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Opportunity costs of carbon sequestration in a forest concession in central Africa

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Abstract

Background: A large proportion of the tropical rain forests of central Africa undergo periodic selective logging for timber harvesting. The REDD+ mechanism could promote less intensive logging if revenue from the additional carbon stored in the forest compensates financially for the reduced timber yield.

Results: Carbon stocks, and timber yields, and their associated values, were predicted at the scale of a forest concession in Gabon over a project scenario of 40 yr with reduced logging intensity. Considering that the timber contribution margin (i.e. the selling price of timber minus its production costs) varies between 10 and US$40 m^{-3}, the minimum price of carbon that enables carbon revenues to compensate forgone timber benefits ranges between US$4.4 and US$25.9/tCO_2 depending on the management scenario implemented.

Conclusions: Where multiple suppliers of emission reductions compete in a REDD+ carbon market, tropical timber companies are likely to change their management practices only if very favourable conditions are met, namely if the timber contribution margin remains low enough and if alternative management practices and associated incentives are appropriately chosen.

Keywords: Break-even price; Carbon credit; Forest degradation; Forest management; REDD+; Tropical forest; Diameter cutting limit; Felling cycle; Forest dynamics

Background

Tropical forests of central Africa provide both global and regional ecosystem services [1]. They provide provisioning services to the people that live within and around the forests. In several countries of central Africa, timber is the second most important sector of the economy after oil [2]. Non-timber forest products extracted from forests, including game animals, are important to local populations [3]. Forests provide regulating services such as climate change mitigation by carbon storage from the atmosphere, with a likely increase in forest productivity due to the increase in atmospheric CO_2 [4,5]. Forests also provide cultural services. The Lopé National Park in Gabon, for instance, that has been classified as a cultural and natural property of the UNESCO World Heritage, is part of a network of forest national parks that besides delivering provisioning and regulating services, aims at promoting ecotourism and wildlife observation [6].

The multiple possible uses of tropical forests in central Africa imply the existence of trade-offs between different forest users and ecosystem services [7-9]. With the increasing interest in reduced emissions from deforestation and forest degradation, conservation, sustainable management of forests, and enhancement of forest carbon stocks (REDD+; [10]), a salient trade-off is arising between timber production and carbon sequestration. Many carbon cost-benefit studies have either been devoted to plantations (i.e., afforestation, and reforestation; [8,11,12]), or to comparisons between timber production and forest conversion to crops as alternatives to forest conservation [13-16]. Less attention has been given so far to changes in natural forest management practices, in particular to the outcomes of variations of timber harvesting intensity and associated policy scenarios (but see [17]). Phat et al. [18] developed management scenarios and estimated carbon

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offset benefits from both carbon accrued through regeneration and growth of trees in residual stands. The authors calculated the minimum price of carbon needed to offset the costs of reduced impact logging (RIL) relative to conventional harvest practices but did not consider other costs related to the implementation of improved practices, which can be substantial (e.g., foregone benefits of reduced timber harvests) and the financial consequences of management decisions. Related work by Sasaki et al. [19] calculated the annual equivalent value in one hectare for six alternative land use transitions in Cambodia considering total costs (i.e., costs to the government, to the logging companies, and to REDD+ implementers) and rents (i.e., derived from timber sales, taxes and royalties, and potential carbon sales) for a range of stakeholders. The authors then compared changes in the annual equivalent value of these alternative land uses under different carbon prices and discount rates. Their results found highest values for both the business as usual and the timber-REDD+ scenarios.

Few carbon cost-benefit studies have been conducted in Africa as compared to other parts of the world. Chisholm [7] investigated the trade-off between water and carbon in timber plantations in South Africa; Bellassen and Gitz [20] and Merger et al. [21] investigated the trade-off between shifting cultivation and forest conservation in Cameroon and Tanzania, respectively; in their study of the potential of improved management of natural forests of central Africa to mitigate climate change, Durrieu et al. [22] restricted their investigation to the quantitative characterization of the carbon balance. Thus, whereas a large portion of central African forests is covered with natural productive forests under concession and management plans, we are not aware of any carbon cost-benefit studies dealing with the analysis of policy scenarios that consider changes in management practices in these forests [9].

The management of natural forests under concession in central Africa has specific features that could make them eligible to REDD+ [9] along different lines of the already approved REDD+ initiative in two Peruvian logging concessions [23]. In this study, we considered two management practices that could be modified to improve carbon storage to the detriment of timber production over the time horizon of a felling cycle. The first one is the lengthening of the felling cycle [11]. The second one is the raising of the minimum diameter cutting limits. This study addresses two main questions in the particular case of a forest concession in Gabon: (1) what is the carbon accretion potential of these two management options; and, (2) what is the break-even price of carbon credits that would make each of these two policy options cost-neutral to the concessions holder? In contrast to prior research [18,19], our approach captures the opportunity costs of alternative management scenarios through time, including the foregone benefits linked to specific policy options. Our work intends to construct a break-even value for the price of carbon that would be needed to cover the opportunity costs of plausible policy scenarios. We highlight that even if we recognize the attributes that RIL-based practices can have for carbon and other forest ecosystem services, we consider that an attempt to model changes that include RIL implementation and other improved forest management practices would be far beyond what could be realistically aimed in the short term in Gabonese forests.

The opportunity costs of carbon accrediting management options are assessed from the viewpoint of the forest concessionaire (i.e., the party with the right to log), at the spatial scale of a forest concession, and at the time horizon of a REDD+ project (i.e. 40 yr). This time horizon seems like a good compromise between the timing of forest ecological dynamics and the limited attractiveness of long-term economic planning due to politico-economic uncertainty. Because the characteristics of future REDD+ projects are not yet clear, we used the methods defined by the Verified Carbon Standard (VCS) for improved forest management projects [24,25] to calculate the break-even carbon price and associated risk assessment for lengthened cutting cycles and increased minimum cutting diameters. Whenever relevant, we also complied with the technical standards defined by the forest legislation in Gabon. In particular, management parameters (including tree species growth rates, logging damage, etc.) were taken from the management plan of the forest concession. Computations were based on real tree population data from the forest concession in Gabon, with a virtual implementation of the REDD+ project in this concession following the VCS methodology. All future forest dynamics (including during the virtual REDD+ project) were predicted using a classical model of forest dynamics based on transition matrices [26].

Results

Timber and carbon dynamics

The initial harvestable timber volume in the forest concession in Gabon was 27.4 m^3 ha^{-1} (logging intensity: 90% of available number of commercial trees) or 30.4 m^3 ha^{-1} (logging intensity: 100%). Harvested volumes varied between 0.39 and 1.35 m^3 ha^{-1} yr^{-1} depending on the year and on the management scenario (Figure 1A). The baseline scenario (i.e., business-as-usual), that corresponds to the current management practices, yielded the highest harvested volumes until the 25th year (Figure 1A, solid line), at which time the whole concession had been logged once. Starting in year 26, the concession underwent a second cut but harvested volumes were then much lower from the first cut (by 65%

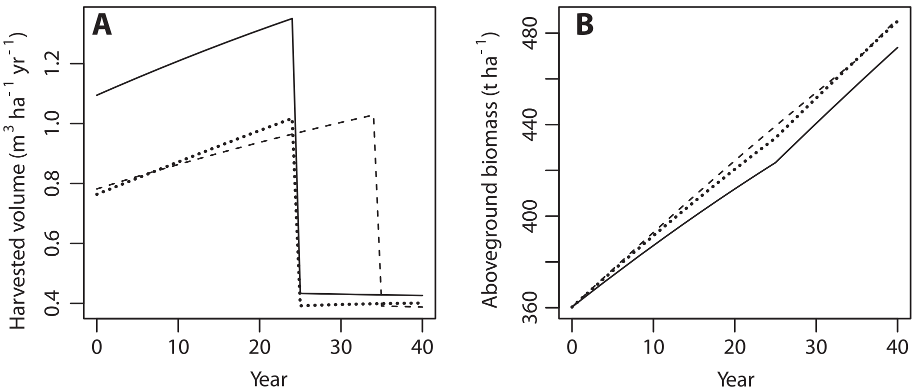

Figure 1 Temporal forecasts in the Haut-Abanga forest concession, Gabon. Harvested wood volume (panel **A**) and aboveground biomass (panel **B**) are forecast according to three management scenarios: solid line is the reference scenario (T^{ref}, d_s^{ref}); dashed line is an alternative scenario with a longer felling cycle $T = T^{\mathrm{ref}} + 10$ yr; and dotted line is an alternative scenario with higher cutting limit diameters $d_s = d_s^{\mathrm{ref}} + 10$ cm.

on average). This result means that the first cut took advantage of the initial stock, which was then depleted for the subsequent rotations (i.e. primary forest premium, as coined by [27]). When the diameter cutting limits were raised, harvested volumes decreased (by 24% on average for +10 cm; Figure 1A, dotted line). When the felling cycle was lengthened, harvested volumes also decreased (by 9% on average for +10 yr) when compared to the baseline scenario but it remained longer at its highest level (Figure 1A, dashed line).

The initial aboveground biomass in the concession was 360.3 $\mathrm{t\,ha^{-1}}$, and increased up to $473.7 - 486.4$ $\mathrm{t\,ha^{-1}}$ depending on the management scenario (Figure 1B). On a concession level, biomass increased despite logging because of selectiveness of timber harvesting. Biomass increments were higher with any alternative than with the baseline scenario (Figure 2). However the net carbon benefit did not necessarily accumulate over time (see Figure 2A, for instance, where the net benefit decreases from year 25 to year 35).

To illustrate how carbon credits were issued, consider for example the project scenario with a longer rotation (+10 yr, Figure 2A). In year 1, the net carbon benefit was 0.92 $\mathrm{tCO_2\ ha^{-1}}$, and so 0.92 carbon credits were issuable. In year 2, the net carbon benefit increased by an additional 0.93 $\mathrm{tCO_2\ ha^{-1}}$ that were issuable as carbon credits. This lasted till year 17 when the accumulated number of issuable carbon credits reached the long-term average of net carbon benefit. No carbon credit was issuable after year 17. This particular calendar of credits issuance follows from the VCS methodology [24] and enables carbon revenues to be quickly obtained after the start of the project. Other methodologies to issue carbon credits have been proposed in the context of the Clean Development Mechanism [12] and would distribute carbon revenues more evenly across the lifetime of the project. All issuable credits summed up to 16.73 $\mathrm{tCO_2\ ha^{-1}}$ during the 40 yr project lifetime but due to the buffer for the non-permanence risk, 13.0 carbon credits would actually be issued.

Opportunity cost

The break-even price of carbon sequestration (i.e. the minimum price for a ton of CO_2 which a forest company would have to receive for the carbon revenues of project scenario to compensate the financial timber losses relative to the baseline scenario) depends on the contribution margins of the sold timber. As long as the same contribution margin π_s is used for all commercial species, the break-even carbon price π_C^* is proportional to this common value. Hence, we do not need to compute the value of π_C^* for all values of π_s: if π_{ref}^* is the break-even carbon price for a reference value of the contribution margin of for example, US\$25 $\mathrm{m^{-3}}$, then the break-even carbon price for a contribution margin of π_s (in US\$ $\mathrm{m^{-3}}$) is $\pi_s/25 \times \pi_{\mathrm{ref}}^*$. Therefore, we report the break-even carbon price only for the median $\pi_s = \text{US\$}25\ \mathrm{m^{-3}}$ (Table 1).

For a contribution margin of US\$25 $\mathrm{m^{-3}}$, the break-even price of carbon was US\$11.0–16.2/$\mathrm{tCO_2}$ depending on the project scenario (Table 1). When lengthening the rotation from an additional 5 yr to an additional 10 or 15 yr, the gain in carbon credits for each type of credit increased but so did the loss in the net present value of timber so that, eventually, the break-even price for both was about US\$11/$\mathrm{tCO_2}$ for a contribution margin of US\$25 $\mathrm{m^{-3}}$. Similarly, raising the diameter cutting limit from an additional 10 cm to 20, 30 or 40 cm did not much affect the opportunity cost of carbon sequestration. The break-even price was higher when the diameter cutting limit was increased by 10 cm than when the cutting cycle was lengthened by 10 yr (Table 1).

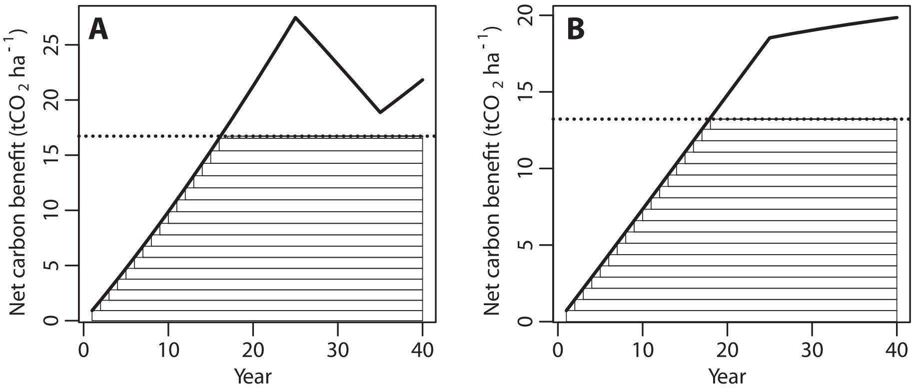

Figure 2 Net carbon benefit and issuable carbon credits in each year in the Haut-Abanga concession. The net carbon benefit (thick solid lines) and the issuable carbon credits (bars) are relative to a reference management scenario (T^{ref}, d_s^{ref}). The dotted line is the long-term average of net carbon benefits and the horizontal bars represent the net carbon benefits that area issued each year. **A**. Alternative scenario with a longer rotation $T = T^{\mathrm{ref}} + 10$ yr. **B**. Alternative scenario with higher diameter cutting limits $d_s = d_s^{\mathrm{ref}} + 10$ cm.

The VCS [25] recommends to account for uncertainties in the estimates of carbon emissions. Hence, a sensitivity analysis was conducted to assess how the break-even price of CO_2 varies with ecological and economic parameters. The elasticity of the break-even price of carbon to a parameter of the model gives the relative change of the break-even price that is brought by a relative change of this parameter. It quantifies how uncertainty on the parameter value propagates to the estimate of the break-even price. To save space, we present the results of the sensitivity analysis only for the project scenario with a longer rotation $T^{\mathrm{ref}} + 10$ yr. As the break-even price of carbon is directly proportional to the contribution margin of wood, the elasticity of π_C^* to all joined π_s was 1 (Figure 3A). However, as expected, not all species' prices affected the break-even price of carbon in the same way, with the price of *Aucoumea klaineana* (the most important commercial species) alone being responsible for half the variation of the break-even price (Figure 3B), while the other commercial species were jointly responsible for the other half of the variation of π_C^*. The elasticity of the break-even price to the discount rate was low (4%) because most of the credits were issued in the first years of the project.

The elasticity of π_C^* to all joined wood densities was 1 (Figure 3A), evidencing a proportionality dependence of the break-even carbon price on this parameter. The same held true for the biomass for each size-class (for a hypothetical reference species with a wood density of 1 g cm^{-3}) and for the volume for each size-class and species (Figure 3A). In comparison, the break-even carbon price was much less sensitive to logging damage, species-specific growth rates and mortality rates, and to the initial tree densities by species and diameter class (Figure 3A and Additional file 1).

Discussion

The opportunity cost of carbon sequestration in a forest concession in central Africa was assessed for different management scenarios, and the corresponding break-even prices of carbon were estimated. Beyond the specific

Table 1 Opportunity cost of carbon sequestration for different alternative management scenarios in the Haut-Abanga concession

Scenario	ΔVolume ($m^3 ha^{-1}$)	∑Credits ($tCO_2 ha^{-1}$)	ΔPVT_T (US\$ ha^{-1})	π_C^* (US\$/tCO_2)
Lengthened rotation (+5 yr)	1.8	7.1	34.2	11.0
Lengthened rotation (+10 yr)	3.3	13.0	60.5	11.1
Lengthened rotation (+15 yr)	4.7	18.2	81.2	11.1
Raised cutting limits (+10 cm)	8.9	10.3	65.6	15.8
Raised cutting limits (+20 cm)	17.5	19.5	124.2	15.9
Raised cutting limits (+30 cm)	24.5	26.3	166.2	16.1
Raised cutting limits (+40 cm)	29.5	30.7	193.6	16.2

The break-even price of carbon sequestration π_C^* is computed for a contribution margin of US\$25 m^{-3} for all commercial species. ∑Credits is the sum of carbon credits. ΔVolume is the total reduction in harvested wood volume. ΔPVT_T is the loss in the net present value of timber.

value of the opportunity cost of carbon calculated for each scenario, the underlying model seems useful. Tropical productive natural forests are not managed in the same way as temperate forests or plantations, so modelling tools for carbon accounting developed for these forests (e.g. [28-30]) do not properly transfer to tropical realities. The current study provides a way to account for carbon in this context.

The break-even carbon price represents the minimum financial compensation a forest company would have to receive to change from the reference management to an improved management scenario [31]. This price is lower than what would actually generate a benefit from the carbon project. Considering that the timber contribution margin could vary between US\$10 and US\$40 m^{-3}, the opportunity cost of carbon sequestration ranged between US\$4.4 and US\$25.9/tCO_2 depending on the management scenario implemented (Table 1 and considering that π_C^* is proportional to π_s). The range is broad, but it is consistent with the range of opportunity costs values commonly reported for forestry projects [13,15,16,20,21,32-35]. Because there is no standard model to compute the opportunity cost, a direct comparison of opportunity cost values across studies seems irrelevant.

Our results are useful to identify some trends about opportunity costs for forest interventions in tropical countries. Many afforestation/reforestation projects have opportunity costs <US\$8/tCO_2 [11,12]. For REDD+ projects in tropical forests, opportunity costs are also often <US\$8/tCO_2, even if higher costs can occasionally be found when forest conservation is compared with highly profitable land-uses such as oil-palm cultivation [16,21,34].

Lengthening the felling cycle or raising cutting limits are not the only improved management practices that could be considered in a REDD+ porfolio. Adoption of RIL and silviculture practices could also be feasible REDD+ activities [19]. Contrary to changes of the management parameters that match the current logging practices, RIL implementation requires up-front capital investments in timber inventories, staff training, and sometimes new machinery, along with substantial modifications in working practices and monitoring [36]. Therefore, a REDD+ project based on RIL would require higher implementation costs than a REDD+ project based on changes of management parameters, and is perhaps less plausible in the short-term, at least in our study country. On the other hand, RIL-adoption may provide carbon revenues while maintaining timber revenues at a level close to the baseline. Considering that the same reasons why RIL has not been widely embraced may apply in the context of REDD+ [37], RIL was not the first improved management alternative that we considered.

Ours results question the representativeness of the Gabonese forest concession used for central African rain forests. The expected harvested timber volume in this operation (27 m^3 ha^{-1}) was greater than what is generally achieved in this region (< 15 m^3 ha^{-1}, [9]), meaning that logging in our study was less selective than in the rest of the central African region. One effect of this intensive timber harvest is a high carbon break-even price. The initial stand biomass in the Haut-Abanga concession (360 $t\,ha^{-1}$) was within the range of values commonly found in the central African moist forests (i.e., 404 $t\,ha^{-1}$ with 348–488 $t\,ha^{-1}$ 95% confidence interval, according to [5]). In contrast, biomass was estimated to accumulate at high average rate of 2.8 $t\,ha^{-1}\,yr^{-1}$ in the baseline scenario and at 3.1 $t\,ha^{-1}\,yr^{-1}$ in the alternative scenarios. Because logging removes biomass through harvested timber and logging damage [38-40], for which we accounted in the model, the predicted biomass accumulation in the absence of logging is even greater (4.9 $t\,ha^{-1}\,yr^{-1}$

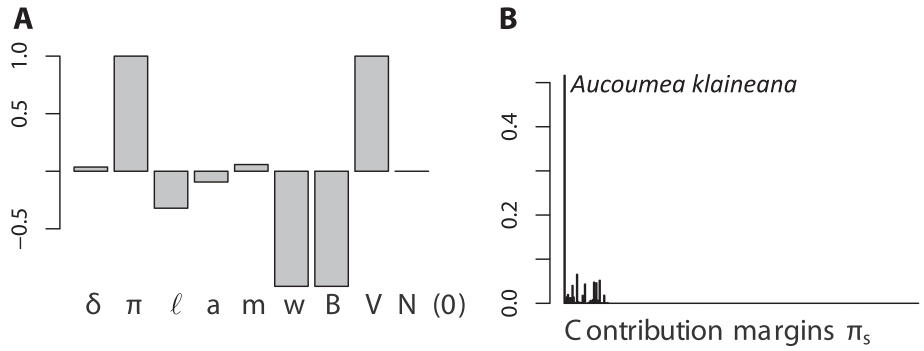

Figure 3 Results of sensitivity analyses to determine break-even price of carbon. **A**. Elasticities of the break-even price π_C^* to δ = discount rate, $\boldsymbol{\pi}$ = vector of specific contribution margins, ℓ = logging damage, **a** = vector of specific growth rates, **m** = vector of specific mortality rates, **w** = vector of specific wood densities, **B** = vector of class-dependent biomasses, **V** = matrix of species- and class-dependent volumes, and **N**(0) = matrix of initial numbers of trees per species and diameter class. **B**. Elasticities of π_C^* to the species-specific contribution margin π_s. Total number of bars is 313, and *Aucoumea klaineana* corresponds to the first bar.

on average across the first 40 yr). By comparison, Lewis et al. [5] found a mean biomass accumulation of 1.26 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ (95% confidence interval: 0.44–1.88) in undisturbed forests of central Africa, whereas Gourlet-Fleury et al. [41] found a mean biomass accumulation of 4.82 ± 1.22 $\mathrm{t\ ha^{-1}\ yr^{-1}}$ for logged plots in central Africa. Nevertheless, what matters for assessing the opportunity cost is not the biomass accumulation rate, but differences in accumulated biomass among management scenarios. An overestimated biomass accumulation rate does not necessarily result in an overvalued biomass benefit, but should this be the case, it would mean that the carbon break-even price was underestimated.

The high predicted biomass accumulation in the Haut-Abanga can be explained by an overestimated growth rate used for all species, and by the specific size-class distributions of some commercial species. The dbh growth rate used in this study ($a = 0.3\ \mathrm{cm\,yr^{-1}}$) is the one defined in the Haut Abanga management plan. It is consistent with post-logging canopy gaps that boost growth but is greater than what is observed in undisturbed forests in central Africa (0.15–0.20 $\mathrm{cm\,yr^{-1}}$ on average). Combined with a mortality rate of $m = 0.01\ \mathrm{yr^{-1}}$, it corresponds to a mean tree dbh of $10 + a/m = 40$ cm, thus much greater than the observed pre-harvest mean dbh of 27 cm. The dbh growth rate that would match this mean dbh value is $0.172\ \mathrm{cm\,yr^{-1}}$. Nevertheless, because the break-even price of carbon is slightly sensitive to the growth rate, reducing a to $0.172\ \mathrm{cm\,yr^{-1}}$ does not affect much the estimate of the break-even price (Additional file 2).

Regarding the dbh distributions, some dominant species in the Haut-Abanga concession have an unbalanced modal diameter distribution (e.g., pre-harvest dbh distribution of *Aucoumea klaineana* conforms to a normal distribution with mean 56 cm and standard deviation 26 cm, or *Scyphocephalium mannii* with mean 46 cm and std. dev. 18 cm). In the short-run, when the peak of the diameter distribution for these species increments, so does their total biomass because of the accumulation of large trees. In the longer-run, the peak vanishes and biomass decreases (e.g., the predicted total biomass for *A. klaineana* and *S. mannii* in the absence of logging decreases after 42 and 220 yr, respectively), which is not perceptible with a project length of 40 years. Nevertheless, given the low sensitivity of the break-even carbon price to both growth rates and dbh distributions, data on other more influential ecological parameters, in particular wood densities and species-specific allometric equations, should be improved.

Some simplifying assumptions that were made in our model could be relaxed to refine the estimated opportunity costs. For instance, the dependence of logging damage on logging intensity, and thus differences in logging damage between management scenarios, was not considered. We explored the consequences of relaxing this assumpion by replacing the constant damage rate of 10% by a function of the density of logged trees [42]. This dependence resulted in a reduction of the break-even price of carbon to US\$8–9/$\mathrm{tCO_2}$ for a contribution margin of US\$25 $\mathrm{m^{-3}}$ (Additional file 2). This study was carbon-focused and did not consider non-carbon-related payments for ecosystem services [16]. The residual value of the forest at the end of the carbon project [43], or the feedback of the change of forest management on the timber market price were also disregarded. Nevertheless, these processes are likely to have marginal influences on carbon opportunity costs, without any a priori idea about whether this influence would be positive or negative. More importantly, we restricted the gain-loss analysis to the forest concessionaire, and did not integrate economic and environmental costs and benefits beyond timber production [44]. Integrating the whole chain of production and transformation, from logging to wood products export, would presumably provide other insights into carbon opportunity costs. However, as long as the articulation between the national scale for REDD+ project accounting and the local scale where carbon projects are implemented is not clarified, it is not clear what the cost-benefit analysis should encompass.

Conclusions

At a global scale where multiple suppliers of emission reductions would compete in a REDD+ carbon market [34,45,46], tropical timber companies would change their management practices because of REDD+ opportunities only if very favourable conditions are met, namely if the timber contribution margin remains low enough and if alternative management practices and associated incentives are appropriately chosen. The current average price of carbon for improved forest management projects (US\$10.4/$\mathrm{tCO_2}$ in 2012 and US\$10/$\mathrm{tCO_2}$ in 2011; [47,48]) is unlikely to prompt forest concessionaires to forgo timber benefits. All in all, the approach we used to calculate the break-even price of carbon seems useful to inform on the available systems of incentives that could be part of the implementation of REDD+ mechanism as it pertains to different forest management scenarios. As such, the scenario analyses proposed represents only one of the elements of the still undefined REDD+ architecture (i.e. subnational and national programs) and unregulated markets for REDD+ credits. Other components related to governance (i.e. capacity of concessionaries to enforce their rights so as to exclude others from harvesting their timber and ability of governments to sanction those who illegally log and capture logging taxes), as well as other factors associated with delivery risks (e.g. mortality induced by drought, fire, and other disturbances) will determine the ultimate opportunity costs of policy scenarios based on contrasting forest management practices.

Methods

Study site and project scenario

The study was undertaken at the Haut-Abanga forest concession (288 627 ha) of the forest company Rougier-Gabon (between 10°30'–11°30'E in longitude and between 0°15'–0°50'N in latitude; [49]), at the western border of the Monts de Cristal mountain range. Altitudes vary between 250–1022 m. Climate is equatorial, with an annual rainfall between 1800–2000 mm depending on slope aspect, and mean annual temperatures between 24–26°C. The geological formation is an Archean basement with metamorphic and granitic rocks. Soils are mainly ferralitic sandy-clayey or clayey. The Haut-Abanga concession is covered with tropical moist forest, the dominant families being Burseraceae (18% of the basal area), Myristicaceae (15%), Caesalpiniaceae (15%) and Euphorbiaceae (9%) [49].

The management techniques considered in this study comply with the current legislation in Gabon that defines the technical norms for management of state-owned productive forests [50-52]. Accordingly, forest logging occurs periodically every T years, and between two successive logging operations, the forest is left for natural recovery. Because the forest concession is subsequently divided into quinquennial blocks, the length of the felling cycle T must be a multiple of 5 yr. Moreover, it must be greater than or equal to 20 yr. Logging of a commercial tree species s consists of removal of a fixed proportion of all trees with a diameter at breast height (dbh) greater than or equal to a cutting limit d_s. This cutting limit must be greater than an administrative minimum cutting limit A_s [53] (see Additional file 3 for species-specific values of A_s). A management scenario is thus defined by the set of $S + 1$ parameters (where S is the number of species), chosen by the forest concessionaire to comply with legal sustainability requirements: the length of the felling cycle T (the same for all species), and the dbh cutting limit d_s for each species s.

In this study, the baseline management scenario, denoted (T^{ref}, d_s^{ref}), was defined by $T^{\mathrm{ref}} = 25$ yr and $d_s^{\mathrm{ref}} = A_s$. This baseline scenario corresponds to the current management plan of the Haut Abanga concession, which ensures that the stock recovery rate for each species is above its legal minimum. Two alternative scenarios (denoted *j*) were considered: (1) a project scenario (T, d_s^{ref}) in which $T > T^{\mathrm{ref}}$, with a longer felling cycle but the same cutting limits; and (2) a project scenario (T^{ref}, d_s) in which $d_s > d_s^{\mathrm{ref}}$, with higher cutting limits but the same length of the felling cycle (i.e., 25 yr). Because T must be a multiple of 5 yr and less than the project longevity, the possible values for T are limited: $T = T^{\mathrm{ref}}+5$, $+10$ or $+15$ yr. Because administrative cutting limits are multiple of 10 cm and because the forest inventory in Haut Abanga was correspondingly based on 10 cm-wide diameter classes, cutting limits were raised by +10, +20, +30 or +40 cm.

Break-even price of carbon

The scenarios were compared to the baseline situation in which the felling cycle is 25 yr and the cutting limits are what is established by law (Additional file 3) by examining the carbon benefits in standing biomass and the associated timber losses (i.e. foregone timber harvest). Financial revenue from timber and carbon (i.e. credits for avoided carbon emissions) were computed over the duration Ω of the carbon project, which was equal to $\Omega = 40$ yr for this study. We defined $\mathrm{NPV}_{\mathrm{T}}^{(j)}$ and $\mathrm{NPV}_{\mathrm{C}}^{(j)}$ as the net present value of timber and carbon, respectively, according to project scenario *j*. Following the concept of additionality of the Kyoto Protocol [54], the carbon revenue for scenario *j* follows from the benefit of carbon storage for this scenario as compared to the baseline management scenario. Thus, by definition, $\mathrm{NPV}_{\mathrm{C}}^{\mathrm{ref}} = 0$. The break-even price of carbon sequestration (see definition in section "Opportunity cost" above) for project scenario *j* is:

$$\pi_C^* = \min\left\{\pi_C : \mathrm{NPV}_{\mathrm{C}}^{(j)} \geq \mathrm{NPV}_{\mathrm{T}}^{\mathrm{ref}} - \mathrm{NPV}_{\mathrm{T}}^{(j)}\right\} \quad (1)$$

where π_C is the price of certificates of emission reductions (in US$ per tCO$_2$) that defines the net present value of carbon. Future costs and benefits were discounted (discount rate: $\delta = 12\%$) [55,56], which is a minimum value for the private discount rate in the context of a forest industry in central Africa, where institutional stability is perceived as precarious and for an activity (logging) which is contested by environmental NGOs, making long term commercial prospects more uncertain when compared to other businesses.

Timber revenues

We here consider the standpoint of the concessionaire whose activity is to harvest and sell untransformed timber to a sawmill. Hence, even if the concessionaire is the owner of the sawmill, we do not consider revenues and costs associated with timber transformation. Let $X_s^{(j)}(t)$ be the harvested timber volume of species s at time t at the concession level under project scenario *j*. This timber volume brings a sale revenue of $\pi_s X_s^{(j)}(t)$, where π_s is the contribution margin (in US$ m^{-3}) for species s. The contribution margin here is the difference between the market price of untransformed timber times the proportion of timber that is not lost between the log yard and the mill entry, and all variable costs per unit of timber volume (including variable logging and transportation costs, and variable taxes). The net timber revenue is obtained after deduction of the fixed costs $Q(t)$ associated with logging (including fixed taxes). The net present value of timber under project scenario j at the time horizon of the duration Ω of the carbon project thus is:

$$\mathrm{NPV}_{\mathrm{T}}^{(j)} = \sum_{t=1}^{\Omega} \left\{ \sum_{s} \pi_s X_s^{(j)}(t) - Q(t) \right\} (1+\delta)^{-t} \tag{2}$$

where the summation on s is over logged species only. Because fixed costs $Q(t)$ theoretically do not depend on the management scenario j, they cancel out when computing the difference $\mathrm{NPV}_{\mathrm{T}}^{\mathrm{ref}} - \mathrm{NPV}_{\mathrm{T}}^{(j)}$ and we do not have to estimate them to compute the break-even carbon price π_C^*.

The contribution margin π_s is difficult to assess because it depends on many interacting and fluctuating parameters (e.g., market prices, variable logging costs, transportation costs, variable taxes). Rather than fixing a contribution margin, we chose to consider it as a variable in the range of US\$10–40 m^{-3} [57,58] and to consider the break-even price π_C^* as a function of π_s (the same for all commercial species). Having the same contribution margin π for all commercial species implies that π_C^* is proportional to π.

Carbon revenues

There are many accounting methods for carbon, but two main approaches are distinguished [11,29]. The first approach (the flow approach) is based on the flux of carbon entering the ecosystem and on the price of carbon within a period of time. The second approach (the stock approach) is based on a rent derived from stored carbon for a period of time. Following the VCS [25], we opted for the stock approach. The net carbon benefit (in $\mathrm{tCO_2\,ha^{-1}}$) at time t for the jth management scenario with respect to the baseline scenario is:

$$\Delta C(t) = C^{(j)}(t) - G^{(j)}(t) - \left\{ C^{\mathrm{ref}}(t) - G^{\mathrm{ref}}(t) \right\} - L(t)$$

where $C^{(j)}(t)$ is the carbon stock (in $\mathrm{tCO_2\,ha^{-1}}$) at the concession level, $G^{(j)}(t)$ is the greenhouse gas emissions (in $\mathrm{tCO_2\,ha^{-1}}$) as a result of forest management activities, and $L(t)$ is the greenhouse gas emissions (in $\mathrm{tCO_2\,ha^{-1}}$) due to leakage. Leakage breaks down into leakage due to activity shifting, which is often assumed to be zero for improved forest management projects, and leakage due to market effects [25]. We here assumed that there was no market leakage (i.e, $L(t) \simeq 0$). We also assumed that greenhouse gas emissions due to forest management activities were about the same for all management scenarios, so that $G^{(j)}(t)$ and $G^{\mathrm{ref}}(t)$ cancelled out. Because $G^{(j)}(t)$ is likely to be $< G^{\mathrm{ref}}(t)$, this simplifying assumption minimizes the risk of underestimating the break-even price of carbon, and is thus conservative.

Forest carbon is stored in living trees (both above- and below-ground), dead wood, litter, soil and wood products [25]. We assumed that the difference in below-ground biomass, necromass, litter biomass, or soil carbon among different management scenarios was $<$ 5% of the overall net carbon changes [59] and thus negligible with respect to the aboveground pool. Hence, these contributions to $C^{(j)}(t)$ canceled out when computing the difference $C^{(j)}(t) - C^{\mathrm{ref}}(t)$. Although there is potentially a large economic value associated with the carbon in long-lived wood products, we did not explicitly model these because when the timber is sold from the concession, the rights to capture any carbon value in wood products would presumably be also sold. Although a decision has been adopted at the COP 18 (Doha) to account for carbon storage in wood products, the issue of who, producer or product purchaser, could be credited for the carbon stored, remains unanswered. From the perspective of the land concessionaire, the economic value of carbon in wood products would be reflected by rising timber prices, which we explore in the sensitivity analysis. Therefore, the aboveground biomass is the only type of carbon storage that we considered.

Carbon credits were computed from the net carbon benefit using the VCS guidance for improved forest management projects with harvesting [24]. The long-term average of net carbon benefit was first computed over the duration of the project as: $A = \sum_{t=1}^{\Omega} \Delta C(t)/\Omega$. This long-term average represents the number of carbon credits that correspond to permanent annual emission avoided if these were evenly distributed over the duration of the project. Because carbon benefits were actually not evenly distributed, the number of issuable carbon credits $U(t)$ at time $t \geq 1$ was computed as the annual gain in net carbon benefit provided that this gain was positive and that the accumulated number of issuable carbon credits remained less than A:

$$U(t) = \max \left\{ 0; \min \left\{ \Delta C(t) - \Delta C(t-1); A - \sum_{s<t} U(s) \right\} \right\}$$

This definition ensured that the total number of issuable carbon credits over the duration of the project equalled A: $\sum_{t=1}^{\Omega} U(t) = A$. To account for the non-permanence risk, the number of carbon credits issued at time t was finally determined as a fraction ζ of the issuable carbon credits, the remaining fraction $1 - \zeta$ being the proportion of carbon credits to be withheld as a buffer reserve. Following the risk analysis proposed by the VCS [60], we used $\zeta = 78\%$ (see Additional file 3). Thus, the net present value of carbon credits was:

$$\mathrm{NPV}_{\mathrm{C}}^{(j)} = \pi_C \, \zeta \sum_{t=1}^{\Omega} U(t) \; (1+\delta)^{-t} \tag{3}$$

We did not consider any implementation cost (i.e. the cost of efforts needed to reduce deforestation and forest degradation) or transaction cost (i.e. the cost of establishing and operating the REDD+ project) when computing the net present value of carbon, which means that the break-even carbon price π_C^* given by (1) represents the opportunity cost of carbon [31].

Sensitivity analysis

To compute the break-even price of carbon, we calculated $X_s^{(j)}(t)$ and $C^{(j)}(t)$, the harvested timber volume of species s, and the carbon stock at time t, respectively. These values jointly derive from the state of the forest at that particular time, predicted using a model of forest dynamics based on a set of parameters that we hereafter refer to the 'ecological' parameters.

Because the same response pattern was obtained with sensitivity than with elasticity analyses, we here focus on the latter. The elasticity of the break-even price to a parameter θ is: $e_\theta = \partial \ln \pi_C^* / \partial \ln \theta$. The quantity $e_\theta \times \xi$ gives the proportional change of π_C^* that would be brought by a small proportional perturbation of parameter θ in a proportion ξ. Elasticities can be added to assess the joint impact of several parameters. If $\boldsymbol{\theta} = (\theta_1, \ldots, \theta_n)$ is a vector of n parameters, we define $e_{\boldsymbol{\theta}} = \sum_{i=1} e_{\theta_i}$, so that $e_{\boldsymbol{\theta}} \times \xi$ gives the proportional change of π_C^* that would be obtained if all parameters $\theta_1, \ldots, \theta_n$ were simultaneously changed by the same proportion ξ.

Economic parameters included in the sensitivity analysis are the species-specific contribution margins and the discount rate. In this case, the sensitivity analysis identifies the economic parameters that are to be considered at first to get the best control on the break-even price π_C^*. Ecological parameters are estimated from forest inventories or measured in the field, so they are not known with certainty. Estimation errors on these parameters bring an estimation error on the break-even price π_C^*. The sensitivity analysis in this case identifies the ecological parameters that should be estimated with the best precision to get the best precision on the estimated break-even price.

Model of forest dynamics

The Technical National Guide (TNG) [52] does not recommend any model of forest dynamics, but the so-called stock recovery formula that it uses to assess sustainability implicitly relies on a simplified matrix projection model [61,62]. This simplified model disregards recruitment and is thus inappropriate for long-term forecasts. For this reason, we used a matrix projection model that is simple enough to be consistent with the TNG, yet realistic enough to make long-term forecasts. This model is a Usher [26] matrix projection model with constant transition rates and a population growth rate equal to one. This latter assumption ensures that, in the absence of disturbance (such as logging), no population will indefinitely grow nor decline to extinction, and corresponds to the assumption that in mature undisturbed forests, species abundances remain approximately constant (at least over the mid-term range of our analyses).

The state of any tree species s at time t is defined by the per hectare numbers $N_{is}(t)$ of its individuals in K equal-width diameter classes. These per hectare numbers of trees are defined across operable areas of the forest concession only. Let $\mathbf{N}_s(t) = [N_{1s}(t), \ldots, N_{Ks}(t)]'$ be the $K \times 1$ column vector that compiles the per hectare number of trees in each diameter class for species s, and prime denotes the transpose. Its initial value $\mathbf{N}_s(0)$ is provided by the management inventory. In the absence of disturbance, its temporal change is given by the recurrence formula:

$$\mathbf{N}_s(t+1) = \mathbf{U}_s \, \mathbf{N}_s(t)$$

where $\mathbf{U}_s$ is a $K \times K$ Usher transition matrix with constant rates:

$$\mathbf{U}_s = \begin{bmatrix} q_s{+}f_s & f_s & \cdots & f_s & f_s \\ p_s & q_s & & & \mathbf{0} \\ & p_s & \ddots & & \\ & & \ddots & q_s & \\ \mathbf{0} & & & p_s & p_s{+}q_s \end{bmatrix} \tag{4}$$

where q_s, the stasis rate, represents the probability for a tree of species s to stay alive in the same diameter class between two successive time steps; p_s, the upgrowth rate, represents the probability that a tree stays alive and moves up to the next diameter class between two successive time steps; and f_s, the recruitment rate, represents the probability that a tree generates a newly recruited tree between two successive time steps. The population growth rate, λ_s, corresponds to the dominant eigenvalue of the transition matrix $\mathbf{U}_s$ [63]. For a matrix with constant rates like (4), it can be shown that: $\lambda_s = 1 + f_s - m_s$, where $m_s = 1 - q_s - p_s$ is the mortality rate for species s [62]. Assuming $\lambda_s = 1$ then is equivalent to assuming that the mortality and recruitment rates are equal.

Given $f_s = m_s$, matrix $\mathbf{U}_s$ can be reparameterized using only two transition rates, namely the mortality rate m_s, and $p_s^\star = p_s/(1 - m_s)$. Sometimes called the growth propensity, this latter rate represents the conditional probability that a tree moves up to the next diameter class knowing that it has stayed alive. It can be estimated as: $p_s^\star = a_s \tau / \omega$, where a_s is the average diameter growth rate (in cm yr^{-1}) for species s, τ is the time interval (in yr) between two successive time steps, and ω is the width of the diameter classes (in cm). Hence, to compute the transition matrix $\mathbf{U}_s$ for species s, one only needs to know the mortality rate m_s and the diameter growth rate a_s for this species.

To complete the forest dynamics model, the temporal change of $\mathbf{N}_s(t)$ when a disturbance occurs has to be specified. The only disturbance that we take into account is logging, assuming that the other disturbances impact the different management scenarios in a similar way. Logging is considered to be instantaneous with respect to forest dynamics. If logging occurs at time t, we distinguish the population state $\mathbf{N}_s(t)$ before logging, and its state $\mathbf{N}_s(t^+)$ after logging. Logging harvests a proportion ρ_s of trees of species s with a dbh $\geq d_s$. In addition to harvested trees, logging results in collateral damage and destruction of other trees. In the TNG, logging damage (i.e. trees destroyed by logging) is accounted by a proportion ℓ_i of trees that are removed in the ith diameter class when logging occurs. Hence, in matrix notation:

$$\mathbf{N}_s(t^+) = \mathbf{L}\,\mathbf{H}_s\,\mathbf{N}_s(t)$$

where $\mathbf{L}$ is the $K \times K$ diagonal matrix whose ith element on the diagonal is $1 - \ell_i$, and $\mathbf{H}_s$ is the $K \times K$ diagonal matrix whose ith element on the diagonal is 1 if the upper bound of the ith diameter class is less than d_s, and $1 - \rho_s$ otherwise. Given that the first logging event occurs at time c, the complete description of forest dynamics is:

$$\mathbf{N}_s(t{+}1, c) = \begin{cases} \mathbf{U}_s\,\mathbf{N}_s(t,c) & \text{if } (t-c) \bmod (T/\tau) \neq 0 \\ \mathbf{U}_s\,\mathbf{L}\,\mathbf{H}_s\,\mathbf{N}_s(t,c) & \text{if } (t-c) \bmod (T/\tau) = 0 \end{cases} \tag{5}$$

where mod is the modulo operator, and T/τ gives the length of the felling cycle expressed as a number of time steps rather than in number of years. We added c as an argument to $\mathbf{N}_s$ to highlight the dependence on the logging schedule, given that $\mathbf{N}_s(0,c) \equiv \mathbf{N}_s(0)$ is given by the initial forest inventory for all c.

The management inventory in the Haut-Abanga concession was conducted between 1998 and 2000, using a systematic sampling design based on 0.5-ha sampling plots, with a planned sampling rate of 1% for trees with dbh $\geq$ 20 cm and of 0.2% for trees with 10 cm $<$ dbh $\leq$ 20 cm, and with an achieved rate of 1.2% for the former [49]. This forest inventory provided an estimate $N_{is}(0)$ at the concession level of the initial number of trees in $K = 16$ diameter classes for $S = 313$ morphospecies. Diameter classes are $\omega = 10$ cm wide, starting from 10 cm. Hence, the first class is 10–20 cm, the second class is 20–30 cm, till the sixteenth class that is $\geq$ 160 cm dbh. The mean diameter for the ith diameter class was computed as $D_i = (10i{+}5)$ cm. The pre-harvest dbh distribution of the forest had a typical reverse-J shape that conformed to an exponential distribution with parameter 0.058 cm^{-1}. The 313 morphospecies were assigned by Rougier-Gabon to seven groups: six commercial groups by decreasing order of commercial importance, and one group of protected species (Additional file 3). In this study, we considered that only groups 1 and 2 were logged. Group 1 contains a single species (*Aucoumea klaineana* Pierre, that represents 80% of the wood production in Gabon), and group 2 contains 38 morphospecies. The logging intensity for all management scenarios was $\rho_s = 90\%$ for all logged species. The time step of the matrix model was $\tau = 1$ year. To comply with the dynamics parameters used in the management plan of the Haut-Abanga, we used for all species a dbh growth rate of $a_s = 3\ \text{mm}\,\text{yr}^{-1}$ and a mortality rate of $m_s = 1\%$, which means that the stasis rate was 96.03% while the upgrowth transition rate was 2.97%. The management plan at the Haut-Abanga was based on a constant logging damage rate of 10% [64]. Consistently, and considering that the rate of trees destroyed by logging decreases with tree size [42], we used a logging damage of 10% for the first three classes, then null: $\ell_i = 0.1$ for $i \leq 3$ and $\ell_i = 0$ for $i \geq 4$.

Timber volume dynamics

Timber volume dynamics were obtained by converting tree diameter into volume, using volume equations taken from the management plan of the forest concession when available, or, by default, from the TNG. These are species-specific equations that predict the volume of a tree from its dbh, and are given in Additional file 3. Given that the first logging event occurs at time c, the population-level estimate of harvested timber volume for species s at time t is:

$$W_s(t,c) = \begin{cases} 0 & \text{if } (t-c) \bmod (T/\tau) \neq 0 \\ \mathbf{V}_s'(\mathbf{I} - \mathbf{H}_s)\,\mathbf{N}_s(t,c) & \text{if } (t-c) \bmod (T/\tau) = 0 \end{cases} \tag{6}$$

where $\mathbf{V}_s$ is the $K \times 1$ column vector $[V_s(D_1), \ldots, V_s(D_K)]'$, V_s is the volume equation for species s, D_i is the mean diameter for the ith diameter class, and $\mathbf{I}$ is the $K \times K$ identity matrix. The total harvested wood volume at time t is obtained by summing $W_s(t,c)$ over all logged species (disregarding unlogged species).

The population-level estimates of timber volume were summed across annual cutting units to estimate timber volume at the concession level. Because the forest concession is divided into quinquennial blocks that are in turn divided into annual cutting units, we consider that at every time step a proportion τ/T of the concession is logged. Hence, at the spatial scale of a cutting unit, there is a cyclic succession of logging events every T years, whereas at the concession level, logging occurs continuously. The harvested timber volume for species s at time t at the concession level under management scenario j thus is:

$$X_s^{(j)}(t) = \frac{\tau}{T} \sum_{c=1}^{T/\tau} W_s^{(j)}(t,c) \tag{7}$$

where $W_s^{(j)}$ is computed using (6) under the jth management scenario, and c indexes cutting units within the forest concession, considering that the first unit is initially logged, that the second unit is logged in year τ, and so on till the (T/τ)th unit that is logged in year $T - \tau$.

Carbon dynamics

Carbon dynamics were obtained by converting tree diameter into aboveground carbon, using an allometrical biomass equation. As carbon issues are currently not addressed by the TNG, no biomass equations were recommended by the TNG. Hence, we used Chave et al. [65] commonly used equation for tropical moist forests. The aboveground biomass (in kg) for species s at time t thus is:

$$M_s(t,c) = w_s\,\mathbf{B}'\,\mathbf{N}_s(t,c) \qquad (8)$$

where w_s is the wood density (in $\mathrm{g\,cm^{-3}}$) for species s, and $\mathbf{B}$ is the $K \times 1$ column vector $[B(D_1), \ldots, B(D_K)]'$ defined by $B(D_i) = \exp\{-1.499 + 2.1481\ln(D_i) + 0.207[\ln(D_i)]^2 - 0.0281[\ln(D_i)]^3\}$, where D_i is expressed in cm. The specific wood densities were taken from the Zanne et al. [66] database. When no match at the species level was found, an average value at the genus level was taken. When no match at the genus level was found in the database, the default value of 0.60 $\mathrm{g\ cm^{-3}}$ recommended by Henry *et al.* ([67], p.1383) for tropical African woods was taken. Species-specific wood densities are listed in Additional file 3.

The population-level dry aboveground biomass at time t is obtained by summing $M_s(t,c)$ over all species (including unlogged species). As for timber volumes, this value is then summed across annual cutting units to get the dry aboveground biomass at the concession level. Dry biomass is converted into CO_2 equivalents using fixed conversion rates. Adding all the carbon pools, the carbon stock (in tons of CO_2) at time t at the concession level under management scenario j is:

$$C^{(j)}(t) = \gamma^{-1}\alpha \sum_{s=1}^{S} \frac{\tau}{T} \sum_{c=1}^{T/\tau} M_s^{(j)}(t,c) + C^{(j)}_{\mathrm{prod}}(t) + C^{(j)}_{\mathrm{other}}(t) \qquad (9)$$

where $\gamma = 12/44$ ton of C per ton of CO_2 is the mass proportion of carbon in CO_2, $\alpha = 0.47$ ton of C per ton of biomass is the conversion rate from biomass to carbon (Table 4.3 in [68]), the summation on s is over all species (including unlogged species), $M_s^{(j)}$ is computed using (8) under the jth management scenario, C_{prod} is the carbon stock in long-lived wood products, and C_{other} is the carbon stock in the other pools (below-ground biomass and necromass).

Additional files

Additional file 1: Detailed results of the elasticity analysis. The additional file contains detailed results of the elasticity analysis of the break-even price of carbon to ecological parameters.

Additional file 2: Break-even price for different management parameters. The additional file contains estimations of the break-even price of carbon when different values of the management parameters are used.

Additional file 3: Model parameters. The additional file contains the list of mathematical symbols, the risk analysis to determine the number of buffer credits, and the species specific parameters and volume equations.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

NLEO and AN supervised the research project. RM, CR, FC and NP designed the model to estimate the REDD+ cost elements. MN and NP undertook the analyses. NP drafted the manuscript. SGF and CR co-authored the manuscript. FC was responsible for review of the manuscript and provision of comments. All authors read and approved the final manuscript.

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Additional file 1

Opportunity cost of carbon sequestration with respect to timber production in a forest concession in central Africa: Detailed results of the elasticity analysis

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Elasticities of the break-even price of carbon to ecological parameters

The sensitivity of the break-even price π_C^* of carbon to a parameter θ is:

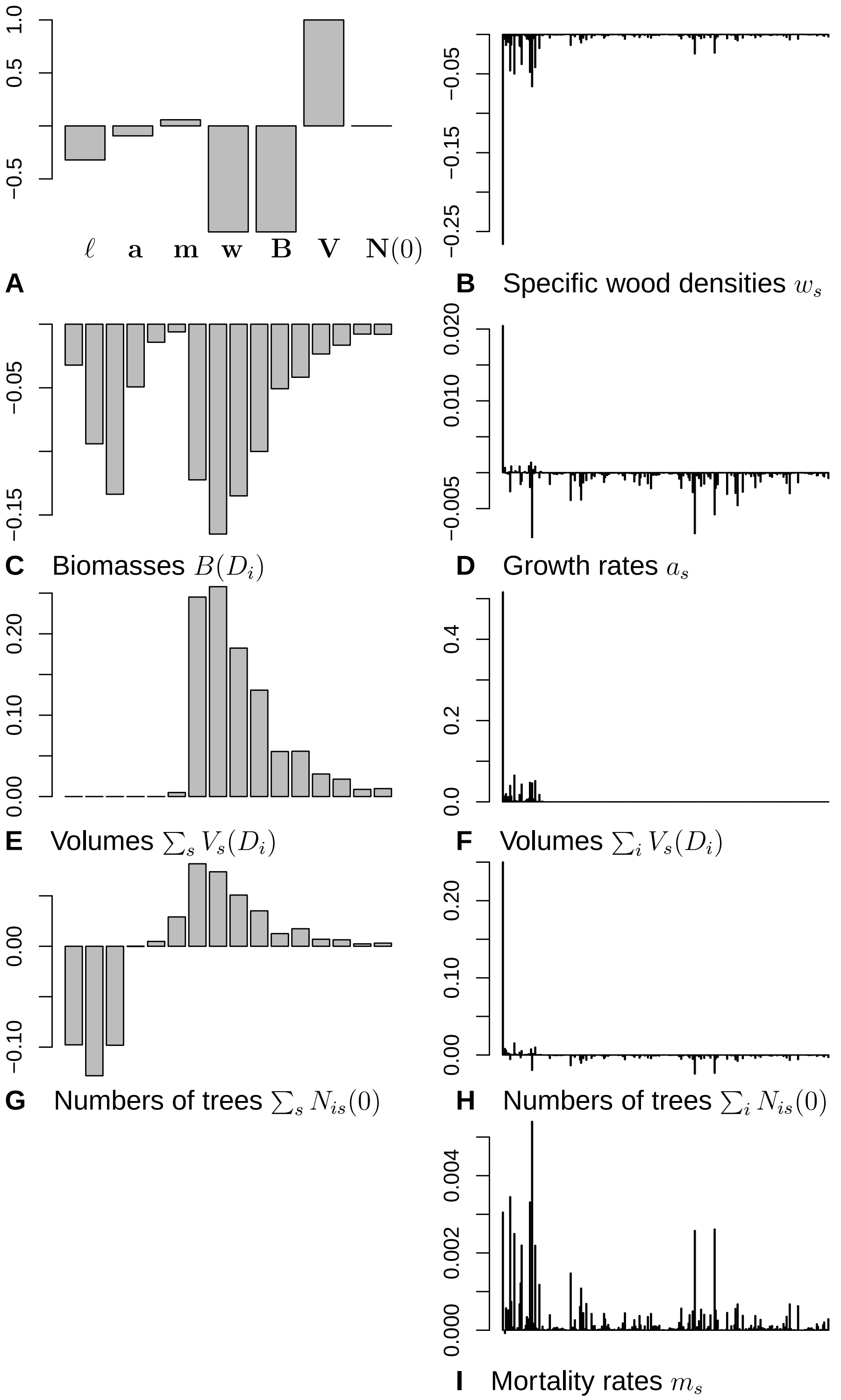
$$\sigma_\theta = \frac{\partial \pi_C^*}{\partial \theta}$$

whereas the elasticity of the break-even price to this parameter is:

$$e_\theta = \frac{\partial \ln \pi_C^*}{\partial \ln \theta} = \left(\frac{\partial \pi_C^*}{\partial \theta}\right)\left(\frac{\theta}{\pi_C^*}\right)$$

$\sigma_\theta \times \Delta$ gives the amount by which π_C^* changes if parameter θ is changed by a small additive perturbation Δ. $e_\theta \times \xi$ gives the proportional change of π_C^* that is brought by a small proportional perturbation of parameter θ in a proportion ξ. Sensitivities and elasticities can be added to assess the joint impact of several parameters. If $\theta = (\theta_1, \ldots, \theta_n)$ is a vector of n parameters, we define $\sigma_\theta = \sum_{i=1}^{n} \sigma_{\theta_i}$ and $e_\theta = \sum_{i=1} e_{\theta_i}$. Then, $\sigma_\theta \times \Delta$ gives the amount by which π_C^* changes if all parameters $\theta_1, \ldots, \theta_n$ are simultaneously changed by the same additive perturbation Δ, whereas $e_\theta \times \xi$ gives the proportional change of π_C^* that is obtained if all parameters $\theta_1, \ldots, \theta_n$ are simultaneously changed in the same proportion ξ.

The break-even price is computed for the project scenario with a longer rotation $T^{\text{ref}} + 10$ yr. Expectedly, the elasticities to the specific densities w_s and to the class-dependent biomasses $B(D_i)$ are all negative (Fig.S2-1B, C) since an increase in these parameters brings an increase in the net carbon benefit and consequently a decrease in the break-even price of carbon, whereas the elasticities to $V_s(D_i)$ are all positive (Fig.S2-1E, F) since an increase in these parameters brings an increase in PVT. Most of the elasticities to mortality rates m_s are positive (Fig.S2-1I). The elasticities to the growth rates a_s (Fig.S2-1D) and to the initial number of trees $N_{is}(0)$ (Fig.S2-1G, H) are positive or negative depending on the species and the diameter class. These changing signs reflect the influence of the shape of the diameter distribution. For species like *Aucoumea klaineana* that have a hump-shaped diameter distribution, with many large trees and a deficit of juveniles, increasing the growth rate intensifies the "primary forest premium" effect. For those parameters that are species-specific (Fig.S2-1, right column), the S species impact differently the break-even price, with *A. klaineana* always standing as the species with the greatest impact on π_C^*. For those parameters that vary with the diameter class (Fig.S2-1C, E, G), the K classes also impact differently the break-even price, with one peak (in absolute value) around class 2–3 and/or another peak around class 7–8 (that is close to the cutting limit).



A

B Specific wood densities w_s

C Biomasses $B(D_i)$

D Growth rates a_s

E Volumes $\sum_s V_s(D_i)$

F Volumes $\sum_i V_s(D_i)$

G Numbers of trees $\sum_s N_{is}(0)$

H Numbers of trees $\sum_i N_{is}(0)$

I Mortality rates m_s

Fig. S2-1: Elasticities of the break-even price π_C^* of carbon to ecological parameters. A. Elasticities to vectors of parameters, where ℓ = logging damages, $\mathbf{a} = (a_s)_{s=1\ldots S}$ = growth rates, $\mathbf{m} = (m_s)_{s=1\ldots S}$ = mortality rates, $\mathbf{w} = (w_s)_{s=1\ldots S}$ = wood densities, $\mathbf{B} = [B(D_i)]_{i=1\ldots K}$ = class-dependent biomasses, $\mathbf{V} = [V_s(D_i)]_{s=1\ldots S, i=1\ldots K}$ = species- and class-dependent volumes, and $\mathbf{N}(0) = [N_{is}(0)]_{i=1\ldots K, s=1\ldots S}$ = initial numbers of trees. B–I clarify the elasticities of π_C^* to each element of these vectors, with species-dependent parameters on the right, and class-dependent parameters on the left. For species-dependent parameters, there are $S = 313$ bars and *Aucoumea klaineana* corresponds to the first bar. For class-dependent parameters, there are $K = 16$ bars corresponding to the K diameter classes.

Additional file 2

Opportunity cost of carbon sequestration with respect to timber production in a forest concession in central Africa: Break-even price of carbon for different management parameter values

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In this additional file, we redo the computation of the break-even price of carbon with different values of the management parameters, to assess the robustness of the estimate of the break-even price.

1 Break-even price of carbon when damage rate varies across management scenarios

By default, we used a constant logging damage rate of 10%, irrespective of management scenario. To relax this simplifying assumption, we also computed the break-even price of carbon when logging damage depends on the density of logged trees. We used the relationship given by Picard et al. (2012) between logging damage ℓ (dimensionless) and the density of logged trees h (in stems ha^{-1}):

$$\ell = 1 - \frac{1}{(1+0.09135h)^{0.7046}}$$

where h is computed from $\mathbf{N}_s$ using: $h = \sum_s \mathbf{1}'(\mathbf{I}-\mathbf{H}_s)\mathbf{N}_s$, where the sum on s is over commercial species only, and $\mathbf{1}$ is the vector of length K full of ones (see section "Model of forest dynamics" of the manuscript). The resulting break-even price of carbon for a contribution margin of US\$25/m^3 is given in Table S3-1.

2 Break-even price of carbon for a discount rate of 8%

By default, we used of discount rate of 12%. When the discount rate is lowered to 8%, the break-even price of carbon is slightly modified (Table S3-2), which is consistent with the result of the sensitivity analysis that showed that the break-even price of carbon was slightly sensitive to the discount rate.

Tab. S3-1: Opportunity cost of carbon sequestration for different alternative management scenarios in the Haut-Abanga concession, when logging damage is a function of the density of logged trees. The break-even price of carbon sequestration π_C^* is computed for a contribution margin of US\$25/m^3 for all commercial species. $\sum$Credits is the sum of carbon credits. ΔVolume is the total reduction in harvested wood volume. ΔPVT$_\mathrm{T}$ is the loss in the net present value of timber.

Scenario	ΔVolume (m^{3}ha^{-1})	$\sum$Credits (tCO$_2$ha^{-1})	ΔPVT$_\mathrm{T}$ (US\$/ha)	π_C^* (US\$/tCO$_2$)
Lengthened rotation (+5 yr)	1.8	8.5	34.2	8.9
Lengthened rotation (+10 yr)	3.3	16.0	60.5	8.9
Lengthened rotation (+15 yr)	4.7	22.7	81.2	8.8
Raised cutting limits (+10 cm)	8.9	22.6	65.5	7.9
Raised cutting limits (+20 cm)	17.5	41.9	124.2	8.1
Raised cutting limits (+30 cm)	24.5	55.3	166.2	8.4
Raised cutting limits (+40 cm)	29.5	63.5	193.6	8.6

Tab. S3-2: Opportunity cost of carbon sequestration for different alternative management scenarios in the Haut-Abanga concession, for a discount rate of 8%. The break-even price of carbon sequestration π_C^* is computed for a contribution margin of US\$25/m^3 for all commercial species. $\sum$Credits is the sum of carbon credits. ΔVolume is the total reduction in harvested wood volume. ΔPVT$_\mathrm{T}$ is the loss in the net present value of timber.

Scenario	ΔVolume (m^{3}ha^{-1})	$\sum$Credits (tCO$_2$ha^{-1})	ΔPVT$_\mathrm{T}$ (US\$/ha)	π_C^* (US\$/tCO$_2$)
Lengthened rotation (+5 yr)	1.8	7.1	41.6	10.5
Lengthened rotation (+10 yr)	3.3	13.0	75.3	10.7
Lengthened rotation (+15 yr)	4.7	18.2	102.9	10.9
Raised cutting limits (+10 cm)	8.9	10.3	89.4	16.7
Raised cutting limits (+20 cm)	17.5	19.5	170.4	16.9
Raised cutting limits (+30 cm)	24.5	26.3	229.9	17.1
Raised cutting limits (+40 cm)	29.5	30.7	269.5	17.3

3 Break-even price of carbon for a growth rate of 0.172 cm yr^{-1}

By default, we used a dbh growth rate of $a = 0.3$ cm yr^{-1}, which corresponds to a dbh distribution at steady state (without logging) that is exponential with parameter $m/a = 0.033$ cm^{-1}, where $m = 1\%$ yr^{-1} is the default value of the mortality rate. The pre-harvest dbh distribution in the Haut Abanga concession was exponential with parameter 0.058 cm^{-1}, which corresponds to a dbh growth rate of $a = 0.172$ cm yr^{-1}. When the dbh growth rate is lowered from 0.3 to 0.172 cm yr^{-1}, the carbon stock has an overall trend that is decreasing (Figure S3-1). However, the break-even price of carbon is slightly modified (Table S3-3), which is consistent with the result of the sensitivity analysis that showed that the break-even price of carbon was slightly sensitive to the dbh growth rate.

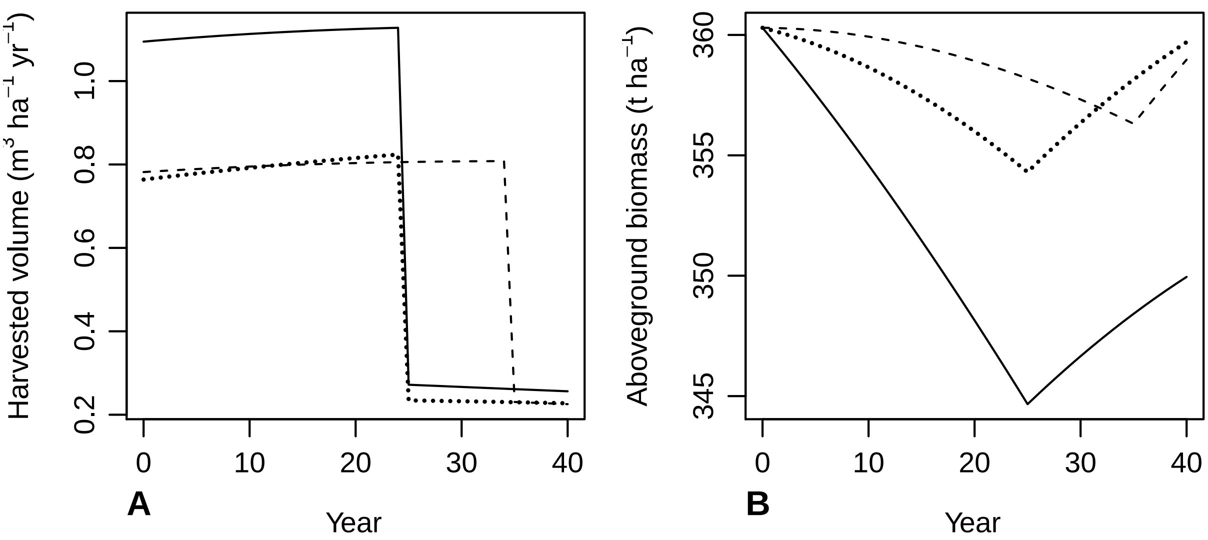

Fig. S3-1: Temporal forecasts in the Haut-Abanga forest concession, Gabon, when using a dbh growth rate of 0.172 cm yr^{-1}. Harvested wood volume (panel A) and aboveground biomass (panel B) are forecast according to three management scenarios: solid line is the reference scenario (T^{ref}, d_s^{ref}); dashed line is an alternative scenario with a longer felling cycle $T = T^{\mathrm{ref}} + 10$ yr; and dotted line is an alternative scenario with higher cutting limit diameters $d_s = d_s^{\mathrm{ref}} + 10$ cm.

Tab. S3-3: Opportunity cost of carbon sequestration for different alternative management scenarios in the Haut-Abanga concession, for a dbh growth rate of 0.172 cm yr^{-1}. The break-even price of carbon sequestration π_C^* is computed for a contribution margin of US\$25/m^3 for all commercial species. $\sum$Credits is the sum of carbon credits. ΔVolume is the total reduction in harvested wood volume. ΔPVT$_\mathrm{T}$ is the loss in the net present value of timber.

Scenario	ΔVolume (m^{3}ha^{-1})	$\sum$Credits (tCO$_2$ha^{-1})	ΔPVT$_\mathrm{T}$ (US\$/ha)	π_C^* (US\$/tCO$_2$)
Lengthened rotation (+5 yr)	1.5	5.9	32.1	11.6
Lengthened rotation (+10 yr)	2.7	10.8	56.7	11.6
Lengthened rotation (+15 yr)	3.9	15.1	75.9	11.6
Raised cutting limits (+10 cm)	8.5	9.2	63.3	16.3
Raised cutting limits (+20 cm)	16.3	17.3	119.2	16.4
Raised cutting limits (+30 cm)	22.2	23.1	157.6	16.4
Raised cutting limits (+40 cm)	26.1	26.7	182.2	16.5

References

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Additional file 3

Opportunity cost of carbon sequestration with respect to timber production in a forest concession in central Africa: Model parameters

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1 List of mathematical symbols

1.1 Latin symbols

a_s: the average diameter growth rate (in $\text{cm}\,\text{yr}^{-1}$) for species s
A: long-term average of net carbon benefit
A_s: administrative minimum cutting limit for species s
$\mathbf{B}$: the biomass vector = $K \times 1$ column vector $[B(D_1), \ldots, B(D_K)]'$
$B(D)$: aboveground dry biomass of a tree with dbh D and whose wood density equals 1 $\text{g}\,\text{cm}^{-3}$
c: time index for a logging event; correspondingly, c also indexes annual cutting units within the forest concession (identifying the 1st annual cutting unit as the one that is cut at year 1, the 2nd unit as the one that is cut at year 2, etc.)
$C(t)$: carbon stock at time t at the concession level
C_{prod}: carbon stock in long-lived wood products
C_{other}: carbon stock in other compartments than standing aboveground biomass and long-lived wood products
D_i: the mean diameter for the ith diameter class
d_s: cutting limit dbh for species s
e_θ: the elasticity of the break-even price π_C to parameter θ
f_s: the recruitment rate for species s = the probability for a tree of species s to generate a newly recruited tree between two successive time steps
$G(t)$: greenhouse gas emission at time t as a result of forest management activities
h: density of logged trees
$\mathbf{H}_s$: the harvest matrix = $K \times K$ diagonal matrix whose ith element on the diagonal is 1 if the upper bound of the ith diameter class is less than d_s, and $1 - \rho_s$ otherwise
i: index of a diameter class ($1 \leq i \leq K$)
$\mathbf{I}$: the $K \times K$ identity matrix
j: index of a management scenario
K: number of diameter classes
ℓ_i: logging damage rate in diameter class i = proportion of trees that are removed due to damage in the ith diameter class when logging occurs
$L(t)$: greenhouse gas emission at time t due to leakage

$\mathbf{L}$: the logging damage matrix = $K \times K$ diagonal matrix whose ith element on the diagonal is ℓ_i

m_s: mortality rate for species s = the probability for a tree of species s to die between two successive time steps

$M_s(t,c)$: cumulative biomass for species s at time t, given that logging occurred at time c

$\mathbf{N}_s(0)$: $K \times 1$ column vector $[N_{1s}(0), \ldots, N_{Ks}(0)]'$

n: index of a parameter of the model

$N_{is}(0)$: the initial number of trees of species s in the ith diameter class, as provided by the management inventory

$\mathbf{N}_s(t,c)$: $K \times 1$ column vector $[N_{1s}(t,c), \ldots, N_{Ks}(t,c)]'$

$N_{is}(t,c)$: the number of individuals of species s in diameter class i at time t, given that logging occurred at time c

$\mathrm{NPV}_{\mathrm{C}}^{(j)}$: net present value of carbon under project scenario j

$\mathrm{NPV}_{\mathrm{T}}^{(j)}$: net present value of timber under project scenario j

$p_s^\star$: growth propensity $= p_s/(1-m_s)$ = the conditional probability for a tree of species s to move up to the next diameter class between two successive time steps knowing that it has stayed alive

p_s: the upgrowth rate = the probability for a tree of species s to stay alive and move up to the next diameter class between two successive time steps

q_s: the stasis rate = the probability for a tree of species s to stay alive in the same diameter class between two successive time steps

Q: fixed costs of logging (including fixed taxes)

r: proportion of timber that is lost between the log yard and the mill entry

s: index of a species ($1 \leq s \leq S$)

S: number of species

t: index of time

T: the rotation = the length of the felling cycle (must be a multiple of 5 years)

$(T,\, d_s^{\mathrm{ref}})$: management scenario where $T > T^{\mathrm{ref}}$, with a longer felling cycle but the same cutting limits

$(T^{\mathrm{ref}},\, d_s^{\mathrm{ref}})$: reference management scenario

$(T^{\mathrm{ref}},\, d_s)$: management scenario where $d_s > d_s^{\mathrm{ref}}$, with higher cutting limits but the same rotation

$U(t)$: number of issuable carbon credits at time t

$\mathbf{U}_s$: $K \times K$ Usher transition matrix for species s

$\mathbf{V}$: $(S \times K)$-vector $(\mathbf{V}_1, \ldots, \mathbf{V}_S)$

$\mathbf{V}_s$: $K \times 1$ column vector $[V_s(D_1), \ldots, V_s(D_K)]'$

$V_s(D)$: volume of a tree with species s and dbh D

$\mathbf{w}$: S-vector $(w_1, \ldots, w_S)$

w_s: wood density (in $\mathrm{g\,cm^{-3}}$)

$W_s(t,c)$: harvested timber volume for species s at time t, given that logging occurred at time c

$X_s(t)$: harvested timber volume for species s at time t at the concession level

1.2 Greek symbols

α: conversion rate from dry biomass to carbon = 0.47 ton of C per ton of dry biomass

β_s: variable costs (including variable logging costs, transportation costs, and variable taxes) for species s

γ: mass proportion of carbon in CO_2 = 0.273 ton of C per ton of CO_2

δ: discount rate

Δ: a small additive change of a parameter value
$\Delta C(t)$: net carbon benefit (in tCO_2 ha^{-1}) at time t with respect to the reference scenario
ζ: fraction of issuable carbon credits that can be issued, the remaining fraction being withheld as a buffer reserve for the non-permanence risk
$\boldsymbol{\theta}$: a vector of parameters of the model
θ: a parameter of the model
λ_s: population growth rate for species s
ξ: a small proportional change of a parameter value
π: S-vector $(\pi_1, \ldots, \pi_S)$ of the specific contribution margins
π_C: the price of certificates of emission reductions (in US\$ per tCO_2)
π_C^*: the break-even price of carbon credits (in US\$ per tCO_2)
π_s: contribution margin for species s
ϖ_s: market price of untransformed timber for species s
ρ_s: logging intensity = proportion of all trees with a dbh greater than or equal to d_s that are harvested by logging
σ_θ: the sensitivity of the break-even price π_C to parameter θ
τ: time interval (in yr) between two successive time steps
ω: the width of the diameter classes (in cm)
Ω: duration of the carbon project (in yr; must be a multiple of 5 years)

1.3 Non-alphabetic symbols

$\mathbf{1}$: vector of length K full of ones

2 Risk analysis for an improved forest management REDD+ project in Haut Abanga, Gabon

The risk analysis aims at determining the non-permanence risk rating, which shall be used to determine the number of buffer credits that the project shall deposit into a pooled buffer account. The risk analysis was conducted following the VCS non-permanence risk tool version 3.2 (Verified Carbon Standard, 2012) and yielded an overall risk rating of 22 (Table S1-1). In comparison, TEREA (2013) for a virtual improved forest management REDD+ project in the Haut Nyong, Cameroon, obtained an overall risk rating of 24. For the Maï Ndombé REDD+ project in the Democratic Republic of Congo (project #934 in the VCS project database), an overall risk rating of 25 was used. For the Pikounda REDD+ project in Congo (project #1052 in the VCS project database), an overall risk rating of 21 was used.

Tab. S1-1: Risk analysis at Haut Abanga, Gabon.

	Risk	Value	Score	Explanation
A. Internal risks				
	A1. Project management risks			
a)	Species planted (where applicable) associated with more than 25% of the stocks on which GHG credits have previously been issued are not native or proven to be adapted to the same or similar agro-ecological zone(s) in which the project is located.	2	0	The Haut Abanga forest is a natural forest with no plantations that contribute to the project.

	Risk	Value	Score	Explanation
b)	Ongoing enforcement to prevent encroachment by outside actors is required to protect more than 50% of stocks on which GHG credits have previously been issued.	2	0	The Haut Abanga forest is an isolated area with no outside actors nearby.
c)	Management team does not include individuals with significant experience in all skills necessary to successfully undertake all project activities (ie, any area of required experience is not covered by at least one individual with at least 5 years experience in the area).	2	0	Forest concessionaires are already trained on sustainable forest management. Lengthening the felling cycle or raising diameter cuting limits does not require new skills.
d)	Management team does not maintain a presence in the country or is located more than a day of travel from the project site, considering all parcels or polygons in the project area.	2	0	The forest concessionaire maintains a permanent presence in the project area and in Libreville (less than a day of travel fromt the site).
e)	Mitigation: Management team includes individuals with significant experience in AFOLU project design and implementation, carbon accounting and reporting (eg, individuals who have successfully managed projects through validation, verification and issuance of GHG credits) under the VCS Program or other approved GHG programs.	−2	0	The forest concessionaire is not well trained on REDD+ projects.
f)	Mitigation: Adaptive management plan in place.	−2	0	Current forest management plans are not adaptive (in the sense given by VCS).
	Total for project management		0	
	A2. Financial viability risks			
a-d)	Project cash flow breakeven point greater than 4 and up to 7 years from the current risk assessment	0–3	1	The project would include support from donors interested in the development of alternative forest management practices.
e-h)	Project has secured 40% to less than 80% of funding needed to cover the total cash out required before the project reaches breakeven	0–3	1	Forest concessionaires are cautious regarding REDD+ projects and would not run into them without ensuring that enough funding is available.
i)	Mitigation: Project has available as callable financial resources at least 50% of total cash out before project reaches breakeven	−2	0	
	Total for financial viability		2	
	A3. Opportunity costs risks			
a-f)	NPV from the most profitable alternative land use activity is expected to be at least 100% more than that associated with project activities; or where baseline activities are subsistence-driven, net positive community impacts are not demonstrated	0–8	8	The NPV were computed on the basis of a contribution margin of $\pi_s = 25$ US\$/m^3 for timber and of a carbon price of 12,7 US\$/tCO$_2$.
g)	Mitigation: Project proponent is a non-profit organization	−2	0	The project proponent is from the private sector.

	Risk	Value	Score	Explanation
h-i)	Mitigation: Project is protected by legally binding commitment (see Section 2.2.4) to continue management practices that protect the credited carbon stocks over the length of the project crediting period. Or: Project is protected by legally binding commitment (see Section 2.2.4) to continue management practices that protect the credited carbon stocks over at least 100 years	-2	-2	The FSC certification of the Haut Abanga concession could possibly ensure that the improved management practices are continued over the length of the project period.
	Total for opportunity costs		6	
	A4. Project longevity risks			
b)	With legal agreement or requirement to continue the management practice	$30-L/2$	10	Considering that the FSC certification is a legal agreement and that the project longevity (L, in years) is 40 years.
	Total for project longevity		10	
	Total for internal risks		18	(≤ 35 for eligibility)
B. External risks				
	B1. Land tenure and resource access/impacts risks			
a-b)	Ownership and resource access/use rights are held by different entity(s)	0–2	2	Land is government owned and the project proponent holds a lease or concession
c)	In more than 5% of the project area, there exist disputes over land tenure or ownership	10	0	There is no dispute over land tenure or ownership in Haut Abanga
d)	There exist disputes over access/use rights (or overlapping rights)	5	0	Mining can generate dispute over access/use rights in forest concessions in Gabon, but there is no mining permit in Haut Abanga.
e)	WRC projects unable to demonstrate that potential upstream and sea impacts that could undermine issued credits in the next 10 years are irrelevant or expected to be insignificant, or that there is a plan in place for effectively mitigating such impacts.	2	0	Not applicable.
f)	Mitigation: Project area is protected by legally binding commitment (eg, a conservation easement or protected area) to continue management practices that protect carbon stocks over the length of the project crediting period	-2	0	Project area is not a protected area.
g)	Mitigation: Where disputes over land tenure, ownership or access/use rights exist, documented evidence is provided that projects have implemented activities to resolve the disputes or clarify overlapping claims	-2	0	Not applicable.
	Total for land tenure and resource access/impacts		2	
	B2. Community engagement risks			
a-b)	Less than 20 percent of households living within 20 km of the project boundary outside the project area, and who are reliant on the project area, have been consulted	5	5	
c)	Mitigation: The project generates net positive impacts on the social and economic well-being of the local communities who derive livelihoods from the project area	-5	-5	Reducing logging intensity improves the availability of non-wood forest products, especially those originating from commercial species.
	Total for community engagement		0	
	B3. Political risks			

	Risk	Value	Score	Explanation
a-e)	Governance score of -0.79 to less than -0.32	0–6	4	The mean of Governance Scores of Gabon across the six indicators of the World Bank Institute's Worldwide Governance Indicators, averaged over 2008–2012 equals -0.555.
f)	Mitigation: Country is implementing REDD+ Readiness or other activities, as set out in Section 2.3.3.	-2	-2	Gabon has an established national PEFC standards body.
	Total for political risks		2	
	Total for external risks		4	(≤ 20 for eligibility)
C. Natural risks				
	Fire		0	
	Pest and disease outbreaks		0	
	Extreme weather		0	
	Geological risk		0	
	Other natural risk		0	
	Total for natural risks		0	(≤ 35 for eligibility)
	Overall risk rating		22	(≤ 60 for eligibility)

3 Species specific parameters and volume equations

Species nomenclature follows the African Plant Database version 3.3.4 of the Conservatoire et Jardin botaniques de la ville de Genve, Switzerland and South African National Biodiversity Institute, Pretoria, retrieved September 2011 from `http://www.ville-ge.ch/musinfo/bd/cjb/africa/`. For volume equations, dbh is expressed in m and volume is given in m^3. Wood density (w_s) is in g cm^{-3}. The administrative minimum cutting limits (A_s) are in cm.

Group	Name	Latin name	w_s	A_s	Volume equation
1	Okoume	*Aucoumea klaineana*	0.3781	70	$-1.8236D + 10.725D^2$
2	Acajou	*Khaya ivorensis*	0.4305	80	$10.82D^{1.89}$
2	Agba (Tola)	*Prioria balsamifera*	0.4133	80	$11.7D^{2.16}$
2	Andoung 66	*Tetraberlinia polyphylla*	0.5301	70	$9.28D^{2.07}$
2	Andoung Heitz	*Aphanocalyx heitzii*	0.4592	70	$9.28D^{2.07}$
2	Andoung Le Testu	*Bikinia letestui*	0.6	70	$9.28D^{2.07}$
2	Anzem Rouge	*Copaifera religiosa*	0.5231	90	$9.72D^{2.46}$
2	Azobe	*Lophira alata*	0.8972	80	$9.72D^{2.46}$
2	Beli	*Julbernardia pellegriniana*	0.6846	100	$9.28D^{2.07}$
2	Bosse Clair	*Guarea cedrata*	0.5074	80	$9.72D^{2.46}$
2	Bosse Fonce	*Guarea thompsonii*	0.5596	80	$9.72D^{2.46}$
2	Dabema	*Piptadeniastrum africanum*	0.6004	70	$9.72D^{2.46}$
2	Dibetou	*Lovoa trichilioides*	0.4554	80	$0.48 + 10.2D^2$
2	Doussie Bella	*Afzelia sp.* (except *bipindensis*, *pachyloba*)	0.6888	80	$9.72D^{2.46}$
2	Doussie Blanc	*Afzelia bipindensis*	0.706	80	$0.6 + 10.8D^2$
2	Doussie Pachyloba	*Afzelia pachyloba*	0.6725	80	$9.72D^{2.46}$
2	Ebiara	*Berlinia bracteosa*	0.6071	70	$9.28D^{2.07}$
2	Eyoum	*Dialium sp.*	0.83	70	$9.72D^{2.46}$
2	Gheombi	*Sindoropsis letestui*	0.6449	70	$9.28D^{2.07}$
2	Gombe	*Didelotia letouzeyi*	0.501	70	$9.28D^{2.07}$
2	Igaganga	*Dacryodes igaganga*	0.5388	70	$9.72D^{2.46}$
2	Iroko	*Milicia excelsa*	0.5795	100	$1.05 + 10.08D^2$
2	Izombe	*Testulea gabonensis*	0.6465	80	$9.72D^{2.46}$

Group	Name	Latin name	w_s	A_s	Volume equation
2	Kevazingo (Bubinga)	*Guibourtia tessmannii*	0.7641	100	$1.05+10.08D^2$
2	Kosipo	*Entandrophragma candollei*	0.5959	110	$10.82D^{1.89}$
2	Movingui	*Distemonanthus benthamianus*	0.6014	80	$0.04+9.07D^2$
2	Okan	*Cylicodiscus gabunensis*	0.7998	70	$9.72D^{2.46}$
2	Olon	*Zanthoxylum heitzii*	0.4317	70	$9.72D^{2.46}$
2	Omvong	*Dialium pachyphyllum*	0.9225	70	$9.72D^{2.46}$
2	Ossabel	*Dacryodes normandii*	0.5152	60	$9.2D^{1.9}$
2	Ovengkol	*Guibourtia ehie*	0.7096	60	$9.72D^{2.46}$
2	Padouk	*Pterocarpus soyauxii*	0.6402	80	$9.72D^{2.46}$
2	Pau Rosa	*Bobgunnia fistuloides*	0.6	70	$9.72D^{2.46}$
2	Sapelli	*Entandrophragma cylindricum*	0.5782	110	$10.82D^{1.89}$
2	Sipo	*Entandrophragma utile*	0.5436	110	$10.82D^{1.89}$
2	Tali	*Erythrophleum ivorense*	0.7747	70	$9.72D^{2.46}$
2	Tiama Blanc	*Entandrophragma angolense*	0.4702	90	$10.82D^{1.89}$
2	Tiama Noir=Acuminata	*Entandrophragma congoense*	0.4736	80	$10.82D^{1.89}$
2	Wenge	*Millettia laurentii*	0.7469	70	$9.72D^{2.46}$
3	Andoung Durand	*Bikinia durandii*	0.6	70	$9.28D^{2.07}$
3	Andoung Inc	*Bikinia sp.* (except *letestui*, *durandii*, *coriacea*)	0.6	70	$9.28D^{2.07}$
3	Andoung Morel	*Bikinia coriacea*	0.6	70	$9.28D^{2.07}$
3	Anzem Noir, Andem-E.	*Copaifera mildbraedii*	0.6589	90	$9.28D^{2.07}$
4	Aiele	*Canarium schweinfurthii*	0.4121	80	$9.72D^{2.46}$
4	Alen	*Detarium macrocarpum*	0.7026	70	$9.72D^{2.46}$
4	Alep	*Desbordesia glaucescens*	0.9209	70	$9.72D^{2.46}$
4	Alone	*Bombax brevicuspe*	0.4008	70	$9.72D^{2.46}$
4	Alumbi	*Julbernardia seretii*	0.6888	70	$9.72D^{2.46}$
4	Angoa	*Erismadelphus exsul*	0.5841	70	$9.72D^{2.46}$
4	Angueuk	*Ongokea gore*	0.7471	70	$9.72D^{2.46}$
4	Bilinga	*Nauclea diderrichii*	0.67	80	$9.72D^{2.46}$
4	Ebiara-Minkoul	*Berlinia confusa*	0.602	60	$9.28D^{2.07}$
4	Ekaba, Ekop	*Tetraberlinia bifoliolata*	0.4968	70	$9.72D^{2.46}$
4	Faro	*Daniellia sp.*	0.448	70	$9.72D^{2.46}$
4	Fromager	*Ceiba pentandra*	0.2838	70	$9.72D^{2.46}$
4	Ilomba	*Pycnanthus angolensis*	0.3975	70	$11.24D^{1.96}$
4	Kotibe	*Nesogordonia leplaei*	0.7174	70	$9.72D^{2.46}$
4	Limbali	*Gilbertiodendron dewevrei*	0.707	70	$10.34D^{2.22}$
4	Longhi Abam	*Chrysophyllum lacourtianum*	0.6305	70	$9.72D^{2.46}$
4	Longhi Bouk	*Chrysophyllum boukokonse*	0.6458	70	$9.72D^{2.46}$
4	Longhi Mbemame	*Chrysophyllum africanum*	0.63	70	$9.72D^{2.46}$
4	Longhi Perpulchra	*Chrysophyllum perpulchrum*	0.7052	70	$9.28D^{2.07}$
4	Longhi Subnuda	*Chrysophyllum subnudum*	0.6402	70	$9.72D^{2.46}$
4	Mekogho (Faux-Tali)	*Pachyelasma tessmannii*	0.7381	70	$9.72D^{2.46}$
4	Mukulungu	*Autranella congolensis*	0.78	90	$9.72D^{2.46}$
4	Niove	*Staudtia kamerunensis*	0.7886	60	$11.24D^{1.96}$
4	Onzabili	*Antrocaryon klaineanum*	0.5231	60	$9.28D^{2.07}$
4	Owui	*Hexalobus crispiflorus*	0.5016	70	$9.72D^{2.46}$
4	Tchitola	*Prioria oxyphylla*	0.5519	70	$9.72D^{2.46}$
5	Abeum	*Gilbertiodendron klainei*	0.6587	70	$9.72D^{2.46}$

Group	Name	Latin name	w_s	A_s	Volume equation
5	Agnuhe	*Pentadesma butyracea*	0.7784	70	$9.72D^{2.46}$
5	Ako	*Antiaris toxicaria*	0.3728	70	$9.72D^{2.46}$
5	Bodioa	*Anopyxis klaineana*	0.7785	70	$9.72D^{2.46}$
5	Bombax	*Bombax buonopozense*	0.3229	70	$9.72D^{2.46}$
5	Coula	*Coula edulis*	0.9135	70	$9.72D^{2.46}$
5	Dacryodes	*Dacryodes klaineana*	0.7177	70	$9.72D^{2.46}$
5	Diania	*Celtis tessmannii*	0.6964	70	$9.72D^{2.46}$
5	Divida	*Scorodophloeus zenkeri*	0.7428	70	$9.72D^{2.46}$
5	Edji	*Amphimas ferrugineus*	0.667	70	$9.72D^{2.46}$
5	Ekoulebang	*Parinari glabra*	0.9127	70	$9.72D^{2.46}$
5	Ekoune	*Coelocaryon preussii*	0.5019	70	$11.24D^{1.96}$
5	Emien	*Alstonia sp.*	0.3874	70	$9.72D^{2.46}$
5	Essang	*Parkia bicolor*	0.4304	70	$9.72D^{2.46}$
5	Essang-Eli	*Parinari sp.*	0.69	70	$9.72D^{2.46}$
5	Essessang	*Ricinodendron heudelotii*	0.2069	70	$9.72D^{2.46}$
5	Essia	*Petersianthus macrocarpus*	0.6905	70	$9.72D^{2.46}$
5	Essong	*Irvingia robur*	0.8026	70	$9.72D^{2.46}$
5	Etom	*Syzygium staudtii*	0.6328	70	$9.72D^{2.46}$
5	Eveuss	*Klainedoxa gabonensis*	0.9241	70	$9.72D^{2.46}$
5	Evino	*Vitex sp.*	0.52	70	$9.72D^{2.46}$
5	Faux Padouk	*Pterocarpus tessmannii*	0.5844	70	$9.72D^{2.46}$
5	Gambeya	*Chrysophyllum sp.* (except *lacourtianum*, *boukokonse*, *africanum*, *perpulchrum*, *subnudum*)	0.6458	70	$9.72D^{2.46}$
5	Kong-Afane	*Letestua durissima*	0.9722	70	$9.72D^{2.46}$
5	Landa	*Erythroxylum mannii*	0.5519	70	$9.72D^{2.46}$
5	Lannea	*Lannea welwitschii*	0.4303	70	$9.72D^{2.46}$
5	Manil	*Symphonia globulifera*	0.595	50	$9.72D^{2.46}$
5	Mbanegue	*Gilletiodendron pierreanum*	0.8904	70	$9.72D^{2.46}$
5	Mubala	*Pentaclethra macrophylla*	0.8241	70	$9.72D^{2.46}$
5	Mvana	*Hylodendron gabunense*	0.7869	70	$9.72D^{2.46}$
5	Ngaba	*Librevillea klainei*	0.9055	70	$9.72D^{2.46}$
5	Ngang Pf	*Hymenostegia pellegrinii*	0.835	70	$9.72D^{2.46}$
5	Ngong Mebame	*Funtumia africana*	0.4156	70	$9.72D^{2.46}$
5	Nieuk	*Fillaeopsis discophora*	0.4838	70	$9.72D^{2.46}$
5	Nka	*Pteleopsis hylodendron*	0.6807	70	$9.72D^{2.46}$
5	Nkagha	*Tessmannia africana*	0.8242	70	$9.72D^{2.46}$
5	Ntana	*Marquesia excelsa*	0.7577	70	$9.72D^{2.46}$
5	Oboto	*Mammea usambarensis*	0.6465	70	$9.72D^{2.46}$
5	Oddonio	*Oddoniodendron sp.*	0.9375	70	$9.72D^{2.46}$
5	Ohia	*Celtis mildbraedii*	0.6027	70	$9.72D^{2.46}$
5	Okolangouma	*Lecomtedoxa klaineana*	0.8621	70	$9.72D^{2.46}$
5	Olene	*Irvingia grandifolia*	0.8006	70	$9.72D^{2.46}$
5	Olonvogo	*Zanthoxylum gilletii*	0.6888	70	$9.72D^{2.46}$
5	Onzan	*Odyendyea gabonensis*	0.6	70	$9.72D^{2.46}$
5	Ossang-Eli	*Parinari hypochrysea*	0.69	70	$9.72D^{2.46}$
5	Ossimiale	*Newtonia leucocarpa*	0.5971	70	$9.72D^{2.46}$
5	Rikio	*Uapaca sp.*	0.645	70	$9.72D^{2.46}$
5	Sene	*Albizia adianthifolia*	0.495	70	$9.72D^{2.46}$

Group	Name	Latin name	w_s	A_s	Volume equation
5	Sorro	*Scyphocephalium mannii*	0.5101	60	$9.72D^{2.46}$
5	Stemeno	*Stemonocoleus micranthus*	0.5809	70	$9.72D^{2.46}$
6	Acioa	*Dactyladenia sp.*	0.6	70	$9.72D^{2.46}$
6	Adjouaba	*Dacryodes klaineana*	0.7177	70	$9.72D^{2.46}$
6	Adzacon	*Lecomtedoxa nogo*	0.8621	70	$9.72D^{2.46}$
6	Adzacon-Aboga	*Manilkara fouilloyana*	0.861	70	$9.72D^{2.46}$
6	Adzem	*Psilanthus mannii*	0.6	70	$9.72D^{2.46}$
6	Afane	*Panda oleosa*	0.5652	70	$9.72D^{2.46}$
6	Afatouk	*Maranthes gabunensis*	0.8292	70	$9.72D^{2.46}$
6	Afina	*Strombosia pustulata*	0.8421	70	$9.72D^{2.46}$
6	Afoupeli	*Hypodaphnis zenkeri*	0.6	70	$9.72D^{2.46}$
6	Ahinebe	*Anthocleista sp.*	0.5266	70	$9.72D^{2.46}$
6	Akak	*Duboscia macrocarpa*	0.6	70	$9.72D^{2.46}$
6	Ake	*Pterygota bequaertii*	0.5243	70	$9.72D^{2.46}$
6	Akeul	*Pausinystalia macroceras*	0.5876	70	$9.72D^{2.46}$
6	Akok	*Baphia sp.*	0.5678	70	$9.72D^{2.46}$
6	Akol	*Ficus exasperata*	0.3444	70	$9.72D^{2.46}$
6	Akom	*Beilschmiedia fulva*	0.5732	70	$9.72D^{2.46}$
6	Akot	*Drypetes gossweileri*	0.6629	70	$9.72D^{2.46}$
6	Alane Beku	*Klaineanthus gaboniae*	0.6	70	$9.72D^{2.46}$
6	Allen-Ocpo	*Dracaena sp.*	0.4166	70	$9.72D^{2.46}$
6	Allophyllus	*Allophylus sp.*	0.53	70	$9.72D^{2.46}$
6	Amvout	*Trichoscypha oddonii*	0.6285	70	$9.72D^{2.46}$
6	Andong	*Strephonema sericeum*	0.6291	70	$9.72D^{2.46}$
6	Angylocalyx	*Angylocalyx sp.*	0.6	70	$9.72D^{2.46}$
6	Anthonotha	*Anthonotha sp.* (except *fragrans*)	0.8241	70	$9.72D^{2.46}$
6	Antidesma	*Antidesma sp.*	0.68	70	$9.72D^{2.46}$
6	Anzilim	*Eurypetalum sp.*	0.6	70	$9.72D^{2.46}$
6	Aphanocalyx	*Aphanocalyx sp.* (except *heitzii*)	0.4592	70	$9.72D^{2.46}$
6	Arbre De La Passion	*Paropsia grewioides*	0.675	70	$9.72D^{2.46}$
6	Assas	*Macaranga sp.*	0.336	70	$9.72D^{2.46}$
6	Atangatier	*Dacryodes edulis*	0.5162	70	$9.72D^{2.46}$
6	Atieghe	*Discoglypremna caloneura*	0.3424	70	$9.72D^{2.46}$
6	Atom	*Dacryodes macrophylla*	0.5533	70	$9.72D^{2.46}$
6	Atsui	*Vismia rubescens*	0.489	70	$9.72D^{2.46}$
6	Aubrevillea	*Aubrevillea sp.*	0.6	70	$9.72D^{2.46}$
6	Avie	*Memecylon sp.*	0.785	70	$9.72D^{2.46}$
6	Avom	*Cleistopholis patens*	0.3556	70	$9.72D^{2.46}$
6	Baikia	*Baikiaea sp.*	0.7545	70	$9.72D^{2.46}$
6	Balanites	*Balanites wilsoniana*	0.6629	70	$9.72D^{2.46}$
6	Balonga (Otounga Gf)	*Balonga buchholzii*	0.6	70	$9.72D^{2.46}$
6	Beniaman	*Tetraberlinia moreliana*	0.5301	70	$9.72D^{2.46}$
6	Berlinia	*Berlinia sp.* (except *bracteosa*, *congolensis*)	0.6139	70	$9.72D^{2.46}$
6	Blighia	*Blighia welwitschii*	0.7819	70	$9.72D^{2.46}$
6	Bong	*Zanthoxylum tessmannii*	0.6003	70	$9.72D^{2.46}$
6	Brazzeia	*Brazzeia sp.*	0.6	70	$9.72D^{2.46}$
6	Camptostylus	*Oncoba mannii*	0.58	70	$9.72D^{2.46}$
6	Canthium	*Canthium sp.*	0.7224	70	$9.72D^{2.46}$

Group	Name	Latin name	w_s	A_s	Volume equation
6	Cassipourea	*Cassipourea sp.*	0.6197	70	$9.72D^{2.46}$
6	Chytranthus	*Chytranthus sp.*	0.6	70	$9.72D^{2.46}$
6	Claoxylon	*Claoxylon sp.*	0.355	70	$9.72D^{2.46}$
6	Coffea	*Coffea sp.*	0.6328	70	$9.72D^{2.46}$
6	Cola	*Cola sp.*	0.5231	70	$9.72D^{2.46}$
6	Conceveiba	*Conceveiba macrostachys*	0.504	70	$9.72D^{2.46}$
6	Crabwood	*Carapa procera*	0.5684	70	$9.72D^{2.46}$
6	Crossopteryx	*Crossopteryx sp.*	0.7017	70	$9.72D^{2.46}$
6	Crudia	*Crudia sp.*	0.8	70	$9.72D^{2.46}$
6	Cryptosepalum	*Cryptosepalum sp.*	0.7601	70	$9.72D^{2.46}$
6	Cuviera	*Cuviera sp.*	0.6	70	$9.72D^{2.46}$
6	Dibeum	*Gilbertiodendron unijugum*	0.6629	70	$9.72D^{2.46}$
6	Domele	*Bertiera sp.*	0.6	70	$9.72D^{2.46}$
6	Drypetes	*Drypetes sp.* (except *gossweileri*)	0.7146	70	$9.72D^{2.46}$
6	Duvigne	*Duvigneaudia inopinata*	0.6	70	$9.72D^{2.46}$
6	Ebam	*Picralima nitida*	0.7749	70	$9.72D^{2.46}$
6	Ebebeng	*Margaritaria discoidea*	0.7195	70	$9.72D^{2.46}$
6	Ebene	*Diospyros sp.* (except *crassiflora*)	0.7	70	$9.28D^{2.07}$
6	Ebene Noir	*Diospyros crassiflora*	0.8261	70	$9.28D^{2.07}$
6	Ebo	*Santiria trimera*	0.5554	70	$9.72D^{2.46}$
6	Eboboku	*Scaphopetalum sp.*	0.6	70	$9.72D^{2.46}$
6	Ebom	*Anonidium mannii*	0.2913	70	$9.72D^{2.46}$
6	Ebom Rouge	unknown	0.6	70	$9.72D^{2.46}$
6	Edzip	*Strombosia grandifolia*	0.8164	70	$9.72D^{2.46}$
6	Efot	*Magnistipula tessmannii*	0.6	70	$9.72D^{2.46}$
6	Egipt	*Strombosiopsis tetrandra*	0.6629	70	$9.72D^{2.46}$
6	Ekaku	*Thomandersia sp.*	0.6	70	$9.72D^{2.46}$
6	Ekat	*Neochevalierodendron stephanii*	0.6	70	$9.72D^{2.46}$
6	Ekoba	*Diogoa zenkeri*	0.6955	70	$9.72D^{2.46}$
6	Emvi	*Homalium longistylum*	0.73	70	$9.72D^{2.46}$
6	Endodesmia	*Endodesmia sp.*	0.6951	70	$9.72D^{2.46}$
6	Endone	*Pausinystalia johimbe*	0.5876	70	$9.72D^{2.46}$
6	Engokom	*Barteria fistulosa*	0.6	70	$9.72D^{2.46}$
6	Engomegoma	*Engomegoma gordonii*	0.6	70	$9.72D^{2.46}$
6	Engona	*Pentaclethra eetveldeana*	0.6629	70	$9.72D^{2.46}$
6	Engong	*Trichoscypha engong*	0.6285	70	$9.72D^{2.46}$
6	Erythrina	*Erythrina sp.*	0.264	70	$9.72D^{2.46}$
6	Esoma	*Rauvolfia caffra*	0.4525	70	$9.72D^{2.46}$
6	Essoula	*Plagiostyles africana*	0.7381	70	$9.72D^{2.46}$
6	Etou	*Treculia africana*	0.6	70	$9.72D^{2.46}$
6	Etua	*Tabernaemontana crassa*	0.5504	70	$9.72D^{2.46}$
6	Evegna	*Microdesmis puberula*	0.6	70	$9.72D^{2.46}$
6	Evegveu	*Irvingia excelsa*	0.8026	70	$9.72D^{2.46}$
6	Evong-Evong	*Spathodea campanulata*	0.2712	70	$9.72D^{2.46}$
6	Ewoleghe	*Bridelia sp.*	0.5328	70	$9.72D^{2.46}$
6	Ezelfou	*Sterculia tragacantha*	0.43	70	$9.72D^{2.46}$
6	Feup	*Isolona hexaloba*	0.6	70	$9.72D^{2.46}$

Group	Name	Latin name	w_s	A_s	Volume equation
6	Ficus Arbre	*Ficus vogeliana*	0.4004	70	$9.72D^{2.46}$
6	Ficus Etrangleur	*Ficus sp.* (except *vogeliana*, *mucuso*, *exasperata*)	0.4004	70	$9.72D^{2.46}$
6	Ganophyllum	*Ganophyllum giganteum*	0.698	70	$9.72D^{2.46}$
6	Garcinia	*Garcinia sp.*	0.7293	70	$9.72D^{2.46}$
6	Gardenia	*Gardenia imperialis*	0.6665	70	$9.72D^{2.46}$
6	Ghekoa	*Vepris soyauxii*	0.6591	70	$9.72D^{2.46}$
6	Gilbertiodendron	*Gilbertiodendron sp.*	0.6629	70	$9.72D^{2.46}$
6	Grewia	*Grewia sp.*	0.57	70	$9.72D^{2.46}$
6	Guarea	*Guarea sp.* (except *cedrata*, *thompsonii*)	0.545	70	$9.72D^{2.46}$
6	Homalium	*Homalium sp.* (except *longistylum*, *letestui*)	0.73	70	$9.72D^{2.46}$
6	Hymeno	*Hymenostegia ngounyensis*	0.8296	70	$9.72D^{2.46}$
6	Inconnue	unknown	0.6	70	$9.72D^{2.46}$
6	Isolona	*Isolona hexaloba*	0.6	70	$9.72D^{2.46}$
6	Ka	*Dichostemma glaucescens*	0.6	70	$9.72D^{2.46}$
6	Kanguele	*Maesopsis eminii*	0.3901	70	$9.72D^{2.46}$
6	Kaoue	*Stachyothyrsus staudtii*	0.645	70	$9.72D^{2.46}$
6	Kobahia	*Christiana africana*	0.6	70	$9.72D^{2.46}$
6	Lebonda	*Trichilia tessmannii*	0.64	70	$9.72D^{2.46}$
6	Lembesse	*Centroplacus glaucinus*	0.6	70	$9.72D^{2.46}$
6	Lepoute	*Maranthes aubrevillei*	0.8292	70	$9.72D^{2.46}$
6	Maranthes	*Maranthes sp.* (except *glabra*, *gabunensis*, *chrysophylla*)	0.8292	70	$9.72D^{2.46}$
6	Mareya	*Mareya sp.*	0.6	70	$9.72D^{2.46}$
6	Mebimengone	*Omphalocarpum elatum*	0.5504	70	$9.72D^{2.46}$
6	Med	*Cyrtogonone argentea*	0.6	70	$9.72D^{2.46}$
6	Medzime Koghe	*Psychotria sp.*	0.52	70	$9.72D^{2.46}$
6	Mengo	*Aoranthe cladantha*	0.8064	70	$9.72D^{2.46}$
6	Mfol	*Annickia chlorantha*	0.4462	70	$9.72D^{2.46}$
6	Miama	*Calpocalyx heitzii*	0.7168	70	$9.72D^{2.46}$
6	Miamengone	*Oncoba welwitschii*	0.58	70	$9.72D^{2.46}$
6	Millettia	*Millettia sp.* (except *laurentii*)	0.7381	70	$9.72D^{2.46}$
6	Mississe	*Calpocalyx sp.* (except *heitzii*)	0.7135	70	$9.72D^{2.46}$
6	Mondjadi	*Crateranthus talbotii*	0.6	70	$9.72D^{2.46}$
6	Morinda	*Morinda lucida*	0.54	70	$9.72D^{2.46}$
6	Mugondi	*Eriocoelum sp.*	0.5231	70	$9.72D^{2.46}$
6	Mvezork	*Homalium letestui*	0.7084	70	$9.72D^{2.46}$
6	Mvouma	*Xylopia quintasii*	0.75	70	$9.72D^{2.46}$
6	Napoleona	*Napoleona sp.*	0.6	70	$9.72D^{2.46}$
6	Ndande	*Xylopia phloiodora*	0.5909	70	$9.72D^{2.46}$
6	Ndong-Eli	*Xylopia hypolampra*	0.6629	70	$9.72D^{2.46}$
6	Ngang Gf	*Hymenostegia klainei*	0.8296	70	$9.72D^{2.46}$
6	Ngang Inconnu	*Hymenostegia sp.* (except *pellegrinii*, *klainei*, *ngounyensis*)	0.8296	70	$9.72D^{2.46}$
6	Ngeul Fv	*Croton sylvaticus*	0.5231	70	$9.72D^{2.46}$

Group	Name	Latin name	w_s	A_s	Volume equation
6	Ngorangorane	*Oncoba glauca*	0.58	70	$9.72D^{2.46}$
6	Ngueul Fb	*Croton mayumbensis*	0.5231	70	$9.72D^{2.46}$
6	Nkonengu	*Beilschmiedia pierreana*	0.5732	70	$9.72D^{2.46}$
6	Nkouarsa	*Tetrapleura tetraptera*	0.5312	70	$9.72D^{2.46}$
6	Nsa	*Maprounea membranacea*	0.57	70	$9.72D^{2.46}$
6	Nsire	unknown	0.6	70	$9.72D^{2.46}$
6	Ntom	*Duguetia staudtii*	0.6332	70	$9.72D^{2.46}$
6	Ntoma Biliba	*Sarcocephalus pobeguinii*, *Nauclea vanderguchtii*	0.4976	70	$9.72D^{2.46}$
6	Ntona	*Xylopia pynaertii*	0.5909	70	$9.72D^{2.46}$
6	Ntsua	*Xylopia rubescens*, *Xylopia staudtii*	0.5909	70	$9.72D^{2.46}$
6	Nzang	*Synsepalum afzelii*	0.8153	70	$9.72D^{2.46}$
6	Nzim Soreu	*Anisophyllea myriosticta*	0.72	70	$9.72D^{2.46}$
6	Oboba	*Myrianthus arboreus*	0.4496	70	$9.72D^{2.46}$
6	Ochtocosmus	*Phyllocosmus sp.*	0.78	70	$9.72D^{2.46}$
6	Oduma	*Prioria joveri*	0.42	70	$9.72D^{2.46}$
6	Odzicouna	*Scytopetalum klaineanum*	0.6155	70	$9.72D^{2.46}$
6	Ofira	*Aubrevillea platycarpa*	0.6	70	$9.72D^{2.46}$
6	Ofoss	*Pseudospondias microcarpa*	0.6	70	$9.72D^{2.46}$
6	Okala	*Xylopia aethiopica*	0.4422	70	$9.72D^{2.46}$
6	Oncoba	*Oncoba sp.* (except *glauca*, *welwitschii*)	0.58	70	$9.72D^{2.46}$
6	Onzem	*Anthonotha fragrans*	0.5291	70	$9.72D^{2.46}$
6	Otounga	*Polyalthia suaveolens*	0.6951	70	$9.72D^{2.46}$
6	Ovita	*Afrostyrax sp.*	0.6	70	$9.72D^{2.46}$
6	Ovok	*Cleistopholis glauca*	0.3045	70	$9.72D^{2.46}$
6	Oyem	*Brenania brieyi*	0.6	70	$9.72D^{2.46}$
6	Oyem Tsue	*Rauvolfia vomitoria*	0.4698	70	$9.72D^{2.46}$
6	Oyop	*Chrysophyllum sp.*	0.6458	70	$9.72D^{2.46}$
6	Palmier A Huile	*Elaeis guineensis*	0.6	70	$9.72D^{2.46}$
6	Parasolier	*Musanga cecropioides*	0.2289	70	$9.72D^{2.46}$
6	Passa	*Heisteria parvifolia*	0.705	70	$9.72D^{2.46}$
6	Pierrodendron	*Quassia grandifolia*	0.331	70	$9.72D^{2.46}$
6	Plagiosiphon	*Plagiosiphon sp.*	0.6	70	$9.72D^{2.46}$
6	Protomeg	*Protomegabaria macrophylla*	0.602	70	$9.72D^{2.46}$
6	Rhabdophyllum	*Rhabdophyllum sp.*	0.6	70	$9.72D^{2.46}$
6	Rinorea	*Rinorea sp.*	0.682	70	$9.72D^{2.46}$
6	Rothmania	*Rothmannia sp.*	0.6414	70	$9.72D^{2.46}$
6	Sabifout	*Maesobotrya sp.*	0.6	70	$9.72D^{2.46}$
6	Samanea	*Samanea leptophylla*	0.6	70	$9.72D^{2.46}$
6	Sangoma	*Allanblackia parviflora*	0.5456	70	$9.72D^{2.46}$
6	Sapium	*Sclerocroton sp.*, *Shirakiopsis sp.*	0.6	70	$9.72D^{2.46}$
6	Scottellia	*Scottellia sp.*	0.5485	70	$9.72D^{2.46}$
6	Set	*Cryptosepalum congolanum*	0.7601	70	$9.72D^{2.46}$
6	Sorindeia	*Sorindeia sp.*	0.56	70	$9.72D^{2.46}$
6	Strychnos	*Strychnos sp.*	0.7017	70	$9.72D^{2.46}$
6	Synsepalum	*Synsepalum sp.*	0.6776	70	$9.72D^{2.46}$
6	Tol	*Ficus mucuso*	0.4091	70	$9.72D^{2.46}$

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6	Tricalysia	*Tricalysia sp.*	0.1	70	$9.72D^{2.46}$
6	Trichilia	*Trichilia sp.* (except *tessmannii*)	0.64	70	$9.72D^{2.46}$
6	Trichoscypha	*Trichoscypha sp.* (except *oddonii*, *acuminata*, *engong*)	0.6285	70	$9.72D^{2.46}$
6	Uvariastrum	*Uvariastrum sp.*	0.6	70	$9.72D^{2.46}$
6	Vangueriopsis	*Vangueriella sp.*	0.6	70	$9.72D^{2.46}$
6	Warneckea	*Warneckea sp.*	0.6	70	$9.72D^{2.46}$
6	Xylopia	*Xylopia sp.* (except *aethiopica*, *hypolampra*, *staudtii*, *quintasii*, *rubescens*)	0.5909	70	$9.72D^{2.46}$
7	Andok	*Irvingia gabonensis*	0.7902	70	$9.72D^{2.46}$
7	Bahia (Abura)	*Hallea ledermannii*	0.4685	70	$9.72D^{2.46}$
7	Douka	*Tieghemella africana*	0.6201	100	$0.72+11.32D^2$
7	Moabi	*Baillonella toxisperma*	0.7259	100	$11.59D^{1.94}$
7	Ovoga (Afo)	*Poga oleosa*	0.3657	60	$9.72D^{2.46}$
7	Ozigo	*Dacryodes buettneri*	0.5001	80	$9.2D^{1.9}$

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