Fine Roots Dynamics in a Tropical Moist Forest: Case of Two Forest Groves in the Congo Basin

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Ifo, S. A., Koubouana, F., Nganga, D., Bocko, Y. and Mantota, A. 2015. Fine Roots Dynamics in a Tropical Moist Forest: Case of Two Forest Groves in the Congo Basin. *Baltic Forestry* 21(2): 204–211.

Abstract

The paper contributes new data on fine root production in tropical forests from the Teke Plateau, an underexplored area of Africa that is dominated by grove forests. Importantly, this study contributes to our understanding of the role of the successional age of vegetation and the impacts of water availability on ecosystem functions, which may assist in predicting how tropical vegetation will change in the future due to climate change driven rainfall changes and more direct human interventions.

We used ingrowth cores to study the influence of the forest structure on fine roots production and turnover in two different forests types, a gallery forest (GF) and a hill-slope forest clump (HF) in the Teke Plateau in Congo. We found a significant higher fine root biomass in the 0-20 cm horizon between the GF and HF; however, for the 20-40 cm horizons no significant differences were found between the two forest types. Nevertheless, there is a huge difference on the whole profile (0-40 cm), with 9.45 ± 8.23 kg m^{-2} for the GF and 4.26 ± 1.28 kg m^{-2} for the HF ($p < 0.05$). The annual production of fine roots was 0.46 ± 0.24 and 0.36 ± 0.02 kg m^{-2} yr^{-1} in the GF and the HF for the horizon 0-20 cm, and of 0.21 ± 0.19 and 0.20 ± 0.08 g m^{-2} yr^{1} for the horizon 20-40 cm. These differences are not significant ($p > 0.05$). The differences in fine root biomass between the two types of forest are not explained by differences in production, but by differences in turnover. This difference between the two forest types can be explained by differences in forest structure. The measured basal area was 16.68 $m^2 \cdot ha^{-1}$ and 6.66 $m^2 \cdot ha^{-1}$ in the GF and the HF, respectively. We also noted a mean tree density of 640 stems per ha in the GF against 119 stems per ha in the HF.

Keywords: fine roots, turnover, Teke Plateau, forest grove, Congo RC

Introduction

The carbon balance of the earth's ecosystem plays a major role in the surface temperature regulation of our planet, since carbon dioxide (CO_2) strongly influences the global radiation budget (Schimel 1995). One of the major components of the carbon cycle is soil, which has regular carbon inputs through aboveground and belowground biomass turnover. Belowground litter, resulting from the mortality of fine roots (≤ 2 mm in diameter), contributes to a significant degree of carbon transfer from the atmosphere to the soil (Raich and Nadelhoffe 1989, Lebègue et al. 2004). Fine roots constitute a small (< 5%) but highly dynamic fraction of total standing root biomass and contribute to much of the carbon transfer from aboveground to belowground components (Gill and Jackson 2000).

Fine root production has been estimated to account for up to 33% of global annual Net Primary Production, NPP (Gill and Jackson 2000). Root production may account for about half of the carbon cycled per year in many forests (Vogt et al. 1996). Fine roots play many roles in the dynamics of several forest ecosystems. Fine roots control the uptake of water and nutrients from the soil, and thus control the photosynthesis rate (van Cleve et al. 1991). They also play a critical role in biogeochemical processes and primary production (Silver et al. 2005).

Fine root turnover allows the plant to forage the soil and reach fertile micro sites not accessible by existing roots, and thus collect bio-elements released by fresh litter or from other vegetable remains in decomposition (Persson 1980, Lebègue et al. 2004). In addition, fine roots are a key element for belowground carbon sequestration (Norby et al. 1994). Fine root turnover contributes significantly to soil organic matter pools, making fine root turnover rates potentially important modulators of soil carbon cycling (Gill and Jackson 2000). Despite the important role that fine roots play in forest ecosystems, there are few studies that compare them with other plant compartments and our knowledge on the dynamics of fine root remains insufficient. Different approaches have been used to study fine root biomass in the field as reviewed in Vogt et al. (1998), but there are no reliable methods for the direct study of root biomass and production of roots, and the existing methods used are controversial (Vogt et al. 1998).

In the Republic of the Congo, different studies were done during the last fifty years have shown the growth of forest on the savannah of the Teke Plateau (Schwartz et al. 1996). The same observation was made for the whole of the humid tropics, particularly in central Africa, where savannahs tend to yield to forest. The Teke Plateau is characterized by the existence of several small forest islands of modest size (of one to a few hectares), but their sum can be important on the whole Teke Plateau (Schwartz et al. 1996). Studies on evaluating aboveground biomass of carbon was conducted in the GF of the Teke Plateau and shown an important amount of above ground biomass (Ekoungoulou et al. 2015), and coarse woody debris (Ifo et al. 2015).

To our knowledge, there are no published data on fine root dynamics in the tropical forests of Congo (Brazzaville), and the role, which fine roots play in the carbon budget of these forests, has not been determined.

In this study, samples of soil were taken at different periods along a year in each type of the studied forests. The overall objective of this study is to compare the production of fine roots between hill-slope forest clump and the gallery forest. More specifically, this work helps to understand the role of age and the nature of the ecosystem on the production of fine roots and its turnover.

Methods

Study site and materials

Study site

This study was conducted on the Iboubikro site (3°11’ S, 15°28’ E), located 140 km to the north east of the city of Brazzaville, on the Teke Plateau (Figure 1).

Yearly rainfall is about 2100 mm with one pronounced dry season of 4 months from June to September (2006-2008) and average temperature is 26°C.

The soils in the area are acidic and sandy Arenesols (Schwartz and Namri 2002), with clay content varying between 0.3 and 7.6 %. The C/N ratio varies from 17.6 in areas dominated by *Loudetia simplex* to 14.5 in forests dominated by *Milletia Laurentii* (Makany, 1976).

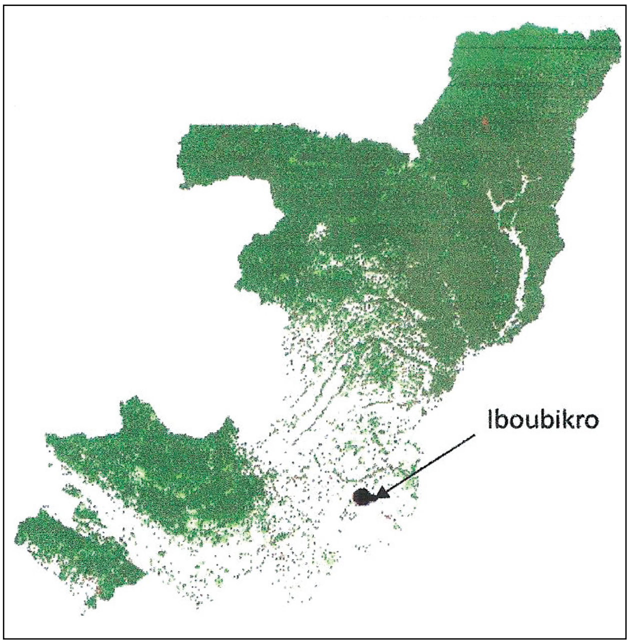

Figure 1. Localisation of the experimental site in the map of Congo

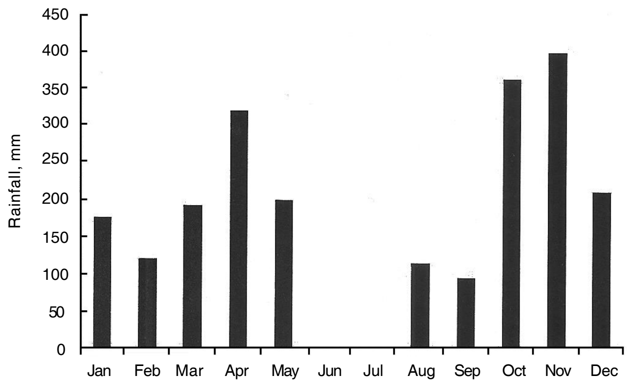

Figure 2. Monthly trends of rainfall at Iboubikro (PPG’s collecting data)

On the one hand, two experimental sites were situated in a hill-slope forest clump dominated by *Musanga cecropioides* (R. Brown.) [Cecropiaceae] and *Macaranga barteri* [Euphorbiaceae] and, on the other hand, in a gallery forest dominated by *Colletoecema dewevrei* (De Wild) and *Eriocoelum microspermum* (Gilg ex Radlk.) [Sapindaceae]. The list of plant species found in two mentioned forests is presented in Table 1. Three plots of 40m × 40 m were delimitated in

Table 1. Main species in two studied forest groves

Type of forest	Genus/species	Family
Gallery forest	*Caloncoba welwitschii* (Oliv.) Gilg	Flacourtiaceae
	Colletoecema dewevrei (De Wild.) E.M.A. Petit	Rubiaceae
	Megaphrynium macrostachyum (Benth.) Milne-Redh	Marantaceae
	Landolphia owariensis P. Beauv.	Apocynaceae
	Dacryodes sp	Burseraceae
	Eriocoelum microspermum Radlk. Ex De Wild.	Sapindaceae
	Bacteria fustilosa	Passifloraceae
	Hymenocardia ulmoides Oliv.	Phyllanthaceae
	Markhamia sissilis (Benth.) K.Schum. ex Engl.	Bignoniaceae
	Piptadeniastrum africanum (Hook.f) Brenan (Dabema)	Mimosaceae
	Panchovia laurentii (De Wild.) Gilg ex De Wild	Sapindaceae
	Sorindeia juglandifolia (A.Rich.) Planch. ex Oliv	Anacardiaceae
	Pentacletra eetveldeana de Wild.	Mimosaceae
Hill-slope forest clump	*Macaranga barteri* Muell.Arg.	Euphorbiaceae
	Musanga cecropioides (R. Brown)	Cecropiaceae
	Caloncoba welwitschii (Oliv.) Gilg	Flacourtiaceae
	Anthocleista schweinfurthii Gilg	Loganiaceae

each forest taking into account the distribution of tree species characterizing these forests. The height of trees varies from 20 to 28 m in the gallery forest, and from 15 to 21 m in the hill-slope forest clump.

Field data

Root mat biomass

Root mat is a dense cover made by fine roots on the forest surface or just below the surface in tropical forest ecosystems. Total biomass of the root mat was estimated by using a root auger (8 cm in diameter). Sampling took place respectively on November 17, 2007, in the gallery forest and on March 1, 2008, in the hill-slope forest clump. Overall eighteen root mat samples were collected in each forest type. Samples were cleaned of all plant detritus and washed to remove soil and brought back to the laboratory, where they were over dried for four days at 65 °C, then weighed. The biomass of fine root has been expressed in kg m^{-2}.

Fine roots biomass

Fine root biomass from two forest sites was studied by using a root auger (8 cm in diameter), Ø is the diameter of samples collected in each of two forests, and eighteen soil cores were sampled at a rate of six per sampling plot on November 17^{th}, 2007, in the gallery forest and, on March 1, 2008, in the hill-slope forest clump, respectively. Collection of soil cores (height = 20 cm, Ø = 8 cm) was completed on two soils horizons (0-20 cm and 20-40 cm). An *in situ* sorting was carried out in order to separate fine roots (Ø = diameter < 2 mm) from larger roots (Ø > 2 mm) using the calliper. After sorting, the soil separated from the roots was put back into the hole taking care to maintain the apparent density as far nearest to the ground initial state as possible. This was done following the sampled soil horizons, with the 20-40 cm layer put back first followed by the 0-20 cm layer. This represented the samples at t_0. The roots were classified according to their diameter, wrapped in plastic bags, and brought back to the laboratory, where they were oven dried at 65°C for four days and then weighed after removal of all soil particles using a brush.

The biomass of fine root is expressed per kg·m^{-2} and was defined using the following formula:

$$B = \frac{M_0}{S}, \tag{1}$$

where: B is the root biomass (kg·m^{-2}); S is the size of area, m^2; and M_0 is the root biomass, kg.

Fine roots production

Analysis of fine roots production in two forests was carried out in the same eighteen sampling plots used for fine roots biomass assessment. This method consists of fine root re-colonization in previously root-free holes (Steele et al. 1997; Vogt et al. 1998). Such samples are called “ingrowth cores”. Ingrowth coring is one of the most common methods used to measure root production. In this study soil core samples have been collected three months (t_1) and twelve months (t_2) after the first sampling (t_0). An *in situ* sorting was carried out with the aim to separate living fine roots from dead roots. Then fine roots were treated *in situ* using the same laboratory techniques as described for the fine roots biomass analysis.

To avoid artefacts related to the soil sampling techniques, calculation of fine root production inside the ingrowth core was done not for the period between t_0 and t_1 but rather for the period between t_0 and t_2. Total fine roots production at the end of Δt period is obtained by using Equation 2.

Production, Φ, is calculated with the aid of the following equation:

$$\Phi = \frac{\Delta B(T_2 - T_1)}{T_2 - T_1} x365, \tag{2}$$

where: Φ is the annual production of fine roots; ΔB is the variation of dry biomass over a time period, $\Delta t = T_1 - T_2$, is the time between the two dates of re-sampling.

Total fine roots production is expressed in kg·m^{-2}·yr^{-1}

$$\Phi = \frac{\Delta B(T_2 - T_1)}{T_2 - T_1} \times 365$$

Then total fine roots turnover (T) can be calculated with Equation 3:

$$T = \Phi / B_0, \tag{3}$$

where: Φ is the annual fine roots production, and B_0 is the fine roots biomass of the t_0 sampling. T is expressed in year^{-1} (yr^{-1}).

Mean lifespan of the roots is equal to *1/T* and expressed in years.

Tree density and basal area in the sampling plots

In three experimental plots established in each type of forest groves, tree circumference was measured using a metric tape at breast height (1.30 m from the ground). However, during the analysis of results only trees with a circumference 31.43 cm, corresponding to a diameter at breast height (DBH) 10 cm, were taken into account.

Then several classes of trees were defined according to their diameter as follows: class I: DBH = 10-19.99 cm; class II: DBH = 20-20.99 cm; and class III: DBH = 30-39.99 cm.

Data analysis

For each studied variable, the mean and standard deviation were calculated. A variance analysis to a factor (with the aid of SAS 9.0 software) was used to compare the values of mean obtained from two studied types of forests. The threshold of probability determining the significant differences is $P < .05$

Results

Biomass of the root mat

The comparison of the root mat biomass between the two studied forests revealed that root biomass was significantly different ($p < 0.001$). We obtained a biomass of 2.42 ± 0.19 kg·m^{-2} in the gallery forest against 1.24 ± 0.11 kg·m^{-2} in the hill-slope forest clump (Figure 3).

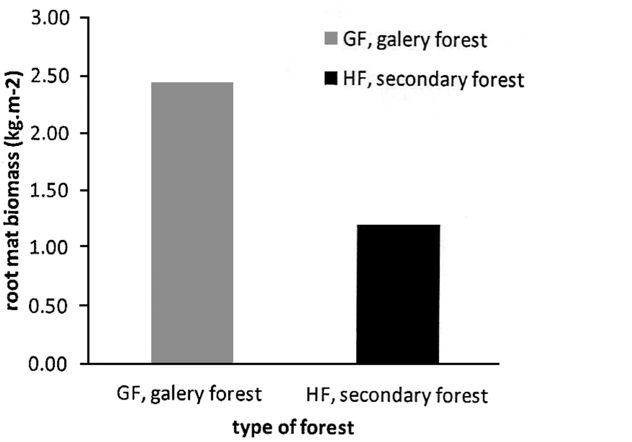

Figure 3. Biomass of root mat in the two forest groves of the mean of 18 measurements per forest with vertical bars representing the SE

Fine root biomass horizons 0 to 20 cm and 20 to 40 cm.

Fine roots biomass obtained from the horizon 0-20 cm was 0.77 ± 0.13 kg·m^{-2} in the gallery forest and 0.30 ± 0.02 kg m^{-2} in the hill-slope forest clump. This difference is significant ($p < 0.05$). For the horizon 20-40 cm, fine roots biomass is 0.17 ± 0.03 and 0.12 ± 0.05 kg m^{-2} for the gallery forest and the hill-slope forest clump, respectively.

In the gallery forest, fine roots biomass in the 20-40 cm horizon was about 4.5 times less than in the upper horizon (0-20 cm), whereas in the hill-slope forest clump the biomass of fine root was 2.5 times lower than that obtained in the upper horizon (0-20 cm). In two studied forests it was observed a vertical distribution of fine root biomass. We noted a reduction in the fine root biomass from the surface layer towards the lower horizons in both two forest groves. The variance analysis carried out did not reveal any significant difference of fine root biomass for the horizon 0-20 cm ($p > 0.05$) between both two forest groves. In the whole profile 0-40 cm, comparison of the fine root production shows that production is more in the gallery forest (0.94 ± 0.14 kg m^{-2}) than in the hill-slope forest clump (0.43 ± 0.02 kg m^{2}).The mean biomass of fine roots was significantly different between two studied forest types ($p < 0.05$).

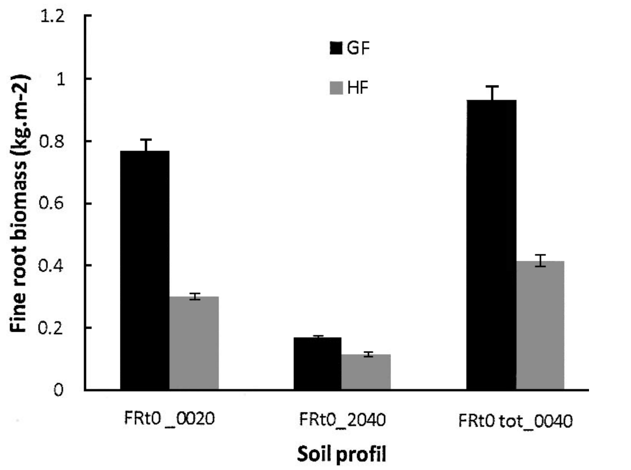

Figure 4: Fine root biomass in the two forests grove overall profile (0-40 cm)

Fine roots production

In 0-20 cm horizon, the annual fine roots production was 0.46 ± 0.04 kg m^{-2}yr^{-1} in the gallery forest and 0.36 ± 0.02 kg m^{-2}yr^{-1} in the hill-slope forest clump but this difference was not significant ($p > 0.05$). In 20-40 cm horizon, observed fine root production was 0.21 and 0.20 kg m^{-2}yr^{-1}, respectively. We did not observe a significant difference between the two forest types ($p > 0.05$). In the entire 0-40 cm profile, fine root production in two studied forest sites is not significantly different ($p > 0.05$).

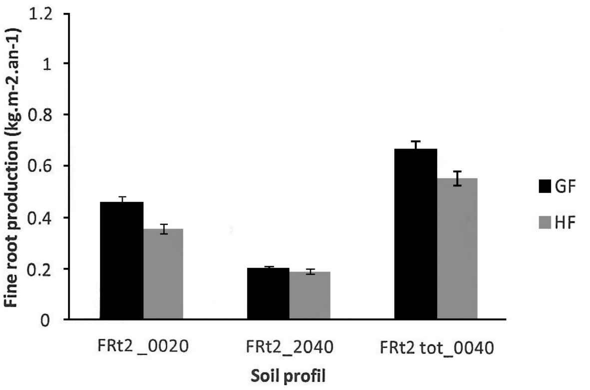

Figure 5. Fine root production in the two forests grove (gallery forest and hill-slope forest clump)

Fine roots Turnover

Results of the fine root turnover obtained in each of two horizons are presented in Table 2. In two studied forests, the turnover of fine roots increased with depth. Fine root turnover is more in the hill-slope forest clump than in the gallery forest. This could be explained by the fact that of the difference of structure between the type of the forest, but also wood density between two studied forests (Table 5).

Table 2. Fine root turnover in two studied forests

	Turnover (yr^{-1}) Soil profile (0-20 cm)	Turnover (yr^{-1}) Soil profil (20-40)	Turnover (yr^{-1}) Soil profile (0-40)
Gallery forest	0.60	1.22	0.71
Hill-slope forest clump	1.19	1.63	1.32

Tree Density and Basal Area

On the one hand, the tree density (stem number per hectare, all species combined, Table 3) varies according to the sampling plot and, on the other hand, according to the type of forest.

The basal area average is more important in the gallery forest than in the hill-slope forest clump (see Table 5 and Figure 6).

The inventory also shows that in the gallery forest the class I trees are better represented than other diameter classes.

Discussion

Root mat biomass

The soils of the Teke Plateau are ferralitic and characterized by significant leaching and are extremely poor in nutrients and exchangeable cations due to high rainfall and soil texture. According to Cuevas and Medina (1988), the observed significant development of the root mat is one of the characteristic adaptive mechanisms in wet tropical forests, particularly in ecosystems growing on poor soils with high leaching rates. In this study site, Iboubikro, where the mean annual rainfall is more than 2000 mm, it appears that the high rainfall and leaching could explain why the root mat is very important in the top soil. This adaptive mechanism specific to tropical rainforest allows better retention and rapid recycling of various bio-elements released during decomposition of tropical litter (Went and Stark 1968; Walter 1971). Some authors affirm that the highest root concentration appears in the first 10 cm of the soil represented by horizons H and A_1 (Maycock and Congdon 2000).

Our study revealed important variations of root mat biomass and fine roots between the gallery forest and the hill-slope forest clump. Several possible reasons could explain these differences in biomass: the first could be the factor of water. As can be seen in the description of the study site, the gallery forest is situated along the Lesio River, whereas the hill-slope forest clump grows on a hill slope, which implies greater water availability for the root system in the gallery forest. The large root mat biomass could also be explained by the observed release of more elaborate bio-elements during litter decomposition in the gallery forest than that made in the hill-slope forest clump.

Table 3. Fine root production in various forest ecosystems

Authors	Type of forest	Localities	Horizon (0-40 cm)	Horizon >40 cm	root size (mm)	root production (g·m^{2-}year^{-1})
Visalakshi (1994)	Tropical	Coromantel, India	10	-	≤2	103-117
Cuevas and Medina (1988)	Tierra Firme	Venezuela	10	-	total	1117
Cuevas and Medina (1988)	Bana	Venezuela	10	-	total	235
Sundarapandian Swamy (1996)	tropical	Kodayar, India	25	-	<3	175-226
this study	hill-slope forest clump	Congo	0-20	-	≤2	361
this study	hill-slope forest clump	Congo	20-40	-	≤2	201
this study	gallery forest	Congo	0-20	-	≤2	460
this study	gallery forest	Congo	20-40	-	≤2	212
Jourdan et al. (2008)	*Eucalyptus saligna*	Brasil	0-30		<2	209-242
Zewdi et al. (2008)	*Ensete ventricosum*	Ethiopia	0-30	-	≤2	233.9–345.1

Table 4. Some data of fine root turnover in the tropical area

Authors	Rainfall (mm)	Locality	Methods	Type of forest	Turnover (yr^{-1})	Especies
Cuevas and Medina (1998)	2500	India	Coring	< 2 mm	0.69	*Euphatorium adenophorum* et *Pinus kesiya*
Schroth and Zech (1995)	1285	Ivory coast	Coring	< 2 mm	2.379	*Terminalia suberba*
Thongo-M'bou (2007)	1400	Congo	Ingrowth coring	< 2mm	2.43 to 3.44	*Eucalyptus*
Jourdan et al. (2008)	1360	Brasil	Ingrowth coring	< 2 mm	2.97	*Eucalyptus saligna*

Table 5. Characteristics of each type of forest

Type of forests	Plots	Number of trees per plot	Tree density	G ($m^2 \cdot ha^{-1}$)	Mean of G ($m^2 \cdot ha^{-1}$)
GF	P1	128	800	19.937± 0.50	16.58 ± 0.38
	P2	113	706	14.45 ± 0.22	
	P3	66	413	15.91 ± 0.34	
	P1	12	75	3.36 ± 0.29	6.66 ± 0.33
	P2	23	144	8.86 ± 0.43	
	P3	22	138	7.78 ± 0.28	

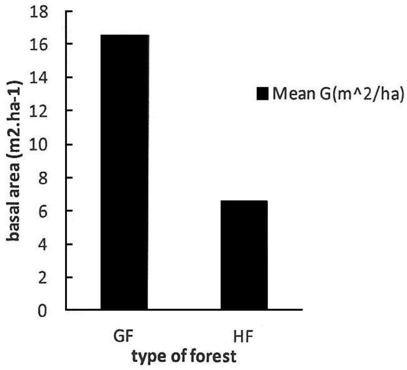

Figure 6. Comparison of mean basal area between two studied types of forest

Studies of litter decomposition carried out in these forests showed that litter decomposed more rapidly in the gallery forest than in the hill-slope forest clump (Ifo et al. 2011). This could explain the fact that the FRB (0-20 cm) was more important in the GF than in the HF.

The quantities of fine root biomass observed in the two sites on the 0-40 cm profile are in the range of the average values for wet tropical forests (Singh and Singh 1981, Vance and Nadkari 1992), but they are higher, when compared with results obtained from natural forests as well as from forest plantations (Visalakshi 1994).

The results of the study also revealed a vertical distribution of fine root biomass in two studied horizons 0-20 cm and 20-40 cm. The highest values for fine root biomass are observed in the 0-20 cm horizon and the lowest in the 20-40 cm horizon. Under gallery forest, fine root biomass observed in the 0-20 cm horizon is 2.54 times higher than fine root biomass observed in the 20-40 cm horizon. Similar observations have been made in the hill-slope forest clump.

Several studies regarding the vertical distribution of fine root biomass have been carried out (Xiao et al. 2008, Heinsoo et al. 2009), and many authors observed that 40 to 60 % of fine root biomass are localized in the upper horizon, 0 20 cm (Xiao et al. 2008, Heinsoo et al. 2009). This vertical distribution of fine root could be correlated with the availability of bio-elements and water, because fine roots ensure rapid mineral absorption of bio-elements. Several other phenomena could explain the observed vertical distribution of fine roots: fine root architecture, soil physico-chemical properties, ground litter quantity, as well as microbiological factors (Sundarapandian and Swamy 1996, Pregitzer et al. 2000).

The fine litter decomposition analysis that was carried out simultaneously in two studied forest types revealed high decomposition rates and consequently mineral release into soil pool. During the rainy season, 60 to 67% of the initial mass of litter is decomposed (Ifo et al. 2011). The chemical poorness of tropical soils is compensated by the development of dense fine root mats in the near-surface zone in order to reduce the loss of bio-elements by leaching. The significant differences in fine roots biomass observed between two studied forests types could also be due to the specific species composition in two studied forest ecosystems.

Moreover, tree density and mean basal area per hectare are more important in the gallery forest than in the hill-slope forest clump (Ifo 2010a). The presence of an important number of tree of the class indicate that the forest in our study area is a growing forest. Recent study showed a high carbon stock in the gallery forest (Ekoungoulou et al. 2015). This could be another determining factor for the development of the root mat and fine roots. There were significantly more trees with a diameter higher than 10 cm in the gallery forest, than in the hill-slope forest clump.

Fine roots Production

Results of fine root production rates for two observed forests are similar to data for other wet medium tropical forests published in literature (Singh and Singh 1981, Sundarapandian and Swamy 1996, Cuevas and Medina 1988, Zewdi et al. 2008) but also for forest plantations. The results obtained in the hill-slope forest clump are close to values reported by Jourdan et al. (2008) in a *Eucalyptus saligna* plantation in Brazil.

Measuring fine root production in the natural environment is extremely difficult and published data show large variabilities (Cuevas and Medina 1988) reflecting the need for a standardised reliable method. The method of 'ingrowth core' used in this study can be recommended for ecosystems with very fast tree growth, as is in the case with young tropical forests (Vogt et al. 1998). Table 3 shows some results on fine roots production obtained in tropical forests.

Fine roots Turnover

There are many factors that may affect the lifespan of a root. For instance, Eissenstat and Yanai (1997) hypothesized that herbivore pressure, competition for carbon among various plant parts and seasonality may all affect root lifespan. In our study we have studied the factors, which could explain the lifespan of fine root in two studied forests, where field data were collected.

Fine roots turnover (the proportion of fine roots renewed per annum) is a crucial component of carbon sequestration in forest ecosystems and also an important source of primary plant productivity (Norby and Jackson 2000, Gill and Jackson 2000). According to these authors, fine roots turnover in forest ecosystems varied from 0.02 to 2.64 yr^{-1}, with an average of 0.56 yr^{-1}. In our study fine root turnover in the gallery forest was 0.71 yr^{-1} and 1.32 yr^{-1} for the hill slope forest clump (Table 2). The results obtained in our study are similar to the data obtained in other forest ecosystems. However, they are lower than those obtained by Schroth and Zech (1995) in a tropical *Terminalia superba* forest in Ivory Coast, but also lower than those obtained by Jourdan et al. (2008). Table 4 summarizes some published data. In our study we could not obtain data on fine root turnover in tropical forest ecosystems in the Congo Basin. Therefore, results obtained through this study cannot be compared with those obtained in other natural forest areas. However, the values obtained in two studied sites are lower than fine roots turnover observed by Thongo-M'Bou (2008), who has employed the 'ingrowth core' method for *Eucalyptus* plantations in south-west Congo (2.43 to 3.44 $year^{-1}$).

Because we have not collected soil temperature, the results obtained at the time of this study are incomplete in the sense that they do not make it possible to identify the influence of individual species in the dynamics of fine roots within two studied types of forests. Indeed, Eissenstat and Yanai (1997) affirmed that the turnover of fine roots varies largely inside monoclonal plant species and between the plant species but also through forest ecosystems.

Conclusion

From this study, it is clear that two studied forests are different. The obtained results show a large stock of root mat and root biomass in the 0-40 cm profile. These differences are largely influenced by forest structure. Carbon flow towards the soil related to the renewal of fine roots is similar in these two forests within the studied period, fine root production being similar in the gallery forest and the hill-slope forest clump while it was observed a strong difference in basal area between both mentioned forest types. This could indicate less significance of water and nutrients, or other factors that remain to be investigated. We can conclude that available water could define the fine root biomass and fine root production in the tropical forest as known to us. In our study, it was shown that not the deficit of rainfall in the study site is the cause but the soil structure or texture between the HF and GF.

Acknowledgements

The research was conducted on plots established and maintained with funding provided by the International Foundation for Science (IFS). The skillful technical assistance provided by Pierre Mbemba during data collection in the field is gratefully acknowledged. We also thank all the staff of the Gorilla sanctuary (John Espinall Foundation) for their support during field measurements and the Ministry of Sustainable Forest Management for allowing us to work in the Gorilla sanctuary.

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Received 10 March 2013
Accepted 08 October 2015