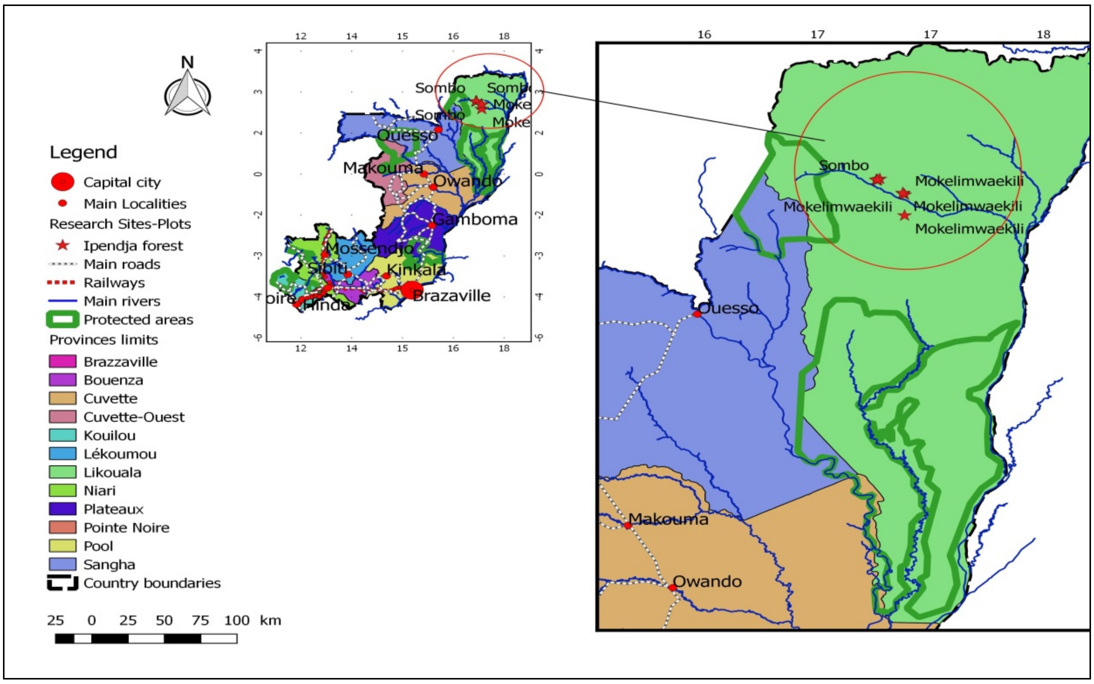

Figure 1. Location of Study Area

2.1.1 Climate

The tropical climate country is characterized by heavy precipitation and high temperatures and humidity. The Equator crosses the country just north of Liranga. In the north a dry season extends from November through March and a rainy season from April through October, whereas in the south the reverse is true. On both sides of the Equator, however, local climates exist with two dry and two wet seasons. Annual precipitation is abundant throughout the country, but seasonal and regional variations are important. Precipitation averages more than 48 inches (1,200 mm) annually but often surpasses 80 inches (2,000 mm) (ANAC, 2016). Temperatures are relatively stable, with little variation between seasons. More variation occurs between day and night, when the difference between the highs and lows averages about 27 °F (15 °C). Over most of the country, annual average temperatures range between the high 60s and low 80s F (low and high 20s C), although in the south the cooling effect of the Benguela current may produce temperatures as low as the mid-50s F (low 10s C). The average daily humidity is around 80 percent.

However, the Impfondo station, located around 60 kilometers in southeast of the massif to be developed, shows that this dry season tends to disappear in the northeast part (STC, 2016). So, the Ipendja forest management unit (UFA) therefore presently suffers with an equatorial climate with no real dry season, with minimum precipitation in January and February (> 50mm) and peaks from September to December (> 150mm), for an annual total of around 1600 mm (ANAC, 2016). With amplitude ranging from 2 to 2.5 °C, the average annual temperature is around 25 °C (ANAC, 2016).

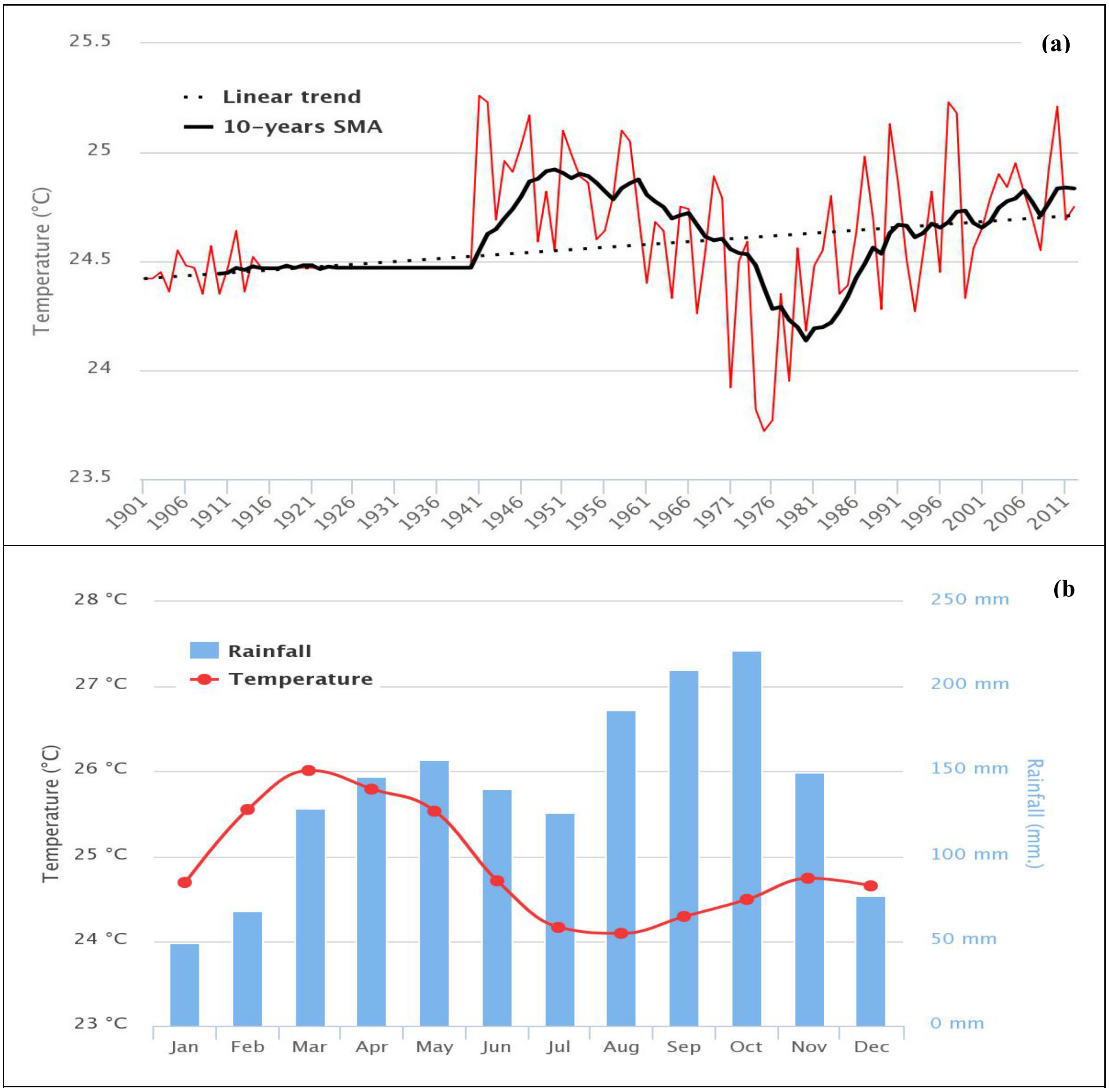

Figure 2. Annual Mean Temperatures of Ipendja Forest Management Unit from 1901 to 2011 (a). Temperature (a) Has Been Adapted from the Source of Global Climate Monitor (Retrieved 22 March, 2017, from http://www.globalclimatemonitor.org). Climograph of the Main Meteorological Station around the Study Area with the Mean from 1978 to 2015 (b)

2.1.2 Soils

About two-thirds of the country is covered with coarse-grained soils that contain sand and gravel. Lateritic soils, with a high proportion of iron and aluminum sesquioxydes, characterize low-lying areas. Because of the hot and humid climate, organic matter is decomposed by rapid bacterial action before it can accumulate into humus; moreover, top soil is washed away by the heavy rains (Ekoungoulou et al., 2018a). In the savanna regions, the fertile alluvial soils are threatened with erosion by wind as well as rain. A diverse pattern of coarse- and fine-grained soils covers the plateaus and hills (STC, 2016). The forest massif to be developed is located in the Congolese cuvette, covered with recent deposits of the Quaternary, composed mainly by sandstone, clay, sands and silts over several tens of meters of depth (Ekoungoulou et al., 2018b). Resulting by the climatic consequence, the soils of Ipendja forest are the ferrallitic type and alluvial hydromorphic (STC, 2016), forming the following secondary minerals: kaolin (type 1/1 alumina silicates); Goethite and Hematite (iron hydroxide) and Gibbs (Alumina hydroxides). From sandy texture and low-cohesion organic lumpy structure, these soils are susceptible to erosion and favourable to soil leaching (STC, 2016; Ekoungoulou et al., 2017). They are composed by a fine-textured top-layer, an intermediate stony induration layer and a lower layer corresponding to the altered bedrock. Fairly poor in base and high pH, soils are very low-fertility and the humus formation layer is very slow (STC, 2016).

2.2 Data Collection

Plot-based and line intersect are both available methods developed by RAINFOR network (Retrieved February 17, 2017, from http://www.rainfor.org) for the Coarse Woody Debris (CWD) measurements. Both methods can be used in existing studies of Coarse Woody Debris (CWD) stocks in RAINFOR plots. Plot-based method is useful for the studies that compare stocks of Coarse Woody Debris (CWD) with inputs from tree mortality within existing one hectare permanent plots. Line intersects method is useful for assessing questions about the stocks of Coarse Woody Debris (CWD) at larger scales for assessing, i.e., the degree to which the plots are representative of the wider landscape. In this study only the line intersects sampling method has been used according to RAINFOR network protocol (Baker & Chao, 2011). Therefore, the field measurements were based on techniques using rectangular plots, each $5000m^2$ (25x200 m; i.e., 0.5ha). The study had retained eight rectangular plots each separated by roughly 1 or 2 km. All 8 plots inventoried were divided into two sites, such as Mokelimwaekili (4 plots) and Sombo (4 plots). Coarse woody debris measurements have been conduct on plots with a slope $<$ 5° (almost flat). Also, measurements have been making solely on the coarse woody debris diameter $\geq$ 10 cm, and only these were marked with a nail and Poly Vinyl Chloride (PVC) plastic label (Pearson & Brown, 2005; Lopez-Gonzalez et al., 2011). The coarse woody debris less than 10 cm of diameter would normally be measured only in fairly young forest. Ipendja forest management unit (UFA) is not a young forest. Also, Ipendja forest is a tropical evergreen lowland terra firme moist forest with a status of old-growth (Mokelimwaekili) and selective logging (Sombo) forests. Therefore, a GPS model Garmin 62CSx has been used to record the plots location (coordinates) in minutes, second and degrees. Altitudes, longitudes, latitudes were then recorded for each plot in study area.

2.2.1 Line Intersects Sampling

Line intersects sampling performed provides a fast method to obtain landscape-level estimates of Coarse Woody Debris (CWD) stocks and allow sampling for the calibration of the decomposition classes and measurement of Coarse Woody Debris (CWD) void space outside the permanent plots (Baker et al., 2004). This method allowed until a total of 2 km of line transect, divided into several smaller units is recommended to provide reasonable precision: five, 400 m transects produced Coarse

Woody Debris (CWD) estimates with a standard error of 20% of the mean in a southwestern Amazon forest (Baker et al., 2007). Ideally, line transects should always be more than 20m apart, to maintain independence, and be established in random directions across the landscape, to avoid bias from directional mortality events due to topography or the predominant wind direction. During the field a measurement of 200 m line transects has been used for by plot (each 200 m x 25 m). The line transects were established in two perpendicular directions, combining ease of set up with these objectives (Pearson & Brown, 2005). Measurements were done with rectangular plots of Coarse Woody Debris (CWD), two measurements have been made along the longest axis and perpendicular to that axis and the geometric mean calculated for use calculating the CWD volume.

2.2.2 Measurement of Fallen Dead Trees and Branches (Logs)

The fallen dead trees and branches have been measured using the method of line intersects sampling (Pearson & Brown, 2005; Baker & Chao, 2011). It was consisting of two lines of 200 m and 25 m in each cardinal direction (North-South and East-West) forming a right angle at the center of a plot. The diameter and height of every piece of Coarse Woody Debris (CWD) which is located in the perimeter of the study plot is systematically measured and the position of the latter by report to one of the ends of sampling line. The measure has been held using a double decameter model Forestry Pro. In each piece of fallen dead trees and branches it was attributed one of the categories of density follows: solid (machete bounces on wood); intermediate (machetes between partly and there is a loss of wood) and rotten (more great loss and the wood is brittle).

2.2.3 Measurement of Standing Dead Trees (Snags)

The snags or standing dead trees have been measured in the eight study plots. The diameter and their state of decomposition were recorded. Standing dead trees were classified into four categories, such as Category 1: Tree with branches and twigs resembling a living tree (except for foliage); Category 2: Tree without twigs but still with large and small branches; Category 3: Trees with large branches only; and Category 4: Trunk only, without branches. For category 4, the height of tree and its diameter at ground level were measured, and the crown diameter was measured. A laser hypsometer (Brand Nikon, model WJ072214, Forestry Pro) has been used to measure the height of snag in each study plot. The diameter for each standing dead tree has been measured by making use of methods for live trees according to Forest Plots (www.forestplots.net) and AfriTRON network (www.afritron.org) protocols (Lopez-Gonzalez et al., 2011). The height of snag has been measured in each study plot.

2.3 Data Analysis

2.3.1 Coarse Woody Debris (CWD)

The Coarse Woody Debris (CWD) were analyzed in two steps, such as analysis of standing dead trees and analysis of fallen dead trees and branches for each study plot in Ipendja forest. Equation proposed by Warren and Olsen (1964) has been used to estimate the volume of fallen dead trees and branches. Equation developed by Mund (2004) has been used to estimate the volume of standing dead trees. The fallen dead trees and branches are also called by logs (Pedlar et al., 2002). The standing dead trees are also called by snags (Pedlar et al., 2002).

2.3.2 Standing Dead Trees (Snags)

Line intercepts sampling only provides information on fallen dead wood. If only line intersects sampling is used, then belt transects 10 m wide on either side of the transect line (Chao et al., 2008; Woodall & Liknes, 2008) should be used to measure, in addition, all standing dead trees and stumps, as described in the previous section.

To calculate the volume of standing dead trees in study area, the following equation developed by Mund (2004) has been used:

$$V_{(m^3)} = \pi \times h \times f \times \left(\frac{D}{2}\right)^2 \quad (1)$$

Where V is the standing dead trees volume per unit area (m^3), Π is 3.14, D is diameter of standing dead trees (cm), *f* is the form factor with the value of 0.627, *h* is height of standing dead trees (m).

2.3.3 Fallen Dead Trees and Branches

The diameter of each piece of fallen dead tree and branch, crossing the sampling line was systematically measured. And a dead piece of wood was measured if and only if more than 50% of the dead wood was above ground, and the sampling line was at least 50% of the diameter of the fallen piece of wood (Walker et al., 2011). Measurement of wood volume on the ground by line intersect consists basically of tallying the diameters of intersected pieces along a sample line. To calculate fallen dead trees and branches, the below equation proposed by Warren and Olsen (1964) has been used:

$$V = \frac{\pi^2(\sum d_i^2)}{8L} \quad (2)$$

Where V is the fallen dead trees and branches volume per unit area (m^3), d_i is the diameter (cm) of log $_i$ and L(m) is the length of the transect line (Warren & Olsen, 1964). The variance of the volume (σ^2) for n transects is weighted by transect lengths (L_j), as recommended by De Vries (1986) cited in Keller et al. (2004), as:

$$\sigma^2 = \left[\sum L_j \left(V_j - \bar{V}\right)^2\right] / \left[(n-1) \times \sum L_j\right] \quad (3)$$

The conversion of results obtained from volume to mass have been performed by setting the 0.5 as value of wood density for each sampling (Pearson & Brown, 2005). To estimate carbon stocks, the mass of Coarse Woody Debris (CWD) has been multiplied by wood density to obtain the carbon for each plot (Pearson & Brown, 2005; Basuki et al., 2009). Moreover, carbon stock is typically derived from live or Coarse Woody Debris (CWD) mass by assuming that 50% of the CWD mass is made up carbon (Brown, 1997; Cairns et al., 1997; Pearson & Brown, 2005; Basuki et al., 2009).

2.3.4 Statistical Analysis

Differences in the mean of Coarse Woody Debris (CWD) mass between the two forest type such as old-growth and selective logging forests were tested using one-way ANOVA, Levene or Tukey's multiple comparison tests. Differences between the measured and predicted Coarse Woody Debris (CWD) mass were tested by the Student's t-test. Kruskal-Wallis test, Wilcoxon test have been applied across plots, sites and between or for each sample case by case. Statistical analyses were performed with *PAST version 3.05* (Hammer et al., 2001) and *Sigma Plot version 10.0* software's. Study area's location map has been performed using the *ArcGIS v.9.3* software.

3. Results

The investigation revealed that a total number of 135 samples of diameter ⩾ 10 cm in the studied plots have been recorded (Table 1). These 135 Coarse Woody Debris (CWD) samples measured were divided into two studied sites, respectively Mokelimwaekili (site 1, n = 57) and Sombo (site 2, n = 78). In Mokelimwaekili forest, 10 samples of standing dead trees and 47 samples of fallen dead trees and branches have been recorded. In Sombo forest, 18 samples of standing dead trees and 60 samples of fallen dead trees and branches have been recorded. It was obvious that stock of coarse woody debris in Mokelimwaekili site (mean = 19.96 Mg ha^{-1}; sum = 79.84 Mg ha^{-1}) were higher than those of Sombo site (mean = 8.9 Mg ha^{-1}; sum = 35 Mg ha^{-1}). Regarding the relative frequency of Coarse Woody Debris (CWD) samples measured, the most representative plot in study area with height relative frequency were plot 4 (27%), followed by plot 7 (19%) and plot 5 (13%). Plot 3 (7%), plot 2 (7%) and plot 1 (2%) had a low relative frequency of coarse woody debris samples in Ipendja mixed evergreen lowland tropical forest (Figure 4a). About the Coarse Woody Debris (CWD) storage, the most representative plot in study sites with height mass of Coarse Woody Debris (CWD) were plot 3 (31.55 Mg ha^{-1}; 27%), followed by plot 4 (19%; 21.46 Mg ha^{-1}), and plot 7 (15%; 17.48 Mg ha^{-1}). Plot 6 (7.07 Mg ha^{-1}; 6%), plot 5 (6 Mg ha^{-1}; 5%), and plot 8 (5.1 Mg ha^{-1}; 5%) had a low frequency of Coarse Woody Debris (CWD) mass (Figure 4b) in Ipendja mixed evergreen lowland tropical forest (Table 1).

In this study, the fallen dead trees and branches have been recorded in all plots studied. It is important to mention that, during this research the standing dead trees have been recording in study plots excluding plot 1. Figure 3c shows that fallen dead trees and branches mass were higher than the standing dead trees mass founded in eight studied plots of Ipendja forest. Figure 3d shows that more standing dead trees samples recorded had a height ranging from 7 to 12 m for Mokelimwaekili forest as well as for Sombo forest. Figure 3a showed relationship between diameter and length of fallen dead trees branches. The logs recorded built up for both Mokelimwaekili and Sombo (Figure 3a). This study shows that plot 3 (31.55 Mg ha^{-1}) were the most important regarding Coarse Woody Debris (CWD) mass (Figure 3b). While the number of Coarse Woody Debris (CWD) samples recorded for plot 3 were few (10 samples, 31.55 Mg ha^{-1}) compared with the number of coarse woody debris samples recorded for plot 4 (36 samples, 21.46 Mg ha^{-1}) as asserted in Table 1.

One-way ANOVA and Levene test showed a significant difference between standing dead trees stocks and fallen dead trees and branches stocks (F = 17.97, df = 7.089, p = 0.003). Kruskal-Wallis test shows that there is a significant difference between fallen dead trees and branches mass and standing dead trees mass ($H(ch_i^2)$: 11.29, p = 0.0007). The *t-test* has been performed for only Coarse Woody Debris (CWD) mass in eight plots, and the results shows that the mean are significantly different (p = 0.002, confidence interval at 95%: 6.8856-21.992). Wilcoxon test (normal approximation inaccurate) shows that the medians are significantly different (p = 0.0078, W: 36, Normal approximation z: 2.52). One-way ANOVA performed using PAST v.3.05 shows that, there is no significant difference between Mokelimwaekili forest and Sombo forest (F = 4.468, df = 5.203, p = 0.086). Levene's test for homogeneity of variance showed a significant difference between Mokelimwaekili and Sombo sites about the coarse woody debris stocks (from mean: p = 0.422, from medians: p = 0.394). Kruskal-Walls test shows that there is no significant difference between Sombo and Mokelimwaekli sites for coarse woody debris storage ($H(ch_i^2)$: 3, p = 0.0832).

Table 1. Various Features of Coarse Woody Debris Recorded in Study Area. D: Average Diameter of Coarse Woody Debris (in cm) Recorded in each Plot; FS: Forest Status; OG: Old-Growth Forest; SL: Selective Logging Forest (Logging Performed in Ipendja UFA from 2002 to 2003 by One Stem per Hectare); CWD: Coarse Woody Debris Mass (Sum of Fallen Dead Trees and Branches Mass, and Standing Dead Trees Mass, in Mg ha^{-1}); MME: Mokelimwaekili Site; Altitude: Altitude (in m) of Each Studied Plot Measured Using a GPS Model Garmin 62CSx; Height: Average Height of Standing Dead Trees Recorded for each Plot in Ipendja Mixed Lowland Evergreen Forest (in m); Length: Average Length of Fallen Dead Trees and Branches for each Plot in Ipendja Mixed Lowland Evergreen Forest (in m); n: Number of Coarse Woody Debris Sample Recorded by Plot in Studied Sites; Logs: Mass of Fallen Dead Trees and Branches for Each Plot (Mg ha^{-1}); Snags: Mass of Standing Dead Trees for Each Plot in Ipendja Forest (Mg ha^{-1})

					Fallen dead trees and branches				Standing dead trees			
Plots	Sites	FS	Altitude	CWD	D	Length	n	logs	D	Height	n	snags
Plot 1	MME	OG	397	15.09	24.75	17.05	2	15.09				
Plot 2	MME	OG	385	11.74	20.65	6.8	6	10.51	47.26	11.33	3	1.24
Plot 3	MME	OG	385	31.55	35.7	6.2	8	31.41	18.7	8.7	2	0.14
Plot 4	MME	OG	390	21.46	28.12	5.6	31	19.49	73.58	7.4	5	1.97
Plot 5	Sombo	SL	378	6	15.12	3.5	11	5.6	33.05	7.5	7	0.4
Plot 6	Sombo	SL	383	7.07	16.9	3.8	16	7.04	13.25	4.66	2	0.03
Plot 7	Sombo	SL	377	17.48	26.32	4.9	23	17.07	37.66	6	3	0.41
Plot 8	Sombo	SL	384	5.12	14.36	5.1	10	5.08	14.21	4.9	6	0.04

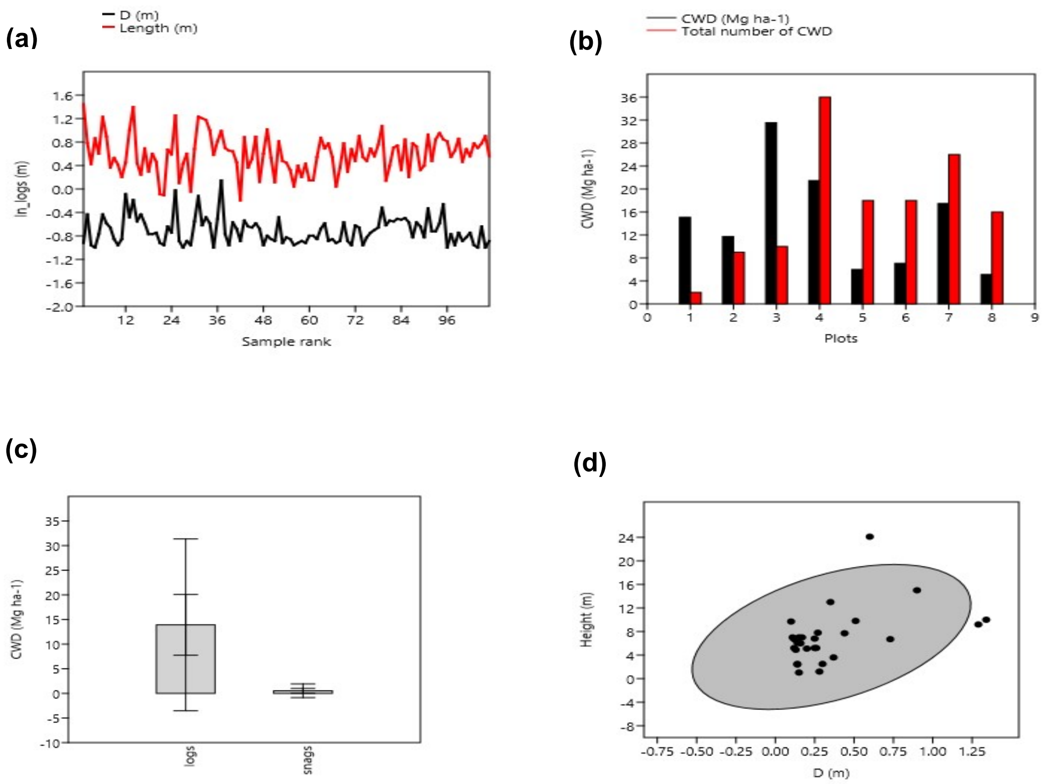

Figure 3. Diameter-Length Relationship of Fallen Dead Trees and Branches in Study Area (a). Distribution of Coarse Woody Debris Storage (CWD; in Mg ha^{-1}) by Plot in Ipendja Forest (b). Variation between Standing Dead Trees Mass (Snags; in Mg ha^{-1}) and Fallen Dead Trees and Branches Mass (logs; in Mg ha^{-1}) with Graph Type Performed as Whisker Length of 95% Interval, Whisker Type: Standard Error, Standard Deviation, and Framein Dtudied Plots (c). Relationship between Diameter-Height of Standing Dead Trees (snags; in Mg ha^{-1}), and Graph Performed with 95% Ellipses, Frame and Filled Regions (d)

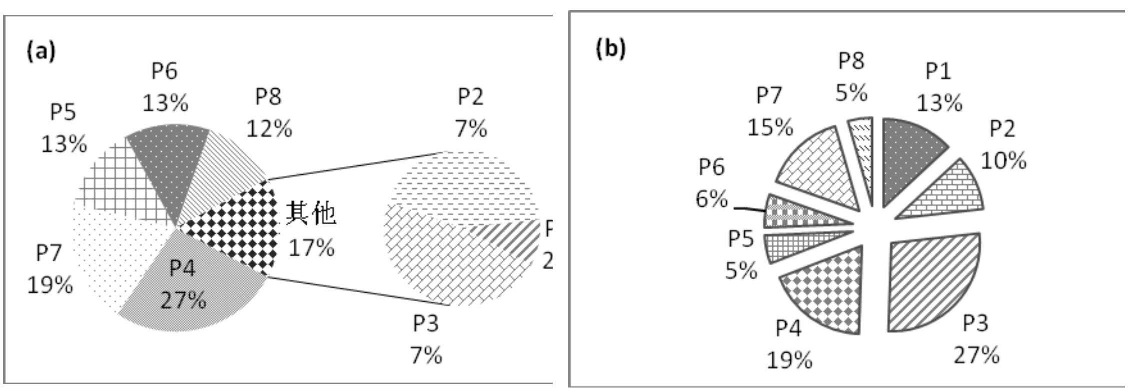

Figure 4. Relative Frequency of Coarse Woody Debris Samples Measured per Plot in Ipendja Forest (a). Relative Frequency of Coarse Woody Debris Storage by Plot in Study Area (b)

4. Discussion

Any Coarse Woody Debris (CWD) that did not allowed the taking into account of these measurement conditions wasn't measured. In this study, we used a 200 m transect line per study plot, which has not been the case in other studies in tropical Africa (Baker et al., 2007; Carlson, 2013; Bocko et al., 2017; Ifo et al., 2017). Baker et al. (2007), Bocko et al. (2017), Ifo et al. (2017) and Carlson (2013) used 400 m, 100 m, 100 m and 800 m transect lines per study plot, respectively, in southern Peru, Congo, Congo and Gabon. Their results showed that the stocks of coarse woody debris increase also with the length of transect line studied. It was obvious that the number of coarse woody debris recorded in Sombo were higher than those of Mokelimwaekili by the fact that Sombo site is a selective logging forest (Logging performed in Ipendja forest management unit from 2002 to 2003 by one stem per hectare), while Mokelimwaekili is an old-growth forest. During inventorying period there are observation highlight of wind break in Sombo site and that forest is in regeneration period. Ifo et al. (2017) mentioned that most of Republic of Congo's primary forests have the wind break phenomenon.

Several factors could explain the changes in coarse woody debris stocks in the study area: forest type, age, structure and dynamics of the studied forests (Baker et al., 2004). Apart from these factors, we can also mention the meteorological phenomenon (hurricanes, storms), but also the natural phenomena of wind break. Meteorological parameters' action has been noted by several other authors among which Keller et al. (2004), Pfeifer et al. (2015) and Ifo et al. (2017). They asserted that among the factors that contribute to the production of coarse woody debris stocks but also to their accumulation on forest soils, there is the action of storms.

De Vries (1986) derived the theoretical variance of the estimation. In this respect there is a subtle difference between Buffon's needle problem and LIS. In the former, needles are independently cast at random onto a lined area. Thus the probability of an intersection for any one needle is independent of the probability of an intersection of any other needle. In LIS, however, it is the needles that are fixed and a line placed at random. Knowledge that a certain needle has been intersected then affects the probability of intersection of the remainder. This introduces a covariance term that cannot, in general, be specified exactly although, given the scale of logging residue applications, this component is almost certainly negligible. A second approximation is introduced by taking $p(1-p) = p$ since p is small. It often appears to be overlooked that Warren and Olsen (1964) derived an expression for the coefficient of variation of V which, when transformed, is equivalent to the expression for the variance given by De Vries (1986). These expressions for the variance involve, of course, the unknown population values. In practice the precision is estimated through the variance of the volume estimates generated by more than one sampling line.

Worldwide, forests have absorbed around 30% of global anthropogenic emissions of carbon dioxide (CO_2) annually, thereby acting as important carbon sinks (Magnusson et al., 2016). It is proposed that leaving large fragments of dead wood, Coarse Woody Debris (CWD), in forest ecosystems may contribute to the forest carbon sink strength (Magnusson et al., 2016). Coarse Woody Debris (CWD) may take years to centuries to degrade completely, and non-respired carbon from CWD may enter the forest soil directly or in the form of dissolved organic Carbon. Although aboveground decomposition of Coarse Woody Debris (CWD) has been studied frequently, little is known about the relative size, composition and fate of different Carbon fluxes from Coarse Woody Debris (CWD) to soils under various substrate-specific and environmental conditions. Thus, the exact contribution of carbon from Coarse Woody Debris (CWD) to carbon sequestration within forest soils is poorly understood and quantified, although understanding CWD degradation and stabilization processes is essential for effective forest carbon sink management. Magnusson et al. (2016) provided insight into these processes on the interface of forest ecology and soil science, and identify knowledge gaps that are critical to understanding of the effects of CWD on the forest soil carbon sink. It may be seen as a "call-to-action" crossing disciplinary boundaries, which proposes the use of compound-specific analytical studies and manipulation studies to elucidate carbon fluxes from Coarse Woody Debris (CWD). Carbon fluxes from decaying Coarse Woody Debris (CWD) can vary considerably due to interspecific and intraspecific differences in composition and different environmental conditions. These variations in carbon from Coarse Woody Debris (CWD) need to be studied in detail and related to recent advances in soil carbon sequestration research.

5. Conclusion

Endogenous factors (aging of the forest ecosystem) or external factors such as the action of very strong winds could explain the differences observed in the two forest types (old-growth and selective logging forests) of Ipendja lowland evergreen terra firme tropical forest. This study also showed that Coarse Woody Debris (CWD) compartment should be taken into account in quantifying tropical forest ecosystems' carbon stocks. This study indicates that carbon storage and emissions in selective logging forests may be markedly different to those in primary forests (old-growth forests). The averages of the coarse woody debris stocks vary clearly between the two characteristics types of studied forest in Ipendja UFA, and also between the standing dead trees stocks and the fallen dead trees and branches stocks. Coarse woody debris stocks increased from old-growth forest to selective logging forest in Ipendja evergreen terra firme lowland forest. This research basically studies the different reference values represent the variability of Coarse Woody Debris (CWD) among forest types which will contribute to reducing uncertainties in current estimates of carbon stocks in central African forest ecosystems. The structural parameters and sampling methods best explain the differences in carbon stocks noted between the two types of studied forests and those found in the literature.

Conflicts of Interest

The authors declare no conflict of interest regarding this paper.

Additional information

Supplementary material related to this paper is available online at: http://www.scholink.org/ojs/index.php/se

Acknowledgements

The authors would like to thank China Scholarship Council (see www.csc.edu.cn) and Beijing Forestry University (see www.bjfu.edu.cn) for supporting this work. This study was also supported by the National Key Research and Development Project of China (2017YFD0600106). We greatly thank Seraphin Bikoumou, Martial Fomekong Tsakeu, Ghislain Teufack Sonna, Meroli Bokouaye, Freddy Iyoki, Wilfrid Bandakoulou, Roger Bassoukaka, Hermann, Jean and Benoit from Thanry-Congo logging company (STC) for them technical assistance during forest inventory data period at Ipendja forest management unit (UFA). Our warm thanks are to Republic of Congo's Ministry of Forest Economy and Sustainable Development, CN-REDD, and Thanry-Congo logging company (STC, Vic-wood Group) for providing facilities about field measurements in Ipendja forest (Likouala Department, northern Republic of Congo). Thanks are extended to Georges Claver Boundzanga from Republic of Congo's Ministry of Forest Economy and Sustainable Development for his valuable contribution regarding this study. It is a pleasure to thank Thechel Ekoungoulou from Food and Agriculture Organization of the United Nations (FAO) for his contribution about this work. Different anonymous referees have provided substantial contribution and the authors address to them their heartfelt thanks.

References

ANAC. (2016). *Annual Report on Republic of Congo's Meteorological National Situation*. National Agency of Congo's Civil Aviation. Brazzaville, Congo (In French).

Baker, T. R., & Chao, K. J. (2011). *Manual for coarse woody debris measurement in RAINFOR plots*. Amazon forest inventory network. Leeds, UK.

Baker, T. R., Coronado, E. N. H., Phillips, O. L., Martin, J., Van der Heijden, G. M. F., Garcia, M., & Espejo, J. S. (2007). Low stocks of coarse woody debris in a south-west Amazonian forest. *Oecologia*, *152*, 495-504. https://doi.org/10.1007/s00442-007-0667-5

Baker, T. R., Phillips, O. L., Malhi, Y., Almeida, S., Arroyo, L., Di Fiore, A., … Vasquez, R. (2004). Variation in Wood Density Determines Spatial Patterns in Amazonian Forest Biomass. *Global Change Biology*, *10*, 545-562. https://doi.org/10.1111/j.1365-2486.2004.00751.x

Basuki, T. M., van Laake, P. E., Skidmore, A. K., & Hussin, Y. A. (2009). Allometric equations for estimating the above-ground biomass in tropical lowland Dipterocarp forests. *Forest Ecology and Management*, *257*, 1684-1694. https://doi.org/10.1016/j.foreco.2009.01.027

Bellassen, V., & Luyssaert, S. (2014). Carbon sequestration: Managing forests in uncertain times. *Nature*, *506*(7487), 153-155. https://doi.org/10.1038/506153a

Bocko, Y. E., Ifo, S. A., & Loumeto, J. J. (2017). Quantification des stocks de carbone de trois pools clés de carbone en Afrique centrale: Cas de la Forestmarécageuse de la Likouala (Nord Congo). *European Scientific Journal*, *13*(5), 438-456. https://doi.org/10.19044/esj.2017.v13n5p438

Brovkin, V., Van Bodegom, P. M., Kleinen, T., Wirth, C., Cornwell, W. K., Cornelissen, J. H. C., & Kattge, J. (2012). Plant-driven variation in decomposition rates improves projections of global litter stock distribution. *Biogeosciences*, *9*(1), 565-576. https://doi.org/10.5194/bg-9-565-2012

Brown, S. (1997). *Estimating Biomass and Biomass Change of Tropical Forests: A Primer*. FAO Forestry Paper 134. Food and Agriculture Organization of the United Nations, Rome, Italy.

Cairns, A. M., Brown, S., Helmer, H. E., & Baumgardner, A. G. (1997). Root biomass allocation in the world's upland forests. *Oecologia*, *111*, 1-11. https://doi.org/10.5194/bg-9-565-2012

Carlson, B. (2013). *Gabon's Overlooked Carbon*. A tropical forest of coarse woody debris. Master: Environmental Management degree, Duke University, USA.

Chambers, J. Q., Higuchi, N., Schimel, J. P., Ferreira, L. V., & Melack, J. M. (2000). Decomposition and carbon cycling of dead trees in tropical forests of Central Amazon. *Oecologia*, *122*, 380-388. https://doi.org/10.1007/s004420050044

Chao, K. J., Phillips, O. L., & Baker, T. R. (2008). Wood density and stocks of coarse woody debris in a northwestern Amazonian landscape. *Canadian Journal of Forest Research*, *38*, 795-805. https://doi.org/10.1139/X07-163

Cornelissen, J. H. C., Sass-Klaassen, U., Poorter, L., Cretin, V., Martin, R., Den Ouden, J., … Hefting, M. M. (2012). Controls on coarse wood decay in temperate tree species: Birth of the LOGLIFE experiment. *Ambio: A Journal of the Human Environment*, *41*(3), 231-245. https://doi.org/10.1007/s13280-012-0304-3

Cornwell, W. K., Cornelissen, J. H. C., Allison, S. D., Bauhus, J., Eggleton, P., Preston, C. M., … Zanne, A. E. (2009). Plant traits and wood fates across the globe: Rotted, burned, or consumed? *Global Change Biology*, *15*(10), 2431-2449. https://doi.org/10.1111/j.1365-2486.2009.01916.x

De Vries, P. G. (1986). *Sampling Theory for Forest Inventory*. A Teach-yourself Course. Springer, Berlin, Germany. https://doi.org/10.1007/978-3-642-71581-5

Ekoungoulou, R. (2014). *Carbon Stocks Evaluation in Tropical Forest, Congo*. Carbon Stocks in Forest Ecosystems. Lambert Academic Publishing, Saarbrucken, Germany.

Ekoungoulou, R., Folega, F., Mukete, B., Ifo, S. A., Loumeto, J. J., Liu, X. D., & Niu, S. K. (2018a). Assessing the effectiveness of protected areas on floristic diversity in tropical forests. *Applied Ecology and Environmental Research*, *16*(1), 837-853. https://doi.org/10.15666/aeer/1601_837853

Ekoungoulou, R., Liu, X. D., Ifo, S. A., Loumeto, J. J., & Folega, F. (2014a). Carbon stock estimation in secondary forest and gallery forest of Congo using allometric equations. *International Journal of Scientific and Technology Research*, *3*(3), 465-474.

Ekoungoulou, R., Liu, X. D., Loumeto, J. J., & Ifo, S. A. (2014b). Tree Above-And Below-Ground Biomass Allometries for Carbon Stocks Estimation in Secondary Forest of Congo. *Journal of Environmental Science, Toxicology and Food Technology*, *8*(4), 09-20.

Ekoungoulou, R., Liu, X. D., Loumeto, J. J., Ifo, S., Bocko, Y. E., Koula, F. E., & Niu, S. K. (2014c). Tree Allometry in Tropical Forest of Congo for Carbon Stocks Estimation in Above-Ground Biomass. *Open Journal of Forestry*, *4*(5), 481-491. https://doi.org/10.4236/ojf.2014.45052

Ekoungoulou, R., Niu, S. K., Loumeto, J. J., Ifo, S. A., Bocko, Y. E., Mikieleko, F. E. K., … Liu, X. D. (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.

Ekoungoulou, R., Nzala, D., Liu, X. D., & Niu, S. K. (2017). Ecological and structural analyses of trees in an evergreen lowland Congo basin forest. *International Journal of Biology*, *10*(1), 31-43. https://doi.org/10.5539/ijb.v10n1p31

Ekoungoulou, R., Nzala, D., Liu, X. D., & Niu, S. K. (2018b). Tree biomass estimation in central African forests using allometric models. *Open Journal of Ecology*, *8*(3), 209-237. https://doi.org/10.4236/oje.2018.83014

Gough, C. M., Vogel, C. S., Kazanski, C., Nagel, L., Flower, C. E., & Curtis, P. S., (2007). Coarse woody debris and the carbon balance of a north temperate forest. *Forest Ecology and Management*, *244*, 60-67. https://doi.org/10.1016/j.foreco.2007.03.039

Grove, S. J. (2002). Saproxylic insect ecology and the sustainable management of forests. *Annual Review of Ecology and Systematics*, *33*, 1-23. https://doi.org/10.1146/annurev.ecolsys.33.010802.150507

Hafner, S. D., Groffman, P. M., & Mitchell, M. J., (2005). Leaching of dissolved organic carbon, dissolved organic nitrogen, and other solutes from coarse woody debris and litter in a mixed forest in New York state. *Biogeochemistry*, *74*(2), 257-282. https://doi.org/10.1007/s10533-004-4722-6

Hammer, O., Harper, D. A. T., & Ryan, P. D. (2001). PAST: Paleontological Statistics Software Package for Education and Data Analysis. *Palaeontologia Electronica*, *4*, 1-9.

Harmon, M. E., & Sexton, J. (1996). *Guidelines for Measurements of Woody Detritus in Forest Ecosystems* (Vol. 20). US LTER Network Office, Seattle (WA), USA.

Harmon, M. E., Franklin, J. F., Swanson, F. J., Sollins, P., Gregory, S., Lattin, J., … Cummins, K. W. (1986). Ecology of coarse woody debris in temperate ecosystems. *Advances in Ecological Research*, *15*, 133-302. https://doi.org/10.1016/S0065-2504(08)60121-X

Ifo, S. A., Mbemba, M., Koubouana, F., & Binsangou, S. (2017). Stock de carbone dans les gros débris ligneux végétaux: Cas des forêts tropicales pluvieuses de la Likouala, République du Congo. *European Scientific Journal*, *13*(12), 384-399. https://doi.org/10.19044/esj.2017.v13n12p384

Kahl, T., Baber, K., Otto, P., Wirth, C., & Bauhus, J. (2015). Drivers of CO_2 emission rates from dead wood logs of 13 tree species in the initial decomposition phase. *Forests*, *6*(7), 2484-2504. https://doi.org/10.3390/f6072484

Keller, M., Palace, M., Asner, P. G., Pereira-Jr., R., & Silva, M. N. J. (2004). Coarse woody debris in undisturbed and logged forests in the eastern Brazilian Amazon. *Global Change Biology*, *10*(5), 784-792. https://doi.org/10.1111/j.1529-8817.2003.00770.x

Kueppers, L. M., Southon, J., Baer, P., & Harte, J., (2004). Dead wood biomass and turnover time, measured by radiocarbon, along a subalpine elevation gradient. *Oecologia*, *141*(4), 641-651. https://doi.org/10.1007/s00442-004-1689-x

Lopez-Gonzalez, G., Lewis, S. L., Burkitt, M., & Phillips, O. L. (2011). ForestPlots.net: A web application and research tool to manage and analyse tropical forest plot data. *Journal of Vegetation Science*, *22*, 610-613. https://doi.org/10.1111/j.1654-1103.2011.01312.x

Luyssaert, S., Inglima, I., Jung, M., Richardson, A., Reichstein, M., Papale, D., … Janssens, I. A. (2007). CO_2 balance of boreal, temperate, and tropical forests derived from a global database. *Global Change Biology*, *13*(12), 2509-2537. https://doi.org/10.1111/j.1365-2486.2007.01439.x

Magnusson, R. I., Tietema, A., Cornelissen, J. H. C., Hefting, M. M., & Kalbitz, K. (2016). Tamm Review: Sequestration of carbon from coarse woody debris in forest soils. *Forest Ecology and Management*, *377*, 1-15. https://doi.org/10.1016/j.foreco.2016.06.033

McFee, W. W., & Stone, E. L. (1966). The persistence of decaying wood in the humus layers of northern forests. *Soil Science Society of America Proceedings*, *30*(4), 513-516. https://doi.org/10.2136/sssaj1966.03615995003000040032x

Moroni, M. T., Morris, D. M., Shaw, C., Stokland, J. N., Harmon, M. E., Fenton, N. J., … Hagemann, U. (2015). Buried wood: A common yet poorly documented form of deadwood. *Ecosystems*, *18*(4), 605-628. https://doi.org/10.1007/s10021-015-9850-4

Mund, M. (2004). *Carbon Pools of European beech forests (Fagus sylvatica) under different silvicultural management*. Thesis. Der Georg-August University, Gottingen, Germany.

Naudts, K., Chen, Y., McGrath, M. J., Ryder, J., Valade, A., Otto, J., & Luyssaert, S. (2016). Europe's forest management did not mitigate climate warming. *Science*, *351*(6273), 597-600. https://doi.org/10.1126/science.aad7270

Nave, L. E., Vance, E. D., Swanston, C. W., & Curtis, P. S. (2010). Harvest impacts on soil carbon storage in temperate forests. *Forest Ecology and Management*, *259*, 857-866. https://doi.org/10.1016/j.foreco.2009.12.009

Ohtsuka, T., Shizu, Y., Hirota, M., Yashiro, Y., Shugang, J., Iimura, Y., & Koizumi, H. (2014). Role of coarse woody debris in the carbon cycle of Takayama forest, Central Japan. *Ecological Research*, *29*(1), 91-101. https://doi.org/10.1007/s11284-013-1102-5

Osone, Y., Toma, T., Warsudi., Sutedjo, & Sato, T. (2016). High stocks of coarse woody debris in a tropical rainforest, East Kalimantan: Coupled impact of forest fires and selective logging. *Forest Ecology and Management*, *374*, 93-101. https://doi.org/10.1016/j.foreco.2016.04.027

Palace, M., Keller, M., Hurtt, G., & Frolking, S. (2012). A review of above ground necromass in tropical forests. In P. Sudarshana, M. Nageswara-Rao, & J. R. Soneji (Eds.), *Tropical*. InTech, Rijeka, Croatia. https://doi.org/10.1016/j.foreco.2016.04.027

Palviainen, M., & Finer, L., (2015). Decomposition and nutrient release from Norway spruce coarse roots and stumps—A 40-year chronosequence study. *Forest Ecology and Management*, *358*, 1-11.

https://doi.org/10.1016/j.foreco.2015.08.036

Pearson, T., & Brown, S. (2005). Guide de mesure et de suivi du carbone dans les forêts et prairies herbeuses. *Winrock international*. Arlington, VA, USA.

Pedlar, J. H., Pearce, J. L., Venier, L. A., & McKenney, D. W. (2002). Coarse woody debris in relation to disturbance and forest type in boreal Canada. *Forest Ecology and Management*, *158*, 189-194. https://doi.org/10.1016/S0378-1127(00)00711-8

Pfeifer, M., Lefebvre, V., Turner, E., Cusack, J., Khoo, M. S., & Ewers, M. R. (2015). Deadwood biomass: An underestimated carbon stock in degraded tropical forests? *Environmental Research letters*, *10*, 044019. https://doi.org/10.1088/1748-9326/10/4/044019

Pregitzer, K. S., & Euskirchen, E. S. (2004). Carbon cycling and storage in world forests: Biome partterns related to forest age. *Global Change Biology*, *10*, 2052-2077. https://doi.org/10.1111/j.1365-2486.2004.00866.x

Rice, A. H., Pyle, E. H., Saleska, S. R., Hutyra, L., Palace, M., Keller, M., … Wofsy, S. C. (2004). Carbon balance and vegetation dynamics in an old-growth Amazonian forest. *Ecological Applications*, *14*, 555-571. https://doi.org/10.1890/02-6006

Russell, M. B., Fraver, S., Aakala, T., Gove, J. H., Woodall, C. W., D'Amato, A. W., & Ducey, M. J. (2015). Quantifying carbon stores and decomposition in dead wood: A review. *Forest Ecology and Management*, *350*, 107-128. https://doi.org/10.1016/j.foreco.2015.04.033

Schulze, E., Wirth, C., & Heimann, M. (2000). Managing forests after Kyoto. *Science*, *289*(5487), 2058-2059. https://doi.org/10.1126/science.289.5487.2058

STC. (2016). *Annual Report of Thanry-Congo Logging Company*. Vic-wood Group. Ipendja, Republic of Congo (In French).

Triska, F. J., & Cromack Jr., K. (1980). *The role of wood debris in forests and streams*. Forests: Fresh Perspectives from Ecosystem Analysis. Oregon State University Press, Corvallis, Oregon, USA.

Walker, S., Pearson, T., Harris, N., Sean, G., Silvia, P., Felipe, C., & Sandra, B. (2011). Procédures Opérationnelles Standards pour la Mesure du Carbone Terrestre. In *Winrock international*. Arlington, VA, USA.

Warren, W. G., & Olsen, P. F. (1964). A line intersects technique for assessing logging waste. *Forest Science*, *10*(3), 267-276.

Wiebe, S. A., Morris, D. M., Luckai, N. J., & Reid, D. E. (2014). The influence of coarse woody debris on soil carbon and nutrient pools 15 years after clearcut harvesting in black spruce-dominated stands in northwestern Ontario, Canada. *Ecoscience*, *21*(1), 11-20. https://doi.org/10.2980/21-1-3647

Woodall, C. W., & Liknes, G. C. (2008). Relationships between forest fine and coarse woody debris carbon stocks across latitudinal gradients in the United States as an indicator of climate change effects. *Ecological indicators*, *8*(5), 686-690. https://doi.org/10.1016/j.ecolind.2007.11.002