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Carbon sequestration in trees and soil in natural and assisted reforestation on the Ibi Village Bateke plateau, Democratic Republic of the Congo

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ABSTRACT

Savannas cover about 76.8 million hectares in the Democratic Republic of Congo (DRC) and are potential sinks for carbon sequestration, which may contribute to the fight against climate change and deforestation and generate carbon credits. Among the means to achieve a reduction in atmospheric CO_2, carbon storage (Sink) in grass or shrub savannas is one solution promoted by international organizations including the Intergovernmental Panel on Climate Change (IPCC). As part of the IBI-Village carbon sink project, we have protected savannas of Bateke plateau against bushfire to determine the carbon sequestration rate. An indirect method based on tree allometric equations (dbh and height) was used to determine the stock of aboveground biomass (AGB). Sampling of soil horizons collected at different depths of soil profiles established according to an altitudinal gradient allowed the estimation of soil carbon stock. The main results are that the gallery forest showed an important reforestation averaging 107,477 t/ha of total biomass or 51,05 Mg C/ha (187,35 Mg CO_2 equivalent /ha sequestered), in comparison with 103,772 t/ha of total biomass or 49,29 Mg C /ha (180,90 Mg CO_2 equivalent /ha sequestered) in the forest island and 22,336 t/ha of total biomass or 10,60 Mg C/ha (38,93 Mg CO_2 equivalent/ha) in the *Acacia auriculiformis* plantation. Defensiveness favors forest species, and thereby accelerates biomass production and thus carbon fixation. The ANOVA used to compare the biomass increments of forest series vs. savannah series has shown that forest series species have twice the biomass increments of savannah series species over the three years of exclusion fire.

Keywords: Biomass, Ibi-village, exclosure, reforestation, shrubland savannas, carbon sequestration.

RESUME

Les savanes couvrent près de 76,8 millions d'ha en République Démocratique du Congo (RDC) et constituent des puits potentiels de séquestration de carbone, susceptibles de contribuer à la lutte contre les changements climatiques et la déforestation et de générer des crédits carbone. Parmi les moyens d'aboutir à une réduction du CO_2 atmosphérique, celui du stockage de carbone (Puits) dans des savanes herbeuses ou arbustives est un des moyens promus par les organismes internationaux dont le groupe d'experts intergouvernemental sur l'évolution du climat (GIEC). Dans le cadre du projet puits carbone d'IBI-Village, nous avons mis en défens des savanes arbustives du plateau des Bateke pour en déterminer le stock de carbone séquestré dans trois types de formations végétales, soit deux formations naturelles et une plantation d'*Acacia auriculiformis*. La méthode indirecte d'allométrie basée sur l'évaluation dendrométrique (Dhp et la hauteur) a été utilisée pour déterminer le stock de la biomasse épigée. L'échantillonnage de profils pédologiques établis selon un gradient altitudinal a permis de déterminer les concentrations du carbone par horizon afin de comptabiliser le stock de carbone dans le sol.

Les principaux résultats obtenus sont: la galerie forestière présente une reforestation importante en moyenne 107,477 t/ha de biomasse totale, soit 51,05 Mg C/ha (187,35 Mg CO_2 équivalent /ha séquestré), l'ilot forestier contient 103,772 t/ha de biomasse, soit 49,29 Mg C/ha (180,90 Mg CO_2 équivalent /ha séquestré) tandis que la plantation d'*Acacia* *auriculiformis* contient 22,336 t/ha de biomasse totale soit 10,60 Mg C (38,93 Mg CO_2 équivalent /ha séquestré). La mise en défens favorise les espèces forestières, et par le fait même accélère la production de biomasse et donc la fixation de carbone. L'ANOVA utilisée pour la comparaison des accroissements en biomasse de groupement d'espèces en série forestière *vs* série savanicole a révélé que les espèces de série forestière présentent le double des accroissements en biomasse des espèces de la série savanicole sur les trois années d'exclusion du feu.

Mots clés : Biomasse, Ibi-village, mise en défens, reforestation, savanes arbustives, séquestration du carbone.

1. INTRODUCTION

The forest carbon presents a major potential as a means to overcome the current global warming (GIEC, 2013). In the Democratic Republic of Congo (DRC), the dense forests that cover 159 million ha (OSFAC, 2010) and savannahs that extend over 76.8 million hectares (Lubini, 1997; Olson *et al*., 2001; Defourny *et al.*, 2011), are important potential sinks that may be involved in the fight against climate change. Savannas are grasslands (White, 1983) with significant potential for carbon sequestration if reforestation can take place (Grace *et al*., 2006; Boulier and Laurent, 2010).

Savannas occupy 20 % of the land area (Scholes and Al, 1996), covering 50 % of the Tropics (Grace *et al.* 2006). According to Beerling and Osborne (2006), savannahs appeared following the coevolution between vegetation, fire and herbivory in connection with the appearance of C4 Poaceae plants playing both the role of fuel and fodder. Their appearance is estimated between 3500-3000 BP (Before present). According to Beer *et al.*, Cited by Malahi (2012), savannas alone contributes to 26 % of the annual total gross primary production that amounts to about 122 Pg C for all tropical forests. Grace *et al.* (2006) reported that the carbon stock sequestered by savannas ranges from 1.8 t/ha of carbon where the shrubs are almost absent to

30 t/ha of carbon in woodlands. The protection of savannahs against uncontrolled fires could allow an increase in natural plant woody biomass; but this process may be slow because species already present in the savannas have been selected based on their fire resistance and are often stunted (Lubini, 1997; Dupuy, 1998).

Bush fires are recurrent and regular in grasslands; their passage often occurs several times a year (Lebrun, 1947 Ballouche and Rasse 2007; Bond, 2008; Nasi *et al*., 2011; Schure *et al*., 2011; Schure *et al*, 2012) and causes the release of greenhouse gases while preventing carbon accumulation. Bush or forest fires are a major factor of deforestation and forest degradation in the world (Ramade, 2008), contributing 10-20% of greenhouse gas emissions (Ramade, 2008; Hairiah *et al*, 2010).

Strategies and / or technologies that promote the carbon sequestration by plants are less expensive compared to other technologies and are preferred to contribute to mitigation efforts of greenhouse gases (Hairiah *et al.*, 2010). Fire exclusion in savannas could allow increasing carbon storage surfaces in the different compartments or reservoirs (sinks) of these ecosystems (aboveground biomass, belowground biomass, dead wood and soil) (Crow, 1978; Cunia, 1987; Brown *et al.*, 1989; Houghton *et al.*, 2001; Chave *et al*., 2001; Chave *et al*, 2009). In favorable climatic conditions, the exclusion of the fire could open the door to a process of transformation of these grasslands into forests. Yet we know very little about such transformation and its impact on carbon storage (Uhl *et al.*, 1997; Hairiah *et al*., 2010; Günter *et al.*, 2011). However, such information is needed to be able to quantify the potential of natural reforestation of savannah ecosystems and integrate this process in a carbon sequestration strategy.

The specific objectives of the study are as follows: i) to quantify the accumulated biomass after three years of fire exclusion in three vegetation types; ii) determine the amount of carbon sequestered in natural reforestations (island and gallery) and assisted reforestation (*Acacia* plantation); iii) to evaluate the stock of carbon in the soil. Specifically, we want to test the following hypothesis: The biomass gain is more important in multispecies natural regeneration stands than in mono-specific stands of *Acacia auriculiformis*.

2. MATERIAL AND METHODS

Our experiment was carried out at Ibi station (4 ° 19'54 " and 4° 24'00 " south latitude, 16 ° 04'36 "and 16 ° 08'00" longitude East), Democratic Republic Congo. The soil and climatic conditions of the site (wet tropical climate and lateritic soils) are described in detail by Lubalega *et al.* (2017). Three types of vegetation (forest Island, gallery forest and *Acacia auriculiformis* plantation) were protected against fire and monitored over three years (Lubalega *et al.*, 2017). The *Acacia auriculiformis* plantation was established in 2007 as a preliminary test of the Bateke Ibi carbon sink, with a spacing of 3m x 3m. The other two vegetation types are forest nuclei present in the savannah (forest island and gallery forest) whose density varies between 400 and 1200 stems per hectare, respectively, with a predominance of *Hymenocardia acida*. Each vegetation type was studied in a total area of 3.75 ha, totaling 11.25 ha for all three types. In each vegetation type, 15 permanent sample plots were established along an altitudinal gradient (660, 610 and 560 m). At each elevation, five permanent plots of 2500 m^2 (50 m x 50 m) were established. Plots were established between June 2010 and April 2011.

The height and diameter at 1.30 m above ground of all stems larger than 5 cm in diameter were measured in June of each of the three years following fire exclusion. In each of the vegetation types studied, three soil profiles of 1.20 m depth were established in the three altitudinal levels (660, 610 and 560 m). In each profile, the litter and three horizons were sampled (0-25cm, 25-70 cm and 70- 120 cm). These soil samples were used to quantify the stock of soil carbon. In total nine soil pits, 27 horizons (layers) were used to determine the amount of carbon in the soil. The soil analysis (total organic carbon) was performed in soil laboratory of the Faculty of Forestry, Geography and Geomatics Laval University, Quebec Canada, following the methods described in Kalra and Maynard (1991). The quantification of above ground biomass was derived from tree height and diameter measurements, and wood density of different species. The allometric equations from Chave *et al.* (2005) were used to estimate biomass from the repeated measurements. The biomass was estimated using the following equation:

$\ln(AGB) = \alpha + \beta 1 \ln(D) + \beta 2 \ln(H) + \beta 3 \ln(\rho)$ with ρ = specific gravity of the timber, expressed in g/cm^3, H = total height of the tree in m, D = diameter of the tree in cm at 1.30 m, AGB = above ground biomass.

Assuming $\beta 1 = 2$, $1 = \beta 2$, $\beta 3 = 1$, the simplified model can be written as $AGB = \exp(\alpha) \rho \times D^2 H$.

Species densities were obtained from the website database of the Zanne *et al.* (2009).

Conversion between biomass and carbon stock was calculated using a factor of 0.475 tons C/tons of dry matter (Chave, 2000). Starting from the diameter distribution, we estimated biomass of each class and each class average is then multiplied by the corresponding number of stems to reconstruct the overall biomass of each vegetation type studied. Then, the CO_2 equivalent was calculated by applying a conversion factor of 3.67 to carbon stock. This indirect method of estimating the total biomass has the advantage of avoiding the destruction of trees in permanent plots.
The main species of natural and assisted reforestations were grouped into series (savannah and forest species) based on studies from Duvigneaud (1949), White (1983), Lubini (2003) and Belesi (2009). The consolidation of forest and savannah species series was used to compare carbon stocks in natural and assisted reforestation.

The soil carbon stock was determined using concentrations of soil organic carbon (SOC) of the different soil horizons. This estimation of soil organic carbon was obtained by the equation:

Stock C (g SOC cm^{-2}) = concentration (g g^{-1}sol SOC) x soil bulk density (g cm^{-3} soil) x depth analyzed horizon (cm). The total amount of SOC stored in the profile (Kirby and Potvin, 2007; Hairiah *et al.*, 2010) was obtained by adding the values of the different layers. Bulk density was derived from our own analysis (unpublished data) of physical properties of samples of different soil layers. Following the density measurements, a density of 1.2 g cm^{-3} soil was used for the first 25 cm and a density of 1.4 g cm^{-3} soil was used between 25 and 120 cm.

Calculating periodic biomass accumulation rate was performed by subtracting the initial biomass from final biomass, all being based on the initial biomass and multiplied by 100.

Repeated measures of biomass were subjected to multivariate analysis of variance (MANOVA) with vegetation type, elevation and time as fixed effects, using the R software (Casgrain and Legendre, 2000). The heteroscedasticity revealed by the Levene test was corrected using a logarithmic transformation. The logarithmic transformation was also used on the raw data of the nine study soil profiles to improve the homogeneity of variances and normality of errors. The Tukey test was used to compare different horizons profiles between study sites.

3. RESULTS

Natural reforestations (gallery forest and Forest Island) present a higher biomass in comparison with the plantation (Figure 1). The gallery averaged 107,48 t / ha of biomass or 51.05 Mg C / ha (187.35 Mg CO_2 equivalent / ha sequestered). The forest island shows an average of 103.77 t/ha or 49.29 Mg C / ha (180.9 Mg CO_2 equivalent/ha sequestered) while the *Acacia auriculiformis* plantation contains about 22.33 t/ha or 10.60 Mg C/ha (equivalent 38.93 CO_2 Mg /ha sequestered).

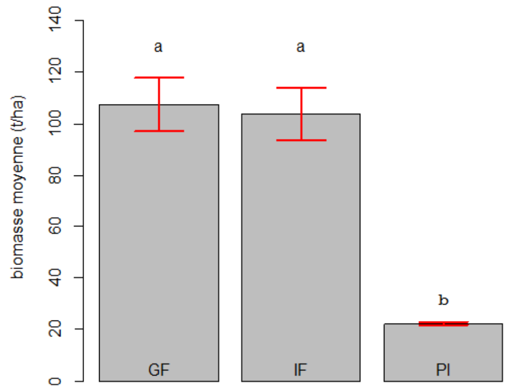

Figure 1. Above-ground biomass (t/ha**)** of trees with diameter larger than 5 cm by vegetation type. (GF): Forest Gallery, (IF): Forest Island**,** (PL) *Acacia auriculiformis* plantation**.**

The MANOVA performed on Above-ground biomass of all species showed a significant triple interaction (Vegetation type * Altitude * Time; p <0.001).

The multivariate analysis of variance performed on 2012 and 2013 annual increments revealed a significant effect of vegetation type (figure 2). Average increments in biomass were higher in the gallery (62.1 t/ha) in comparison with the forest island (40 t/ha) and the *Acacia auriculiformis* plantation (41.3 t/ha). The plantation and the forest island did not differ significantly.

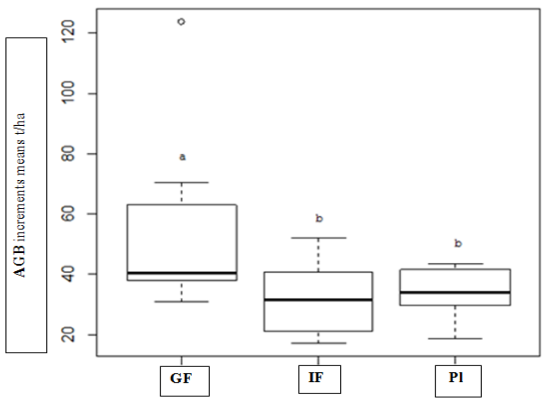

Figure 2. AGB increments by vegetation type. GF: forest gallery, IF: forest island, Pl: plantation

When biomass accumulation is expressed in terms of rates, the results are somewhat different since rates do not differ by vegetation type (figure 3). Periodic rate of biomass accumulation reaches 1.7 % in the gallery forest, 2.5 % in the forest Island and 2.1 % in the *Acacia auriculiformis* plantation.

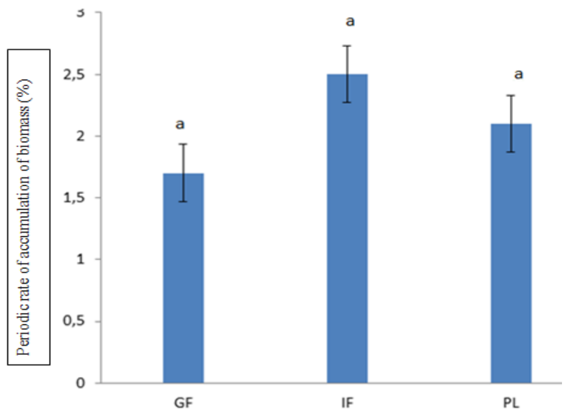

Figure 3. Periodic rate of accumulation of biomass (%) in (GF) Forest Gallery**, (IF)** Island Forest and (PL) *Acacia auriculiformis* Plantation**.**

The dynamics of natural reforestations is strongly influenced by that of forest species. These species have faster diameter and height growth in comparison with savannah species (figure 4). In addition, they also present a higher recruitment rate, regardless of the initial basal area. Beyond approximately 2 m^2/ha, recruitment (trees that reached 5 cm in diameter) comprised only forest species. No recruitment took place in the plantation. Hence, the largest biomass increment was associated with forest species. Forest species showed an average increment in biomass of 53 t / ha, much larger than that of savannah species with an average increment of 37.6 t / ha.

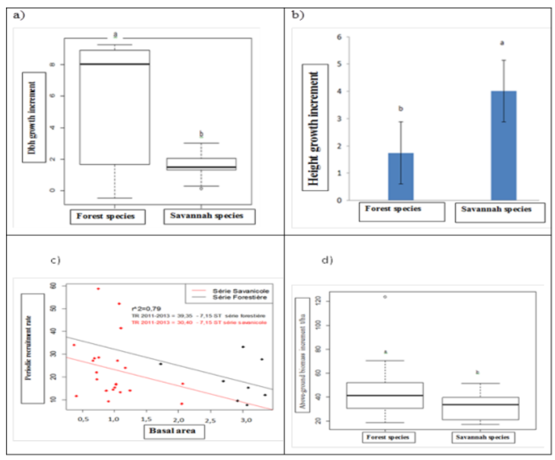

Figure 4. Growth dynamics of forest and savannah species. a): Dbh growth increment, b): height growth increment, c) periodic recruitment rate, and d) above-ground biomass increment.

The soil compartment can also play a significant role in carbon sequestration. The ANOVA performed on the different soil layers showed a significant difference in carbon stocks between layers. The organic soil carbon stock varied between 17.58 Mg carbon per hectare and 169.10 Mg of carbon per hectare. There was a high concentration of organic carbon in the middle soil layers (between 25 cm -70 cm) of all study profiles. With the exception of the litter layer, small stocks were observed in the top soil layer. Comparison of organic soil carbon stock between vegetation types reveals a higher soil carbon content in comparison with the other types (IF and GF). The profiles of the forest island and that of the gallery forest are relatively similar (Figure 5).

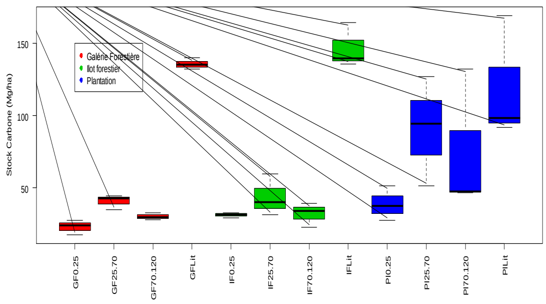

Figure 5. Soil carbon stock in the horizons of three vegetation types**.** GF: forest gallery, IF: forest island**;** PL: *Acacia* plantation. Lit: litter**;** 0-25: first 25 cm of soil; 25-70: soil between 25 and 70 cm depth; 70-120: soil between 70 and 120 cm depth.

4. DISCUSSION

The results show significant potential for carbon storage in natural reforestations following fire exclusion in bushland.

At the end of the study, both natural reforestations (GF and IF) following fire exclusion contained more aboveground biomass comparative to the *Acacia auriculiformis* plantation. Part of this could be linked to the fact that these vegetation types may have started to accumulate biomass earlier than in the plantation. However, natural reforestations presented accumulation rates similar to plantations and the absolute periodic biomass accumulation was even higher than in the plantation. This clearly demonstrates the potential of natural reforestation combined with fire exclusion to increase carbon sequestration in these ecosystems. However, the above-ground biomass and carbon stock of the gallery forest seem slightly high compared to results from other authors, including Durrieu of Madron (2008). This strong above-ground biomass of the forest gallery could be explained by the diversity of species. These results corroborate the observations from Chave (2000) and Chave *et al.* (2005) even though the mature forests studied by these authors did not have the same density compared to our young forests. These young secondary forests are dominated by pioneer species with rapid growth and short life span (Kellman, 1970). The strong presence of pioneer species would explain the high accumulation rates and increases in biomass of natural reforestations. Our results are closer to those of Beer *et al.* (2010) quoted by Malhi (2012) and Grace *et al.* (2006) which take into account the density of savannah ecosystems. The denser shrub or tree savannahs are the more carbon they sequester. In our study, the fire exclusion has initiated a process of promoting densification of forest cores and greater carbon storage.

The potential of natural reforestations as carbon sinks could be related to local climate. The occurrence of savannah in the study region would seem to be more related to the repeated occurrence of fire rather than to the amount of precipitation since the climate could support a closed forest. This would explain the fast dynamics of the vegetation protected against fire.

The effectiveness of natural reforestations in sequestering carbon is closely linked to the dynamics of forest tree species. The development of these species was made possible by three years of fire exclusion. Forest species include a number of species (Lubalega *et al.*, 2016) that provide richness and diversity within the regenerating stand. Forest species showed faster height and diameter growth in comparison with savannah species, leading to larger biomass increments and carbon storage. The carbon sequestration in natural reforestations is associated both to the growth of existing trees and to the recruitment of new ones. No recruitment was observed in the plantation during the study period.

The evolution of above-ground biomass suggests that the natural recovery of the forest following fire exclusion fosters forest series whose photosynthetic capabilities are well known and are the subject of the proposal in the Kyoto Protocol Article 3.3 afforestation and reforestation (Hairiah *et al.*, 2010; Pan *et al*, 2011; Picard et al, 2012; Vanderhaegen *et al.*, 2015).

In addition to its effect on above-ground carbon stocks, reforestation, either natural or through plantation should benefit to other compartments such as below-ground biomass, dead wood, litter and soil (Crow, 1978; Cunia, 1987; Brown *et al.*, 1989; Houghton *et al.*, 2001; Chave *et al.*, 2001; Chave *et al.*, 2009). However, our study did not take into account necromass or root biomass in this study.

Our estimates of soil carbon stocks are somewhat higher than those previously reported (Nair *et al.*, 2011; Kaonga and Bayliss-Smith, 2012; Kim, 2012). The stocks of organic carbon in the various soil layers differed but part of the difference could be related to the fact that the layers do not all have the same thickness. Thus, the top layer has only 25 cm, compared to 45 cm in the middle soil layer. However, this difference, more particularly in the plantation, would not be sufficient to explain the large carbon stocks of the middle layer. Overall, levels of the Bt horizon seem to accumulate large amounts of carbon. This is consistent with the results of Batjes (1996) and Jobbagy and Jackson (2000). The same authors report that 50% of the organic carbon stock occurs deeper than 30 cm. In our study it is important to also point out that the bulk density increases with depth. The sandy soil texture allows an important migration of carbon to the middle layer. Thus, the layers of depths 25-70 cm and 70-120 cm are important elements in the carbon cycle that must be taken into consideration.

Soil carbon stocks were larger in the *Acacia* plantation, even though the above-ground biomass was smaller than in natural regenerations (GF and IF). To explain differences in biomass, we postulated that biomass accumulation could have started earlier in the natural reforestations. This could not explain the differences in soil biomass and further studies would be required to better understand carbon soil dynamics.

Several methodological difficulties arise when we want to estimate non-destructively carbon accumulation for a variety of species. A first one is the conversion of dendrometric data into biomass. Djomo *et al.* (2010) showed that, in the absence of specific allometric equations for each species, the best equations of biomass estimates are those of Chave *et al.* (2005) considering the forest type and availability of explanatory variables. For this study, the models of Chave *et al.* (2005), taking into account the density of the wood, the diameter and height, were used. The comparison of our results with those of other authors (Djomo *et al.*, 2010) who have worked in almost similar conditions in Cameroon leads us to believe that the models of Chave *et al.* (2005) are suitable for estimating biomass tropical trees.

Our results are congruent with our hypothesis. The key for us was to demonstrate that a forest naturally regenerated through fire exclusion is a carbon sink that could be considered for funding under the REDD + program, and constitute an alternative to tree plantation in savannah.

5. CONCLUSION

The current widespread use of fire not only contributes to CO_2 emissions but also prevents carbon sequestration in savannah ecosystems. Fire exclusion in savannah ecosystems favors natural reforestation which provides a carbon sink option. In cases where plantation costs cannot be afforded or where the ecosystem services provided by a diversified natural forest are sought, natural reforestation can act as a complement or an alternative to planting. However, this option does not exclude reforestation with fast growing species in a short period of time which also provides goods and services to humans.

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