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Above-ground biomass and nutrient accumulation in the tropical rainforests of southern Cameroon: effects of logging

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ABSTRACT
Impact of logging activities on nutrient cycling in tropical rainforests of southern Cameroon has been little investigated. A study was initiated by the Tropenbos-Cameroon Programme to determine changes in above-ground phytomass and nutrient stock following selective logging in Ebom rainforest of Southern Cameroon. One hundred and twelve (112) trees were sampled in three undisturbed plots of 10m x10m. Their diameters and dry mass were determined. Allometric equations ($Y = a + b*D + c*D^2$ and $Y = a'*D^{b'}$), relating dry mass of foliage, branches, trunks with barks, and total biomass to diameter at breast height (DBH), were developed to estimate the above-ground tree biomass of undisturbed and disturbed forests. Understorey biomass was estimated by harvesting method. The total above-ground tree biomass is about 583 $t.ha^{-1}$dry mass in the undisturbed forest. This contains 302 $t.ha^{-1}$ C and a nutrient capital of 8888 $kg.ha^{-1}$N, 6953 Ca, 2337 K, 436 P, 311 Mg and 30 kg. ha^{-1} Na. The stores of nutrient in the above-ground biomass was about 2 (311 and 175 kg ha^{-1}) to 16 (436 and 28 kg. ha^{-1}) times higher than in the top soil stock, respectively for Mg and available P. The losses of carbon and nutrients associated with timber extraction represented less than 7% of store in the above-ground biomass for all nutrients. This means that the impact of logging in the Ebom rainforest remains low. However, additional research is needed on nutrient input in the forest from outside as well as on the impact of logging on nutrient leaching in order to get a complete picture of the nutrient cycles.
Key-words: phytomass, nutrient pools, logging, allometric equations, tropical rainforest, Southern Cameroon.

INTRODUCTION

Information on tropical rainforests showed that the substrates on which they grow are often nutrient-poor as a result of intensive weathering and leaching over long periods [1]. Most of the nutrients are stored in the above-ground biomass [2]. These ideas led naturally to the concept of a "typical" tropical rainforest as compared to a "typical" temperate forest [3]. The earlier results, particularly the extent and fragility of these very poor soils may have been overgeneralized [4]. In fact, review of recent research on patterns of mineral storage and cycling in rainforests [5] and [6] and of important components such as phytomass [7] clearly show that rainforests vary from place to place. Some of them occur on fertile soils with a high proportion of the nutrients below-ground [5]. This suggest firstly that the nutrient cycling varies according to the type of forest, particularly their soil types and, secondly, that their management is not a single problem with a single solution, but varies according to a given type [4].

Plant biomass is fundamental to a nutrient cycling study. It represents stored organic matter in the ecosystem and it specifies the numerical value of the ecosystem components. According to Rodin and Bazilevich [8], the nutrients in vegetation make up about four percent of the dry weight biomass. While this quantity of mineral is quite small, it is essential for the proper functioning of the system, and a lack of adequate minerals can limit growth and development of the forest even if other limiting factors are available in excess.

Loss of nutrients from forest is among others caused by logging and leaching [9]. Logging alters nutrient pools and fluxes by nutrient export from the system and increases leaching after a sudden addition of fresh litter onto the forest floor, which decompose and release nutrients. Brouwer [9] has shown that under logging the leaching of Ca, K and Mg were 2 to 10 times higher and that of N was 8 to 17 times higher than in undisturbed forest. Nutrient removal from the forest due to enhanced losses through leaching has a particularly large impact on forests growing on poor soils [10]. Selective logging has been classified as a disturbance of low to moderate intensity [11]. Nevertheless there is much variation in the intensity of selective logging, depending on the proportion of trees that are extracted commercially. Its effects on nutrient losses vary according to this intensity and its duration [12]. In fact, in the Tropical forest of Guyana where the proportion of commercial trees is general low and the average exploitation intensity rarely exceeds 50 m^3 ha^{-1}, the leaching loss for the major cations and N over the first two years after logging increased to about 700-2700% compared to the closed forest [9].

The amount of forested area's in Cameroon is estimated at 21 Mha, of which about 17.5 Mha are identified as productive forests [13]. Forest logging has increased over the last three decennia, probably as the consequence of CFA Franc devaluation [14], increasing from 1 Mm^3 in the 1970's to about 2.5 Mm^3 in 2004 (Foahom and Schmidt, Com. Pers.).

So, as a remedy to the negative impact of logging to biological diversity, the Cameroonian government with the aid of donors strive through research programmes like the Tropenbos Cameroon Programme to develop sustainable management methods and strategies of these forests. This should not only protect the biodiversity but also ensures a sustainable production of the goods and services of these forests at a socially, economically as well as ecologically acceptable level [15]. The sustainable management of rainforest like that of Cameroon requires, without overlooking the interests of the local inhabitants, knowledge of its structure and functioning, such as phytomass and nutrient cycling.

The objective of the present study was to assess above-ground phytomass, carbon and nutrient capital of the natural forest in southern Cameroon, and the effects of timber harvesting on phytomass and nutrient changes are also discussed. This study was carried out within the framework of the Tropenbos Cameroon Programme (TCP).

MATERIAL AND METHODS

Study site and selection of plots

The TCP study site is located in the western part of south Cameroon, between 2° 47'-3° 14' N and 10° 24'-10° 51' E. This part of forests covers an area of about 2000 km^2 and is bordered by the villages of Lolodorf, Akom II and Bipindi (Figure 1). The bed rock is composed of Precambrian metamorphic as well as old volcanic rocks [16]. The soil between 50 and 350 m a.s.l. is a mixture of sand and clay (<25%) and moderately acidic, between 350 and 500 m a.s.l., it is very clayey (35-70%) and strongly acidic [17]. The climate is humid tropical with four seasons: a long (from mid-November to mid-March) and a short dry season (mid-May to mid-August), and a short (mid-March to mid-May) and a long rainy season (mid-August to mid-November). Rainfall decreases progressively from the west to the east of the study area with an annual average of 2836 mm at Kribi, 2096 mm at Lolodorf and 1719 mm at Ebolowa [18]. Annual average temperature ranges from 26.4°C, 24.6 and 24.0°C respectively for the same localities [19].

The vegetation is classified as Biafran Atlantic rainforest, rich in Caesalpiniaceae [20]. The western and central portion of this area with an altitude of slightly less than 700 m a.s.l. are covered with an evergreen forest characterised by tall trees that reach heights of about 60 m; the Eastern part is mountainous and covered by a submontane forest, with a canopy that varies between 15 and 20 m high [17]. The forest has been logged at least twice in the decennia before this study, especially in the Eastern part, with the exception of the mountainous parts. Exploited species are *Lophira alata*, *Erythrophleum ivorensis* and *Pterocarpus soyauxii.* The logging rate was low, averaging 10 m^3. ha^{-1} or about 0.7 tree ha^{-1} [17]. Only trees with DBH ≥ 80 cm and straight boles of at least six meters were felled. Damages caused by this felling and extraction of the logs from the stand affected less than 8% of the forest area [21]. At some places in the forest Bantou people practice shifting agriculture with short fallows [22] while Banyeli Pygmee live from gathering and hunting. Many non timber forest products are harvested [23].

Two one-ha-plots (100*100 m) in the catchments of Bibo'o Minwo (3° 04' N and 10° 40' E) near Ebom were selected, one in undisturbed forest characterized by the absence of recent natural disturbance as well as by the presence of numerous species; the second plot, situated roughly in the same forest with the same type of soil was disturbed six years ago by low intensity logging and characterized by the presence of small gaps and numerous heliophilous species as *Musanga cecropioides*. This plot was logged once before this study. Relevant characteristics of the plots are presented in Table 1. In both plots all trees with a DBH ≥ 1cm were recorded.

Total above-ground tree biomass

The biomass data was obtained from destructive 112 trees collected in 2000 during the main dry season in three sample plots of 10 m x 10 m. Before felling, the species name of the tree was identified, the diameter at breast height (DBH) measured. All trees less than 50 cm in the sample plot were felled. Trees above 50 cm were not felled except one (DBH 79 cm) because of some perturbations like long presence of ants on many target trees and the rainy season started earlier. Trees were felled at ground level with machete or chainsaw according to tree size. The branches, twigs and leaves were separated from the trunk per tree. The sawdust was also collected, weighted and added to the value of branches and trunk. Each category per tree was put in a tarpaulin of 2m x 2m which was folded and attached to a weighting scale of 100 kg, weighted and added to obtain the total fresh mass of a category and also of a tree. Sub-samples of each part were collected, weighted fresh in the field with an electronic balance of 3 kg, and brought to the laboratory, oven dried at 60 °C to obtain the moisture content. The moisture content (MC) of the sample enables to deduce the MC in each category of the tree. It was then possible to obtain the dry mass of each category of a tree using this formula: dry mass = fresh mass – moisture content.

The DBH values per tree and dry weights of the components collected in the three plots were used to develop regression equations for tree biomass. Several models were tested with the aid of the *Graph Pad* computer programme (*Inplot, Inc. 1992, version 4.04*). Firstly, the outliers were removed on scatterplots of residuals versus DBH to reduce the patterns of error variance introduced by larger trees [25]. Only two non-linear models gave good correlation coefficients and low error margins and bias (with variations around the curve), one for the leaves and the other for the branches and stemwood. The following two allometric equations were found valid:

$$Y = a + b*D + c*D^2 \quad (1)$$

$$Y = a'*D^{b'} \quad (2)$$

Where Y is the dry mass (kg) of the components of the trees; D the DBH of each tree (cm); a, b, c, a' and b' are the model parameters to be fitted for each of the components of phytomass.

These above equations were used to estimate the total tree phytomass in the two one-ha-plots (undisturbed and disturbed forests) having the same type of soil.

Understorey biomass

To estimate the understorey biomass, all herbs and trees with DBH < 1 cm were harvested in five subplots of 1 m^2, within each main plot, according to the method used by Kotto-Same *et al.* [26] and Woomer and Palm [24]. All understorey plants were cut at ground level and separated into leaves and woody parts for further analyses. Plant parts, originating within the sub-plot but falling outside of it were also collected and those originating outside of the sub-plot but falling inside of it were rejected.

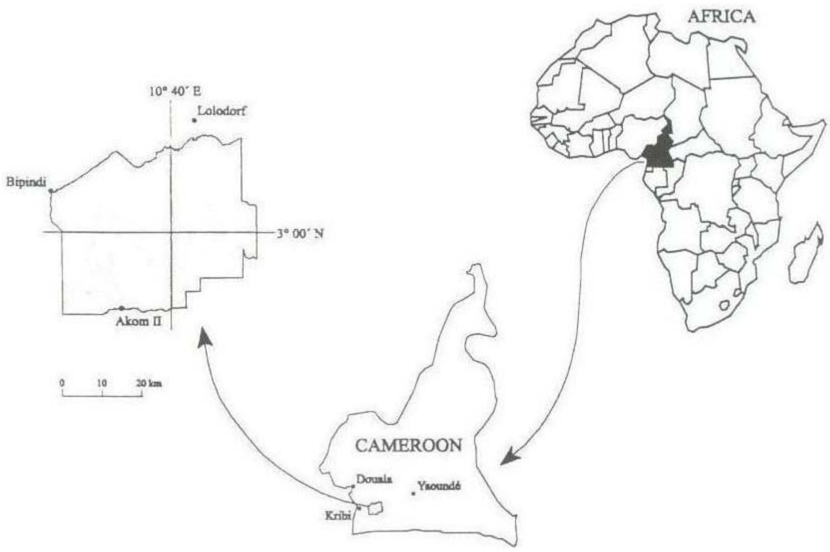

Figure 1: Location of Tropenbos research area in Southwest Cameroon [17].

Table 1: Characteristics of the Ebom rain forest*.

Locality	Ebom forest
Location	3°05'N, 10°41'E
Elevation (m a.s.l.)	440
Rainfall (mm)*	2115.3
Relief intensity (m)	moderate (30-80)
River density	moderate
Vegetation	lowland forest
Soil types	Ultisols/Oxisols (infertile)
Clay (topsoil, 0-10 cm) (%)	20-50 (clayey)
sandy (%)	40-60
pH (water)***	4.7
Carbon (%)***	4-8
Nitrogen (%)***	0.25-0.50.18
C/N	10
Available P (ppm)	12-26
Total P (ppm)***	150-400
K (meq/100g of soil)***	0.1-0.9
Mg (meq/100g of soil)***	0.4-1.6
Ca (meq/100g of soil)***	0.5-4
Al (meq/100g of soil)***	0.5-6

* Source: van Gemerden and Hazeu (1999).
** Annual mean of rainfall collected from 1996 to 2000.
*** topsoil (0-10 cm depth).

Chemical analysis

It was impossible to analyse all samples from all trees and understorey. Hence, in each main plot four sub-samples of each category of tree biomass (leaves, branches, stem wood) and from the five subplots three sub-samples of each category were chose. In total sixty six (66) sub-samples (4 sub-samples x 3 categories x 3 plots of trees + 3 sub-samples x 2 categories x 5 plots of understorey) were analysed. Moreover, for disturbed forest, the plant samples were not analysed because we assumed that this forest is similar to the undisturbed one. Powder samples obtained after grinding all sub-samples through a *Micro Hammer Mill Culatti* grinder equipped with a 1 mm link filter were analysed. The samples were first mineralised by passing the powder through a furnace at 550°C for 40 mn. The ashes were recollected with a diluted HNO3 solution for chemical analyses. Calcium (Ca) and Magnesium (Mg) were determined by atomic absorption spectrophotometer; Potassium (K) and Sodium (Na) by flame spectrophotometer; Phosphorous (P) by vanado - molybdate colorimeter. The nitrogen (N) analysis was done by the Kjeldhal method and its titration by sulphuric acid at 0.01N. Carbon content was detected by oxidation with dichromate after digestion in the presence of oxygenated water.

RESULTS

Structure of the forests

Tree density and basal area in undisturbed forest are with 521 trees per ha and 30 m^2. ha^{-1} (Table 2) higher than in the disturbed plots (417 trees per ha and 28 $m^2.ha^{-1}$). The average diameter, however, is slightly higher in the disturbed plot (23 cm) than in the undisturbed ones (21 cm). This is because there are many trees with DBH 50 to 60 cm in the former. The form of diameter-class distribution of the trees in both plots is similar to the inverted 'J' form (Figure 2). Tree density per diameter-class is generally lower in the disturbed than undisturbed plot, with the exception of the 50 to 60 cm diameter-class and that with a diameter of more than 105 cm

Table 2: Structures of undisturbed and disturbed forests of Ebom.

Structure	Undisturbed plot	Disturbed plot
Density (trees/ha)	521	417
Basal area (m^2/ha)	29.84	28.48
DBH mean (cm)*	21.34	22.91
DBH range (cm)	9.39 – 150	9.20 – 141.72

* Calculated as $\sum$(DBH)/n

Regression equations and standing biomass

In total 112 trees from more than 40 species, with DBHs ranging from 1 to 80 cm were harvested, the majority of DBHs being less than 30 cm. Several phytomass prediction equations were developed. Two were retained as their coefficients of determination were highly significant ($R^2 > 0.97$) and their standard errors estimated low (SEE < 0.02). The total biomass of trees and that of branches and trunks were well fitted to the non linear model, $Y = a'*D^{b'}$, while that of the leaves fitted better to the non linear model, $Y = a + b*D + c*D^2$ (Figure 3, Table 3). Generally, the more trees were added to the models, the more the determining coefficients increased and the more the standard errors estimated decreased (Figure 3).

The tree biomass and that of the understorey were different for the undisturbed and disturbed plots (Table 4). The total phytomass, as well as those of the components (leaves, branches and stemwoods) of the trees were higher in the undisturbed than disturbed plot. The difference between the total phytomass estimated by allometric models (581 and 540 t. ha^{-1}) and the sum of the tree components (582 and 541 t. ha^{-1}) was very small for the two forests. Leaves and branches represented respectively about 0.3 % and 9% of the total tree biomass. Conversely, the understorey biomass in disturbed forest was higher than in undisturbed forest. In both forests understorey biomass forms only a very minor part of the total biomass.

Carbon and nutrient contents in undisturbed forest

Carbon and nutrient contents varied according to the components (Table 5). C and N contents did not differ significantly among tree fractions (C: F = 0.05, P > 0.05 and N: F = 0.50, P > 0.05). Notable is the high C content of the understorey plant parts. With regards to the other nutrient contents, the difference between the components was significant. In the understorey, only Na significantly differed between the leaves and woody parts (t = 194.92, P<0.001). Excepted C (t = 4.38, P<0.05), there is no significant difference (P>0.05) between tree and understorey for nutrients. The nutrient contents order ranging from the highest to the lowest for the leaves (N > P > K ~ Na > Ca ~ Mg) differed from those of the branches and stem wood (N > Ca > K > P > Mg > Na) of the trees. In the understorey, this was for leaves (N > P > Na > Ca > Mg > K) and for wood (N > P > K > Ca ~ Mg > Na).

Carbon and nutrient amounts in undisturbed and disturbed forests

The total nutrient and carbon amounts in the above-ground phytomass were calculated from the phytomass values estimated on the basis of the allometric models. Total carbon amount in the undisturbed forest is 302 $t.ha^{-1}$ with 301 $t.ha^{-1}$ in wood and 1 $t.ha^{-1}$ in leaves. While nutrient amounts varied according to components (Figure 4). Nitrogen had the highest amount, ranging from 10 to 40 times higher than those respectively of P and Mg in the leaves, and from 1 to 304 times higher than those respectively of Ca and Na in wood.

The nutrient amounts stocked in the above-ground phytomass of the disturbed forest was calculated from the nutrient contents estimated in the undisturbed forest, because the two forests had the same characteristics before logging. Like phytomass, nutrient amounts of the trees were higher in the undisturbed than disturbed forest.

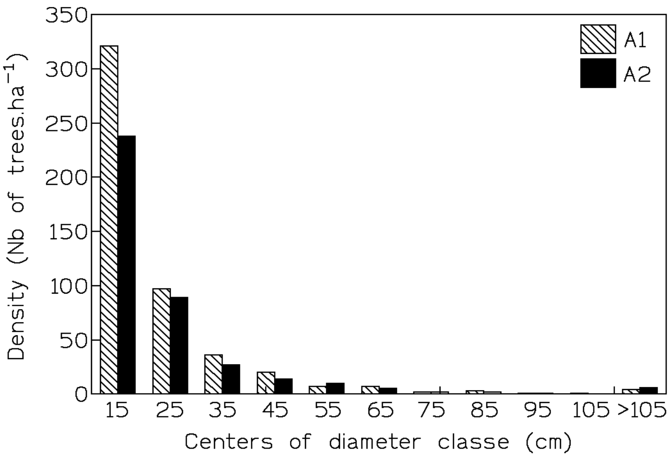

Figure 2: Diameter distribution (from 10 to 150 cm) of trees species in undisturbed (A1) and disturbed (A2) forest in Ebom.

Table 3: Regression equations for tree biomass estimation.

Components	Equations*	R^2 (SEE)**	n***	DBH range(cm)
Leaves	$-0.2183 + 0.1154*D + 0.0021*D^2$	0.973 (0.017)	97	1 – 79
Branches	$0.0806*D^{2.1481}$	0.978 (0.015)	103	1 – 79
Stem	$0.0201*D^{3.0554}$	0.998 (0.001)	102	1 – 79
Total	$0.0538*D^{2.8289}$	0.999 (0.003)	93	1 – 79

* D = tree DBH (cm).
** R^2: coefficient of determination. Values between parentheses represent standard error estimated SEE = $(1-R^2/n-2)^{1/2}$.
*** n: sample size.

Table 4: Aboveground phytomass in undisturbed and disturbed forests.

Components	Undisturbed		Disturbed	
	t/ha	%	t/ha	%
Tree Phytomass:				
Leaves	1.9	0.3	1.7	0.3
Branches	54.2	9.3	49.3	9.1
Stem	525.8	90.3	489.9	90.6
Total (sum of components)	581.9	100.0	540.9	100
Total (allometric model)	581.1		540.1	
Understorey:				
Leaves	0.2	35.9	0.44	44.0
Woody parts	0.4	64.7	0.56	56.0
Total understorey	0.7	100.0	1.00	100.0
Total aboveground phytomass	582.6		541.9	

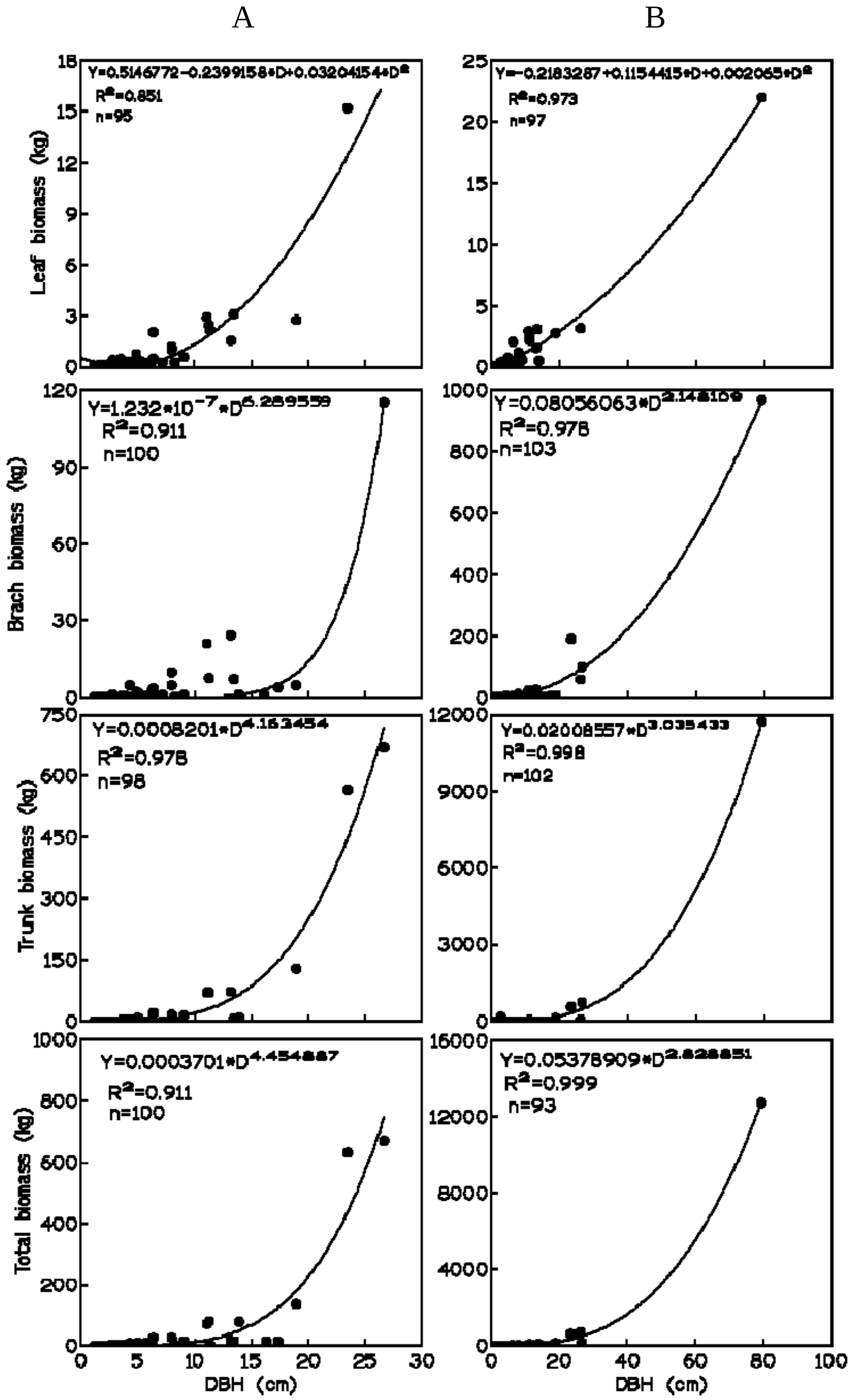

Figure 3: Relationships between dry mass of tree components and DBH between 0-30 cm (A) and between 0-79 cm (B). n = sample size, R^2= coefficient of determination.

Table 5: Mean and standard error (SE, between brackets) of carbon and nutrient contents (%) in aboveground tree and understorey biomass in undisturbed forest

Components	C	N	Ca	Mg	K	Na	P
Tree							
Leaves	49.06 (5.51)	1.77 (0.51)	0.04b (0.01)	0.04b (0.02)	0.05b (0.03)	0.05a (0.01)	0.17a (0.04)
Branches	49.41 (9.09)	1.74 (0.56)	0.88a (0.29)	0.07a (0.02)	0.31ab (0.13)	0.01b (0.01)	0.09b (0.01)
Stemwood	52.04 (8.65)	1.50 (0.56)	1.23a (0.51)	0.05ab (0.03)	0.41a (0.38)	0.01b (0.01)	0.07b (0.02)
Fisher F	0.05ns	0.50ns	28.85***	3.99*	5.40*	62.90***	28.61**
Under storey							
Leaves	55.33 (1.53)	2.12 (0.47)	0.10 (0.05)	0.06 (0.03)	0.04 (0.02)	0.11 (0.01)	0.17 (0.03)
Woody parts	54.33 (8.02)	1.90 (0.26)	0.04 (0.02)	0.04 (0.01)	0.09 (0.04)	0.03 (0.01)	0.21 (0.04)
Student t	0.05 ns	0.49.ns	4.31 ns	0.76 ns	3.91 ns	194.92***	1.28 ns

Different letters indicate that values are significantly different: ns, non significant; * P < 0.05; ** P < 0.01;
**** P< 0.001

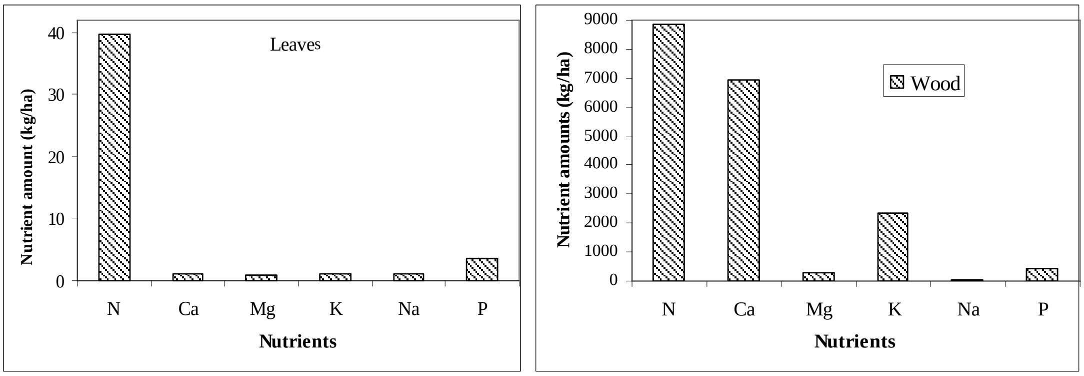

Figure 4: Amount of carbon and nutrients stored in the undisturbed Ebom Forest

DISCUSSION

Structures of undisturbed and disturbed tropical rainforests

The density and basal area of the studied forest are high and well above the pan-African average [27]. This forest is rich in species, but not richer than the surrounding forests [28] and characterized by Caesalpiniaceae with *Lophira alata* and *Sacoglottis gabonensis* as the predominant species. The diameter distribution diagram of all species were similar to Rollet's [27] exponential model, which reflect a geometrical decrease of number of individual per DBH class with increasing tree size. This means there were numerous small diameter trees, indicating regeneration of this forest was not compromised by human activities [21].

The structure of disturbed forest is different to the undisturbed. The tree density and basal area were slightly lower in the disturbed than undisturbed. But the disturbed plot showed a slightly higher average diameter than the undisturbed. This is because the density of tree in 50-60 cm DBH class is higher in the disturbed forest than in the undisturbed. No pre-logging data are available, but probably this plot was better stocked than the undisturbed one.

Above ground phytomass

Equations between dry mass and DBH to estimate the phytomass developed in this study, all showed highly significant coefficients of determination, low standard errors estimated and minimal variations around the curve. This confirmed that the diameter is a good predictor of forest biomass, as was shown by Brown *et al.* [29] and Brown [30]. However, the DBH-values used in our models varied between 2.5 to 80 cm, with many small trees (DBH < 30 cm); a situation that could limit the value of in our models for the prediction of large tree biomass.

Tree phytomass as estimated here could be an overestimation, especially that of the stems and branches, for only one large tree (DBH = 79 cm) was used in the models, a situation that probably explained the high parameter value for b' (Figure 3). The use in the model of a single large tree with a small crown could be, to a large extent, the cause of an underestimation of the leaf biomass; a situation that explained the large difference found between our results and those found in literature (Table 6). With regards to the relative contribution of the different tree components to the total biomass, our results are similar to those of the literature.

The total phytomass in the undisturbed Ebom forest (583 t. ha^{-1}) was higher than those reported by Kanmegne [31] for tropical forest of southern Cameroon (399 t. ha^{-1}) or by van Reuler and Janssen [32] in Ivory-Coast (350-560 t. ha^{-1}). The mean value for tropical rainforest as reported by Brown *et al.* [29] and by Nykvist [33], respectively 192 and 250 t. ha^{-1} are 2 to 3 times lower than those found in this study. Kotto-Same *et al.* [26] reported more than 453 t. ha^{-1} in southern Cameroon. It can be concluded that, notwithstanding the possible limits in our models to estimate large tree biomass, the above-ground phytomass of the Ebom forest ranks among the highest values for rainforest's phytomass growing on Oxisols and Ultisols (Table 6).

Carbon and nutrient storage in above-ground phytomass

The amount of carbon found in above-ground phytomass in Ebom forest was 302 t. ha^{-1}. As could be expected, this value is also large compared to those found in other tropical rainforests developed on the similar type of soils (Table 7). However, the methods to calculate total were different. In all results presented in Table 7, except in the present study, the amount of carbon was estimated by using an average value of 45% of carbon content in biomass. Kotto-Same *et al.* [26] have estimated the total content of the forest of southern Cameroon at 308 t. ha^{-1} of which 204 t. ha^{-1} for above-ground tree phytomass. This value was far lower than ours, even if we used our conversion factors of phytomass to carbon (49% and 52%) to calculate their values (222.14 - 235.74 t. ha^{-1} for above-ground tree phytomass). This difference can be explained by the fact that their result included forest fallows, plantations, etc. The high C content of the understorey parts can not be explained.

The nutrients stored in above-ground phytomass in Ebom were generally large compared to those reported in other tropical rainforests growing on similar soil types, with the exception of Mg (Table 7). The value for this nutrient (311 kg. ha^{-1}) in our study was close to the one found by Poels [34] in Suriname (234 kg.ha^{-1}) and by Kanmegne [31] in southern Cameroon (335 kg. ha^{-1}), but lower than the one found by Russell [36] in Brazil (518 kg. ha^{-1}).

Nutrient accumulation in above-ground phytomass varies per nutrient. In tropical rainforests, it has been reported that nutrients accumulated from the highest to lowest: N>Ca>K>Mg>P ([35]; [34]; [31]). The results of our study show the same trend as those of the literature, except for P which was higher than Mg (Table 7). The leaves were richer in P, K, and Na than the woody parts (branches and stems) and consequently their contribution to the return of nutrients from the canopy towards the soil through litter is higher than that of the other fractions [36]. Thus leaves play an important role in the nutrient cycling mechanism as they rapidly decomposed. The released nutrients are absorbed by the dense fine roots present in the top soil layer [37], while the soil itself is relatively poor in nutrients [17]. Compared to Oxisols elsewhere N content can even be considered as high [38].

Impact of logging on phytomass and nutrient stocks

Total aboveground phytomass in the undisturbed plot (583 t. ha^{-1}) was higher than that in the disturbed one (542 t. ha^{-1}). In the latter, understorey phytomass was slightly higher (0.7 versus 1.0 t. ha^{-1}). Assuming both plots were identical before logging, the difference between the two plots is largely due to logging activities six years ago. Only stemwood was exported out of the system as leaves and branches were left behind. This difference can be considered as phytomass loss from the disturbed plot. Calculated as the difference in stemwood between undisturbed and disturbed plot, this amounts to about 7% (Table 8). Compared with others rainforests with similar conditions (poor soils, high rainfall, > 1800 mm, and low logging intensity) this loss of phytomass is low (Table 8). However it should be noted that during the years after logging phytomass has increased as a result of growth. Therefore the real impact of logging on phytomass was probably low.

As total phytomass is higher in undisturbed than in disturbed forest, so are the carbon and nutrient pools. This difference can be attributed to felling of trees which constitute nutrient reserves. But only a part of the nutrients is lost from the forest through extracting wood, because leaves, branches, fruits, and flowers are left on the forest floor. Hence the carbon and all nutrient loss rates due to the extraction of logs is low, in the same order as phytomass, 7%. Additionally nutrient leaching is possibly enhanced after logging but was not measured in this study. But comparing our results with data from other rainforests with comparable logging activities, enable us to assume that timber exploitation did not significantly enhance nutrient leaching. In fact, van Dam [39] has shown that the effect of disturbance caused by extraction of one to two trees on leaching of N, K, Ca and Mg was less serious than the disturbance caused by the logging of five to ten trees. Brouwer [9] also reported that small gaps of about 500 m^2 did not significantly enhance leaching of nutrients. In the Ebom rainforests, logging activities were low, less than a tree per hectare was extracted during the last exploitation [17] and this level of timber extraction would create gaps of less than 500 m^2.

The soil of the Ebom forest is nutrient poor [17]. A large part of the nutrients is stored in the phytomass, except N and C. The Mg and available P stock in the aboveground biomass in the undisturbed plot is about two (311 and 175 kg/ha) respectively 16 (436 and 28 kg/ha) times higher than in the soil (Table 9). The nutrient losses associated with timber extraction were related to the nutrient stocks in the aboveground biomass and in the soil (Table 9). Compared to aboveground phytomass, nutrient loss amounted to 6 % and is moderate. Compared to the soil stocks, losses were moderate for N and Mg, somewhat larger for Ca and K, and very large and close to soil stock for available P (Table 9). However, there is more P present in the soil and trees can extract this P.

Table 6: Phytomass of tree components and total phytomass (dry weight in $t.ha^{-1}$) of some tropical rainforests on Ultisols and Oxisols with rainfall above 1800 mm.

Country	Leaves	Branches	Stems	Total	Source
Cameroon	2.0	54	528	583	This study
Cameroon	-	-	-	399	Kanmegne [31]
Cameroon	-	-	199	312	Brown *et al.* [29]
Ghana	6.5	-	116	123	Greenland and Kowal [40]
Ivory Coast	-	-	-	350-560	van Reuler and Janssen [32]
Brazil	-	-	-	473	Klinge (1976)*
Brazil	-	-	-	541	Russell [35]*
Suriname	17.6	121	296	434	Poels [34]
Venezuela	-	-	-	301	Medina and Cuevas [41]
Venezuela	9.8			264	Jordan [38]
French Guiana	-	-	210	314	Brown *et al*. [29]
Sri Lanka	-	-	88	205	Brown *et al*. [29]
Panama	11.4	-	355	367	Golley *et al.* (1975)
Panama	7.4	-	252	259	Golley *et al.* [42]

* Source Brouwer [9].

Table 7: Carbon (t.ha-1) and nutrient (kg.ha-1) stocks in phytomass of some rain forests growing on infertile soils (Ultisols/Oxisols), with rainfall above 1800 mm.

Country	C	N	Ca	Mg	K	P	Source
Cameroon	302	8888	6953	311	2337	436	This study
Cameroon	199	3083	1839	335	979	142	Kanmegne [31]
Brazil	213*	2988	514	256	498	66	Klinge (1976)**
Brazil	243*	4192	1371	518	918	79	Russell [35]**
Suriname	195	1519	2474	234	1259	96	Poels [34]
Venezuela	135*	1485	251	67	288	48	Medina and Cuevas [41]

*: values calculated with 45% of carbon.
** source Brouwer [9].

Table 8: Phytomass loss due to logging as difference (in percentage) between undisturbed and disturbed forests.

Location	Forest type	Dry mass t.ha-1	Loss %	Source
Cameroon	Undisturbed forest	526		
	Logged forest	490	6.8*	This study
Guyana	Closed primary forest	254		Rees (1963)**
	Logged forest	190	25.0	Rees (1963)**
Peru	Primary forest	210		Jonkovic (1969)**
	Logged forest (low intensity)	192	8.6	Jonkovic (1969)**
	Logged forest (height intensity)	125	40.5	Jonkovic (1969)**

* Rate of biomass loss calculated from the plots.
** Source Brown [30].

Table 9: Export of tree biomass (t.ha-1) and nutrients (kg.ha-1) from the ecosystem by logging.

Location	Phytomass	N	Ca	Mg	K	P
Stock in undisturbed forest (in total above-ground phytomass)	582	8888	6953	311	2337	436
Stock in disturbed forest (in total above-ground phytomass)	541	8263	6465	289	2173	405
Stock in soil*	n.a.	8900	1785	175	755	28**
Export of nutrients in logs***	36	541	443	18	148	26
Idem as percentage of the undisturbed forest	6.2	6.1	6.4	5.8	6.3	6.0
Idem as percentage of total (aboveground phytomass + soil) stock	n.a.	3.2	5.3	3.9	5.1	6.0

* Soil column of 1 m, except for carbon 10 cm. Source van Gemerden and Hazeu [17]
** Available P
*** calculated from the difference in stem phytomass between the two forest times the nutrient content.

CONCLUSION

This study of the phytomass and its nutrient contents and amounts in the tropical rainforest of Ebom in southern Cameroon on Oxisols/Ultisols has shown that this forest belongs to the richest tropical rainforests in the world, occurring on these poor soils. Mg is the exception. As expected, nutrient concentrations varies with tree component (leaves, branches and stems). In general concentrations are higher in leaves than in wood, particularly for P. In general nutrient amounts stored in the above-ground biomass are larger than those stored in soil, with magnitudes varying from about 2 (Mg) to 16 (available P). N stocks in both are high and of the same order of magnitude. Carbon stored in the soil was four times higher than in the above-ground biomass.

The loss of phytomass and nutrients due to extraction amounts to about 7% of above-ground phytomass and nutrient stocks in undisturbed forest. This can be explained by the low intensity of logging. Six to seven years after logging, phytomass growth and nutrient accumulation restored both to 93% of the stocks in the aboveground phytomass of undisturbed forest.

These results should form the basis for recommendations for sustainable management of tropical rainforests in general and for those in southern Cameroon in particular. However, additional research is needed on nutrient input in the forest from outside as well as on the impact of logging on nutrient leaching in order to get a complete picture of the nutrient cycles. Nevertheless, it would be advisable to leave the logged forest unaltered for at least 10 years more (i.e. a cutting cycle of about 20 year) before new logging activities can take place. This would enable the forest to restore its living phytomass and its nutrients.

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