EFFECT OF SELECTIVE LOGGING ON SOIL ORGANIC CARBON DYNAMICS IN TROPICAL FORESTS IN CENTRAL AND WESTERN AFRICA

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Abstract

Background and aims Forest soils in tropical areas are an important carbon (C) reservoir that can emit considerable amounts of C when they are disturbed by selective logging activities. Nevertheless, changes in soil organic carbon (SOC) are often neglected even within activities that aim to promote the long-term permanence of forest carbon stocks, such as the REDD+ framework. In this purpose, we assessed the effect of selective logging on the SOC levels in three chronosequences in Ghana, Cameroon and Gabon, to evaluate whether selective logging impact significantly the SOC.

Methods In each chronosequence, from unlogged forest to forest that was selectively logged at different times in the past, adjacent plots were investigated by sampling the soil at various depths to 1 m.

Results Both SOC concentrations and stocks drastically decrease after selective logging in all sites. The topsoil (0-30 cm deep) is the layer with the most evident SOC decreases, particularly in the first and second decades after selective logging. The SOC loss is later stabilised, but the C levels remain lower than those of the unlogged forest 40-50 years after selective logging. Unlike the above-ground biomass, the loss of SOC occurs over time and, considering a rotation period of 30 years, the C loss from soil ranges from 20% to 26% of the original SOC stock, which is located in the upper range of C loss reported for biomass (5-30% of the original C).

Conclusions In all the investigated chronosequences, the SOC levels are strongly affected by selective logging activities, and the soils can continue losing C for many years. In conclusion, SOC level measurements are extremely important and should be used to consider whether realistic C emission-removal estimates must be provided. In particular, in the REDD+ framework, which is specifically designed for tropical forests, the loss of SOC remains often neglected.

Introduction

The forests of Western and Central Africa, which comprise 90% of lowland forests, are facing an increasing anthropogenic pressure (Verhegghen et al. 2012). Among different human activities, selective logging, which is the method of cutting only certain selected tree species, is the most widespread type of forest management in the tropical zone of the African continent, where increasing forest areas are allocated to timber concessions (Laporte et al. 2007; Guariguata et al. 2010; Wilson et al. 2010). Although low-intensity selective logging is considered a sustainable forest management (SFM) practice, as any management practice causes disturbances to the forests, which intensity is generally related to the number of harvested trees and the logging equipment. The disturbance from selective logging has been considered to produce effect on the forest structure (Hall et al. 2003; Okuda et al. 2003), species composition (Silva et al. 1995; Magnusson et al. 1999), genetic diversity (Jennings et al. 2001), nutrient cycling (Herbohn and Congdon 1993) and mammal habits in some cases (Stephenson 1993). In addition, logging has been observed to promote human settlement, bush meat trade and forest degradation (Poulsen et al. 2009; Laporte et al. 2007). In Central and Western Africa, the typical harvesting is highly selective: approximately 1-2 trees per hectare at each passage (Addo-Fordjour et al. 2009; Medjibe et al. 2011). However, in many places, loggers make repeated entries and consequently deplete the stock of adult commercial trees, which causes considerable damage to the stands and promotes forest degradation (Karsenty et al. 2006). The consequences of logging are visible in subsequent decades (Hawthorne et al. 2012).

Despite the increasing attention to the C stock changes that occur in the above-ground biomass after selective logging (Gourlet-Fleury et al. 2013; Blanc et al. 2005), there is a lack of information regarding the effect of selective logging on the soil organic carbon (SOC) pool. In tropical areas, soils represent the major C reservoir, where 36-60% of ecosystem C is stored in forest soils (Malhi et al. 1999). Hence, a possible emission of C from soil as a consequence of forest management can have serious implications on the current and future atmospheric CO_2 concentrations. In fact, in tropical areas, the logging activities represent a significant proportion of the gross annual anthropogenic flux of carbon dioxide (CO_2) to the atmosphere (Laporte et al. 2007; Asner et al. 2005; Bryan et al. 2010; Huang and Asner 2010; Matricardi et al. 2010). Logging, even if selective, promotes SOC decomposition by creating gaps in the canopy cover and reducing the inputs of organic matter to soil (Yanai et al. 2003). However, few studies deals with the impact of selective logging on the SOC pool in tropical forests (e.g. Berenguer et al. 2014), particularly in the forests of Sub-Saharan and Central Africa, which account for one-fifth of the global net primary production (Brown and Gaston 1995; Cao et al. 2001). Nevertheless, the interest in the carbon balance of the tropics and especially the impact of forest management on the C cycle remains high (Grace et al. 2014).

International discussions at the United Nations Framework Convention on Climate Change (UNFCCC) have focused on a mechanism that will financially reward countries for verified reductions of C emissions caused by deforestation and forest degradation to conserve and sustainably manage forests and to enhance forest carbon stocks (REDD+ framework). These include developing baseline scenarios against which the reduced greenhouse gases (GhG) emissions and/or enhanced storage of carbon can be measured. In fact, REDD+ is ultimately aimed at incentivising forest protection/enhancement of carbon stocks through performance-based payments for actions that should be fully measured, reported and verified (MRV) at the national level to measure the performance against a reference scenario (UNFCCC 2014). So far six countries have presented their forest reference level and/or emission levels for REDD+ result base payments: Brazil, Columbia, Ecuador, Guyana, Malaysia and Mexico. Among those only Brazil was reviewed while the others are currently under revision. Brazil, Columbia, Mexico and Ecuador have presented their reference level related only for deforestation activities. Columbia and Ecuador have not included the emissions in the SOM pool due to lack of sufficient data, while Brazil and Mexico have considered the emission from the pool as not significant on the basis of literature review (Brazil) or national greenhouse gases inventory data (Mexico). The national reference level of

Malasya relates only to sustainable forest management activities, with no consideration for the soil pool due to the lack of data. Guyana is the only country that have included the soil pool in the reference level related to deforestation activities while in the one related to degradation activities the pool was excluded on the basis of the data provided by Jonson and Curtis (2001) that show that selective logging has no impact on soil carbon over large concessions. All the reference level include the emissions of above and belowground biomass. The quantification of the SOC stock and emission because of forest activities is particularly interesting in the REDD+ framework, where the loss of C from soil continues to be neglected in assessing the performances of REDD+ in tropical areas (Pearson et al. 2014).

Based on the working hypothesis that the SOC will change after a forest disturbance, this work aims to a) evaluate the effect of selective logging on the SOC levels in intact forests from Central and Western Africa, b) assess the resilience of intact forests in term of the SOC levels and c) evaluate whether the assessment of REDD+ activity performance should include the measurement of SOC.

These aims are justified because tropical forests are logged at approximately twenty times the rate at which they are cleared (Asner et al. 2005), and 403 million hectares of tropical forest are officially designated for timber production (Blaser et al. 2011). Therefore, it is important to assess the effects selective logging on the SOC dynamics to evaluate the overall contribution of the managed forests on the global carbon cycle and consequently assess their mitigation potential.

Materials and Methods

Sites description

We focused on an area where most tropical forests of the African continent are located and selective logging is the type of forest management most largely applied: a) Ghana, at the border of the humid forest zone, where native rainforests are few and must be preserved, and b) Cameroon and Gabon, which are within the Congo basin rainforests (Figure 1). The basic characteristics of the three areas are shown in Table 1.

Ghana

The Bobiri forest reserve (6° 40′ 41″N; 1° 19′ 12″W) covers an area of 54.6 km^2 and is located about 30 km east of Kumasi in the Central part of Ghana. The mean annual temperature (MAT) is about 26 °C and the mean annual precipitation (MAP) ranges between 1200 and 1750 mm essentially bimodal, from March to July and from September to November. The altitude of the area is varying between 180 m to 250 m. The geological substrate is represented by metamorphosed lavas and pyroclastic rocks of the Upper Birrimian System (Schlüter 2008), and the typical soils are Oxisols according to the U.S. soil taxonomy. The Bobiri forest lies within the moist semi-deciduous Forest zone (Hall and Swaine 1981). The reserve was created in 1939 when the forest was still untouched (Ghana Forestry Department 1958), and different species were dominating the forest composition, in particular *Celtis* spp. and *Triplochiton scleroxylon K. Schum.* Later, the forest reserve became an experimental site for improving forest management systems, among which selective logging (Asante-Yeboa 2010).

Cameroun

The investigated area falls within a forest concession to a private company, SEFAC, close to the Lobeke National park (2° 37’ 51”N; 15° 59’ 26”), in the southeastern corner of the country. The climate of the area is consistent with a short (September to November) and a long (March to June) wet seasons and a long (December to February) and a short (July to August) dry seasons. The MAT is about 24 °C and relative humidity is generally between 70% and 90%, while MAP is about 1400 mm. The landscape is hilly with the altitude varying from 300 m to 750 m. Semi-evergreen forests dominate the area, with dominant species such as Sterculiaceae (Triplochiton, Pterygota), Ceiba pentandra and Terminalia superba. The geological substrate of the area is represented by Metasediments of the Lower Dja Group from the Neoproterozoic era (Schlüter 2008), and the typical soils are Ultisols according to the U.S. soil taxonomy. At present, SEFAC manages in the southeast part of Cameroon a total concession area of 411,872 ha, all with an approved management plan. The felling rate used for all species is 1% and the rotation period is 30 years (SEFAC 2005)

Gabon

The Lopé National Park is located in the centre of Gabon (00° 12′ 04″; 11° 36′ 05″ E) and covers an area of 4970 km^2 (Figure 1). The MAT varies between 23 °C and 31°C while the MAP, taken from 1984 to 2004 at the *Station d'Etudes des Gorilles et Chimpanzés* (SEGC) in the centre of the study site, is 1474±45 mm. There is a marked seasonality in the distribution of rainfall, with a long dry season between mid-June and mid-September whose severity and duration varies between years. The Park is part of the Congo Basin lowland forests and it is mainly covered by closed canopy rainforests with savannah systems in the north and east edges. Different vegetation types have been described in the Park, including young colonising forest, forests dominated by Aucoumea klaineana and Sacoglottis gabonenis, Marantaceae forests and mature forests (White 1995). According to Schulter (2008), the geological substrate of the area is represented by rocks of the Metamorphic series of the Ogooué river from the Proterozoic era. Having occurred relatively recently, incomplete rock alteration and weathering processes have given rise to soils with particular features, that are comprised within the order of the Oxisols (Martin et al. 1981).

Selective logging chronosequences

To evaluate the effects of selective logging on the SOC levels, a soil chronosequence was identified in each of the three countries. A primary forest stand was selected in each area to represents the starting point of the chronosequence. Historical maps and management plans allowed us to identify forest plots that were logged in different years in the past. Only in Cameroon, the sites were located in a forest concession and underwent a rotation period of 30 years, whereas in Ghana and Gabon, all selected sites underwent only one selective logging entry, and the sites were not further disturbed. The felling rate was the same for the three chronosequences (Table 1). In each country, the different plots of the chronosequence were comparable for soil characteristics (e.g., texture, pH), exposure and vegetation (Table 2). In particular, in Ghana, a chronosequence was identified from the primary forest to the sites that were selectively logged 10, 18 and 50 years ago. In Cameroon, a chronosequence was identified from the primary forest to the sites that were selectively logged 10, 30 and 45 years ago. In this latter case, the 45-year-old logged site underwent the second logging 15 years ago, whereas the 30-year-old site was at the end of the first rotation period. Finally, in Gabon, a chronosequence was identified from the primary forest to the sites that were selectively logged 15 and 40 years ago.

Sampling and SOC assessment

To determine the changes in SOC levels, in each site we investigated a 1 ha plot. Three soil trenches were randomly opened in each plot down to 1 m depth, and the soil samples were collected at the opposite profiles at a 0-5, 5-15, 15-30, 30-50, 50-70 and 70-100 cm depth using a cylinder of known volume to determine also the bulk density. Four additional points were selected, and the soil was collected at the same depths using an auger, to have 10 sample replicates per each layer. Ten samples of the organic horizon were also collected in each plot using a 40 by 40 cm frame.

All samples were oven-dried (60 °C) to a constant mass. The organic horizon was ground in a ball mill, whereas the mineral soil was sieved at 2 mm, and the analyses were performed on the fine earth fraction (<2 mm). The total C was measured on finely ground samples using dry combustion (Thermo-Finnigan Flash EA112 CHN). The SOC stock was calculated for each depth according to Boone *et al.* (1999), considering the C concentration, bulk density, rock fragment content and depth of each layer. Differences in C concentrations and C stocks were determined among all the site of a chronosequence using analysis of variance (ANOVA) with SYSTAT 12. When significant interaction effects were observed multiple comparisons test (Tukey HSD) was done. Statistical significance for ANOVA were tested at α.

Results

Changes in SOC concentration after selective logging

The effect of selective logging on the SOC concentrations is particularly evident in the upper layer from all chronosequences (Table 3). In Ghana, in the 0-5 cm layer, the SOC loss was evident both after 10 and 18 years, as the C concentration decreased by approximately 2 g C kg^{-1} compared to the unlogged forest. In the other layers, no significant difference was observed except in the 15-30 and 30-50 cm layers. After 50 years, the forest recovered its SOC content in the 0-5 cm layer but not in the other layers (Table 3). Similarly, in Cameroon, the SOC loss after selective logging in the 0-5 cm layer was notably high, and the SOC decreased from approximately 7 g C kg^{-1} in the unlogged forest to 4 g C kg^{-1} in both plots that underwent one logging 10 and 30 years ago (Table 3). In the plots that underwent the second logging, the C concentration was much lower: ~2.5 g C kg^{-1}. In the other layers, significant differences between the logged plots and the primary forest were observed only in the 5-15 cm layer. In Gabon, significant changes were detected in all layers except the 30-50 cm one. In the 0-5 cm layer, a significant C decrease was observed also after 40 years since selective logging, where the C concentration decreased by approximately 2 g C kg^{-1} compared to the 4 g C kg^{-1} in the primary forest (Table 3).

Effect of selective logging on SOC stocks and fluxes

In Ghana, in term of SOC stocks, considering the topsoil (0-30 cm), a loss of approximately 14.1±7.8 Mg C ha^{-1} compared to the primary forest was observed 10 years after selective logging, which remained stable both 18 and 50 years after logging (Figure 2a). Considering the entire profile (0-100 cm), the SOC loss was higher: approximately 30 Mg C ha^{-1} in the 10, 18 and 50 year-old logged sites. In Cameroon, the SOC loss from the topsoil was much higher than in Ghana: 24.0±9.4 Mg C ha^{-1} after 10 years. In the following 20 years, the loss remained stable and considerably increased to 37.5±7.9 Mg C ha^{-1} after the second logging entry was performed (Figure 2b). Considering the entire profile, the trend in SOC loss mirrors that of the topsoil. In Gabon, the situation is similar, with a SOC loss from the topsoil of 10.8±6.7 Mg C ha^{-1} after 15 years, which drastically increased to 18.8±6.8 Mg C ha^{-1} after 40 years from logging (Figure 2c). In the entire profile, the C loss was even higher: the soil lost 44.0±19.4 Mg C ha^{-1} after 15 years and 48.4±16.7 Mg C ha^{-1} after 40 years since selective logging. The organic horizon as well is losing C in all the considered sites. In Ghana the unlogged forest has 6.7 Mg C ha^{-1} stored in the organic horizon, that decrease to 5.2±1.9 Mg C ha^{-1} 10 after logging, to increase to 5.8±1.9 Mg C ha^{-1} and 6.1±2.1 Mg C ha^{-1} 18 and 50 years after logging, respectively. In Cameroon there is a similar pattern, with the C in the organic horizon drastically decreasing from 8.1±2.4 Mg C ha^{-1} in the unlogged forest to 2.9±1.4 Mg C ha^{-1} 10 years after logging, 4.0±2.1 Mg C ha^{-1} 30 years after logging and 3.3±1.7 Mg C ha^{-1} 45 years after logging. In Gabon the organic horizon in the unlogged forest has 7.5±1.4 Mg C ha^{-1} that decrease to 3.7±1.4 Mg C ha^{-1} and 3.9±1.7 Mg C ha^{-1} 15 and 40 years after selective logging.

Considering the number of years since the deforestation and the difference in SOC stocks (Δ_{SOC}) between the primary forest and the selectively logged plots, the average annual SOC fluxes for the 0-30 cm depth were derived (Figure 3). In Ghana, the mean annual SOC flux was -1.4 Mg C ha^{-1} yr^{-1} during the 10 years after selective logging, which decreased to -0.3 Mg C ha^{-1} yr^{-1} from 10 to 18 years and to -0.05 from 18 to 50 years since logging (Fig. 3a). In Cameroon, the fluxes are much higher: -2.4 Mg C ha^{-1} yr^{-1} during the first 10 years, +0.1 Mg C ha^{-1} $year^{-1}$ from 10 to 30 years and decreasing again to -1.1 Mg C ha^{-1} yr^{-1} during the 15 years after the second logging (Fig. 3b). In

Gabon, the rates of SOC loss were -0.7 Mg C ha^{-1} yr^{-1} in the first 15 years after logging and -0.3 Mg C ha^{-1} yr^{-1} from 15 to 40 years (Fig. 3c).

Discussion

Resilience of soil organic carbon after selective logging

This study quantifies the amount of SOC lost during several decades after selective-logging activities in tropical forests. The effects of intensified forest management to produce more timber, fuel wood and other forest commodities is one of the most direct causes of variations in forest carbon stocks; however, the substitution benefits of using a larger share of the forest biomass does not always compensate the loss of forest carbon (Hudiburg et al. 2011). Selective logging removes large trees, which are one of the principal carbon reservoirs of a tropical forest (Vieira et al. 2005). Furthermore, all logging activities leave behind large amounts of slash. Decomposing slash and an increased mortality of residual trees lead to an increase in CO_2 emissions for years after the harvest (Blanc et al. 2009, Huang and Asner 2010). In this study, the effect of selective logging on the SOC levels is clearly evident, affecting both C concentrations and stocks. The topsoil, which is the layer where most C of tropical forests is stored, is the most susceptible layer to changes after some disturbance (Chiti et al. 2014). In fact, in all cases, the C concentration always dramatically decreases in the first years after selective logging. This is an important point since a recent study on the effect of selective logging on SOC carried out in the tropical area of Amazonia concluded that the SOC pool from the first 30 cm of selectively logged forests contain a comparable amount of SOC as that of undisturbed forests, suggesting that this pool is resistant to impacts from selective logging (Berenguer et al. 2014). A recent review by Marin-Spiotta et al. (2008) also reports the robustness of forest SOC to disturbances in the tropical area, while a review by Don et al. reported the opposite, despite both reviews were not dealing with selective logging but rather land use changes. On the other hand, these discrepancies concerning the impact of selective logging on the

SOC pool suggest that forest can react differently, highlighting the need to monitor the SOC along time.

Particularly interesting is the case of Cameroon, which enables an evaluation of the effect of the rotation period (30 years) on the soil resilience. Despite the changes that rapidly occurred after the first selective logging, the SOC loss was stabilised at the end of the first rotation period, which indicates an inversion of the process and consequentially a possible SOC accumulation. Furthermore, the consequences of the second logging are dramatic, with the C concentration decreased to critical levels (Table 3). This result is particularly important because in the literature it has been well established that it is impossible for a first-time-logged tropical forest to recover its timber stock within the usual duration of a felling cycle (Putz et al. 2012; Gourlet-Fleury et al. 2013), and the same result can be observed for the SOC levels. Hence, although the first harvest in African and Amazonian forests is often of low intensity and targets only one or two species, subsequent harvests of less-valuable species ensure that these forests experience serious degradation processes. The logging intensity and rotation period are undoubtedly the major determinants of the extent to which the forest carbon stocks are depleted (Blanc et al. 2009; Koltunov et al. 2009, Huang and Asner 2010).

In Ghana, the behaviour is similar, with the forest soil loosing C after selective logging activities until a new equilibrium was established between 10 and 18 years after logging, and the forest soil stopped losing C. Nevertheless, even after 50 years from selective logging, the SOC stock remains significantly lower than that of the unlogged forest, which suggests that the resilience of tropical forests is seriously compromised, and the process to establish a new equilibrium with the previous C stocks can last several decades. This fact is particularly evident in the case of Gabon, where only after 40 years since selective logging, the SOC loss appears stabilised. The long time that these forests require to recover their original SOC stock suggests a contrasting behaviour with the risk of selective logging to promote forest degradation (Berenguer 2014; Nepstad et al. 1999), although two of the investigated cases show a good resilience of forest soils to recover after selective logging. In fact, forest degradation arises mostly from selective logging, where the fraction of trees removed is not sufficient to change the land cover from 'forest' to 'non-forest' (Nepstad et al. 1999; Asner et al., 2005).

The significant effect of selective logging in altering the SOC dynamics can possibly be explained with tree-harvesting operations that unavoidably open canopy gaps, reduce the overall canopy cover, and disturb the soil surface. In the tropical area of South America, Jackson et al. (2002) found that logging caused gaps in more than 25% of the forest canopy, similar to Johns et al. (1996), who observed a 10% canopy reduction after moderate logging. In Central African Republic, Durrieu de Madron et al. (2000) reported gaps in 14–22% of the area because of selective logging. These results show that the harvest of even small numbers of large trees results in substantial canopy opening and promotes SOC decomposition. The strong effect that selective logging activities with a minimal disturbance can have on forests that plausibly reach their equilibrium is evident when we examine the mean SOC fluxes (Figure 4). In fact, the mean annual rates of SOC loss in the three areas considered in this study are comparable to the SOC loss observed following deforestation for plantation purposes in West Africa (Chiti et al. 2014).

From this study the effect of selective logging on the SOC stock and fluxes become extremely clear, indicating how large can be the impact of SOC contribution to total atmospheric CO_2 increase at regional level for areas interested by selective logging activities.

Relevance of soil organic carbon within the REDD+ framework

In tropical areas, REDD+ activities are becoming extremely important (Angelsen et al. 2009). Nevertheless, the role of SOC emissions remains often neglected. As reported in a recent paper from Pearson et al. (2014), SOC emissions as a consequence of selective logging are generally not considered in the REDD+ framework because they appear to have no effect on soil carbon over large concessions because of the relatively small affected area, short duration of the effect and retention of vegetative cover, as shown in a literature review by Johnson and Curtis (2001). Nevertheless, the review of Johnson and Curtis (2001) includes only a few sites in the tropical area, whereas the evidence from this study suggests a different behaviour. In addition, the emission patterns of SOC should be considered over time and not limited to the year of disturbance to demonstrate a cumulative effect over the area. The approach proposed by Pearson et al. (2014) to quantify emission caused by logging received great attention and is currently applied in several countries in the tropical area (see also submission REDD+ Guyana 2015). The results of our study shows that the SOC emissions after selective logging could be relevant and could play a relevant role in the estimates of REDD+ activity performance, summed to the emissions from above ground vegetation that are largely quantified in the literature (Gourlet-Fleury et al. 2013; Blanc et al. 2009). Immediately after logging, the reported decrease in aboveground biomass for the falling rate of approximately 1 tree per hectare is about 8% (17 Mg C ha^{-1}) of the original biomass in Gabon (Medjibe et al. 2011) and about 4% (8 Mg C ha^{-1}) in Central African Republic (Gourlet-Fleury et al. 2013). A long-term plot study in French Guiana showed that conventional logging led to emissions equivalent to more than one-third of the aboveground biomass, and these logged plots were predicted to recover their aboveground carbon within 45 years (Blanc et al. 2009).

Considering a hypothetical rotation period of 30 years for the selective logging plots considered in this study, the SOC loss in 0-30 cm depth relative to the original stock would be notably similar among the three countries: 20% in Ghana, 26% in Cameroon and 25% in Gabon. These percentages are in the upper limit of the earlier reported range of relative C loss of biomass (4-30%). In absolute terms, the SOC loss over the period of 30 years is comparable to those of biomass that occur at the year of the felling: 12 Mg C ha^{-1} in Ghana, 22 Mg C ha^{-1} in Cameroon and 12 Mg C ha^{-1} in Gabon. Because the aboveground biomass can accumulate C much faster than the soil, the importance of measuring the SOC loss because of logging becomes evident, particularly considering the REDD+ framework (Hein and van der Meer (2012). The SOC is often excluded from the considered ecosystem dynamics, whereas this study evidences the necessity to include the SOC measurements to avoid overlooking an important input for the assessment of ecosystem carbon stock changes. Hopefully, the implementation of sustainable forest management (SFM) in the REDD+ mechanism can decrease the process of forest degradation and deforestation. It is worth noting that the entire profile (0-100 cm) should be considered to thoroughly assess the effect of the management practices as also observed by Berebguer et al. (2014), although the costs for this assessment at a large scale may be prohibitive.

Conclusions

The results from this study suggest that selective logging leads to negative consequences for tropical forest ecosystems, which are comparable to those linked to the depletion of timber species or the loss of above-ground biomass. The SOC levels are strongly affected by logging activities, and the soils can continue losing C for many years; the amount of SOC loss is comparable to that of the aboveground biomass vegetation in absolute values but much higher considering the initial C stock. Nevertheless, the forests show a good resilience in terms of SOC stock recovery, and if no further disturbances occur, the forest tends to establish a new equilibrium to prevent the degradation process. Thus, if selective-logging practices are sustainably performed, they can decrease the emissions and represent a promising strategy to decrease soil carbon emission in the REDD+ actions to reduce forest degradation and improve forest management.

In conclusion, despite the difficulty in collecting samples in remote areas, SOC level measurements are extremely important, and one must consider whether realistic emission-removal estimates must be provided.

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Tables and Figures

Country	Site	Latitude	Longitude	Altitude	MAT[Ψ]	MAP[α]	Vegetation	Soil[ϕ]	Logging rate(
				m	°C	mm			species ha^{-1}
Ghana	Bobiri[a]	6.6780°N	-1.3201°W	200	26	1500	Semi deciduous[d]	Oxisols	1-2

Cameroon	SEFAC[b]	2.6308°N	15.9905°E	400	24	1400	Semi evergreen[e]	Ultisols	1-2
Gabon	Lopé[c]	-0.1165°S	11.6012°E	300	25	1500	Semi evergreen[f]	Oxisols	1-2

[a] = Asante-Yeboa 2010; [b] = SEFAC, 2005; [c] = White et al.. 1995; [d] = *Celtis* spp. and *Triplochiton scleroxylon* K. Schum.; [e] = Sterculiaceae (Triplochiton, Pterygota), *Ceiba pentandra* L. Gaertn.; [f] = *Aucoumea klaineana* Pierre and *Sacoglottis gabonenis* (Baill.) Urb., *Diospyros dendo* Welw. ex Hiern. $^{\Psi}$ = Mean Annual Temperature; $^{\alpha}$ = Mean Annual Precipitation; $^{\phi}$ = Soil classification according to Soil Survey Staff (2014).

Table 1 – Basic characteristics of the three areas.

	Sand $^{\phi}$	Silt $^{\phi}$	Clay $^{\phi}$	pH‡	Bulk density	Rock fragments % on total mass
Bobiri-Ghana	g kg^{-1}	g kg^{-1}	g kg^{-1}		Mg m^{-3}	
Primary forest	410±15	350±19	240±14	4.5	1.2±0.1	11±6
10 yr sel. logging	403±12	319±15	278±16	4.8	1.3±0.1	15±9
18 yr sel. logging	417±12	315±19	268±19	4.7	1.4±0.1	13±9
50 yr sel. logging	407±16	312±13	281±12	4.9	1.3±0.2	15±7
SEFAC-Cameroon						
Primary forest	389±13	233±13	378±15	4.3	1.2±0.2	0
10 yr sel. logging	394±13	236±16	370±11	4.6	1.3±0.2	0
30 yr sel. logging	381±17	239±15	380±13	4.8	1.3±0.1	0
45 yr sel. logging	385±19	240±11	375±11	4.8	1.2±0.2	0
Lope'-Gabon						
Primary forest	425±16	198±11	377±15	4.6	1.1±0.2	0
15 yr sel. logging	418±14	215±15	367±14	4.9	1.2±0.1	0
40 yr sel. logging	424±11	212±13	364±14	4.9	1.2±0.1	0

$^{\phi}$ = Determined using the pipette method after destruction of the organic cement by sodium hypochlorite adjusted at pH 9 (Mikutta et al. 2005); ‡ = potentiometrically measured in deionised water with a soil–liquid ratio of 1:2.5.

Table 2- Particle size distribution, pH, bulk density and stoniness of each site of the chronosequences.

Site*	Years since logging	0-5 cm	5-15 cm	15-30 cm	30-50 cm	50-70 cm	70-100 cm
	-	g C kg^{-1}	g C kg^{-1}	g C kg^{-1}	g C kg^{-1}	g C kg^{-1}	g C kg^{-1}
GH	Primary forest	44.4 ± 3.2a	14.1 ± 1.0a	12.3 ± 1.2a	8.2 ± 1.0a	6.9 ± 1.1a	5.2 ± 1.0a
GH	10	26.3 ± 2.9b	24.0 ± 1.8b	8.8 ± 1.0b	4.9 ± 1.1b	6.6 ± 0.9a	4.3 ± 1.1a
GH	18	23.8 ± 1.1b	18.0 ± 1.2a	5.6 ± 1.0c	4.9 ± 0.9b	4.7 ± 1.0a	4.3 ± 1.0a
GH	50	41.1 ± 1.2a	10.4 ± 3.8a	5.7 ± 1.0c	5.3 ± 1b	4.7 ± 1.2a	5.4 ± 0.9a
CM	Primary forest	63.5 ± 3.6a	24.5 ± 0.8a	9.7 ± 0.9a	9.7 ± 1.1a	5.3 ± 0.9a	7.3 ± 1.1a
CM	10	32.7 ± 3.8b	15.4 ± 2.2b	10.5 ± 0.9a	7.5 ± 1.1a	7.1 ± 1.2ab	6.8 ± 1.5a
CM	30	36.4 ± 2.0b	15.9 ± 2.7b	10.7 ± 1.0a	7.6 ± 0.8a	9.6 ± 0.8b	7.5 ± 0.9a
CM	45	23.4 ± 3.5c	14.6 ± 1.1b	7.6 ± 1.1b	7.6 ± 0.9a	6.6 ± 1.2ab	4.6 ± 1.1b
GA	Primary forest	43.1 ± 3.5a	15.2 ± 0.8a	10.8 ± 1.2a	8.7 ± 0.9a	8.3 ± 0.8a	7.5 ± 1.0a
GA	15	33.1 ± 3.5b	8.8 ± 1.1b	8.2 ± 1.0a	9.0 ± 1.1a	4.8 ± 0.9b	4.7 ± 0.9b
GA	40	15.8 ± 3.3c	10.1 ± 2.4b	8.0 ± 0.9a	7.6 ± 0.8a	3.8 ± 0.8b	4.7 ± 0.9b

* GH = Ghana; CM = Cameroon; GA = Gabon

Table 3 - Variation in SOC concentration along the different layers of mineral soil at the three chronosequences. Within each column different letters indicate significant differences (ANOVA; $\alpha = 0.001$) within the same chronosequence.

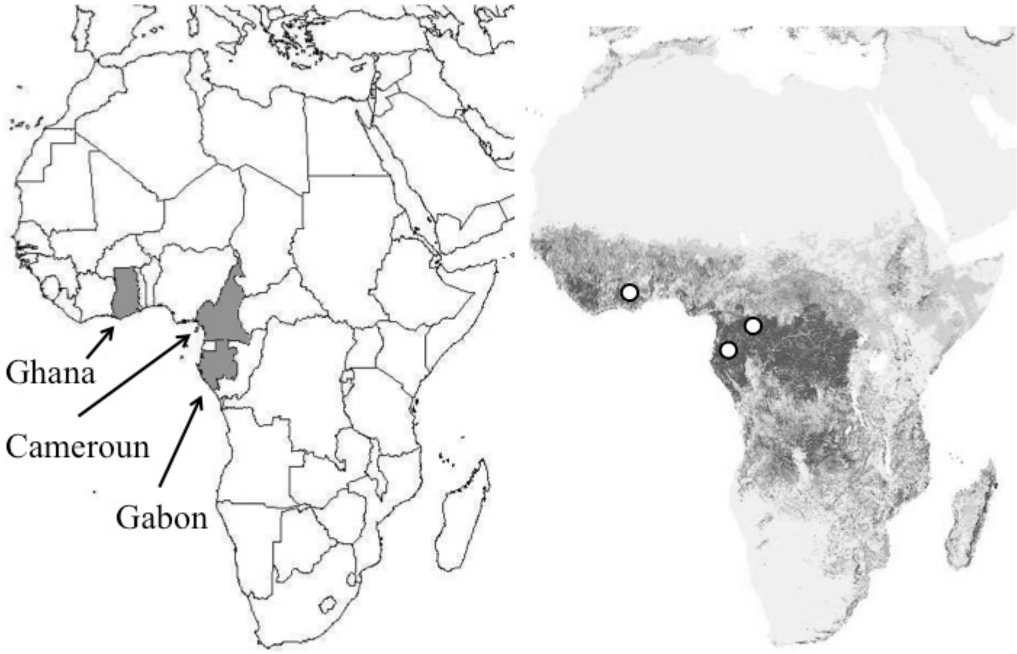

Figure 1 – Position of the three areas within the African continent (left) and within the tropical forest zone of Africa.

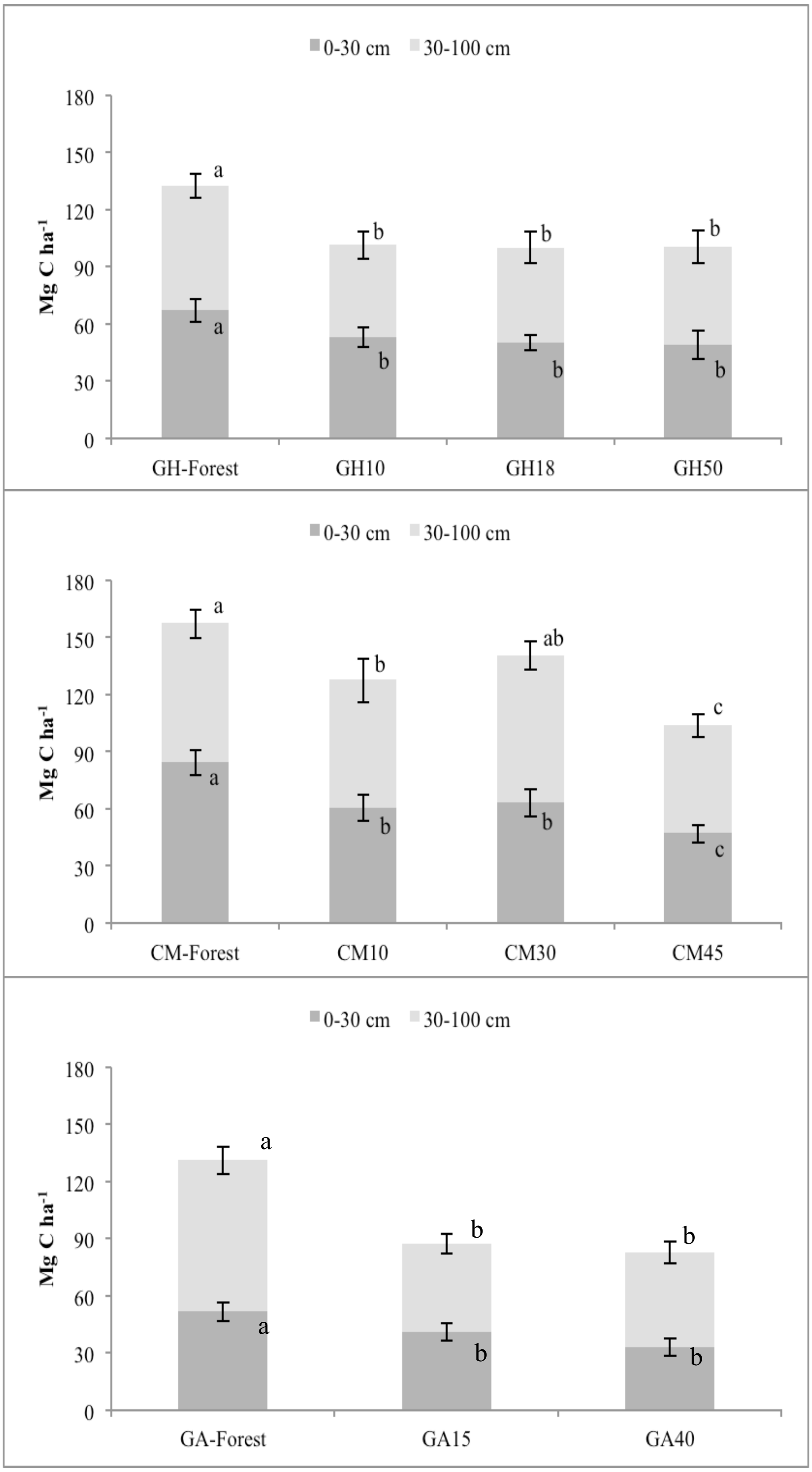

Figure 2 – SOC stock variations in the topsoil (0-30 cm) and subsoil (30-100 cm) of the three chronosequences: a) Ghana, b) Cameroon, c) Gabon. Means followed by the same letters are not

significantly different (Anova; $\alpha = 0.001$). Numbers close to site acronyms indicate the time since deforestation.

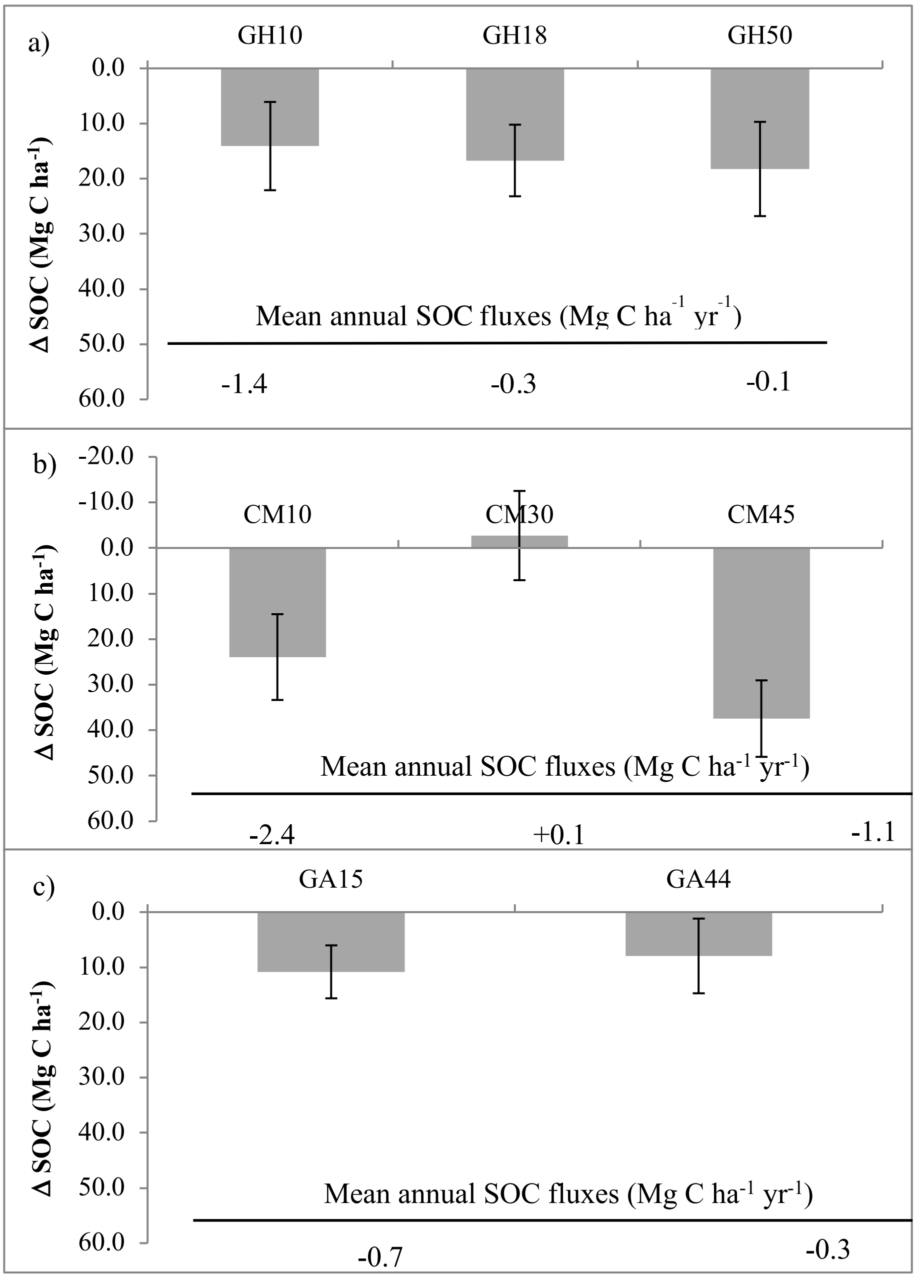

Figure 3 – Variations in SOC stock (Δ SOC) and mean annual SOC fluxes, for the 0–30 cm depth on the three chronosequences: a) Ghana, b) Cameroon and c) Gabon. Negative values means SOC losses. Numbers below each column indicate the SOC fluxes in Mg C ha^{-1} $year^{-1}$. Numbers close to site acronyms indicate the time since deforestation.