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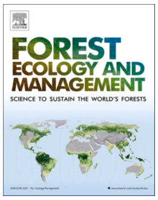

Expected carbon emissions from a rubber plantation in Central Africa

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ABSTRACT

The development of agriculture on degraded lands is increasingly seen as a strategy to boost food availability and economic productivity while minimizing environmental degradation and loss of forests. To understand the effects of agricultural production on forest carbon, we quantify the aboveground carbon (AGC) of a degraded forest in northeast Gabon (the Olam Rubber Gabon concession) designated for development to a rubber plantation. Combining field measurements from 19 1-ha tree plots and aerial LiDAR, we estimate forest AGC stocks and emissions under four development scenarios: no development, 30-year rubber rotation, extended rubber rotation (replanting of plantation in stages at 30 and 40 years), and 30-year oil palm rotation. On average, the degraded forest in the study area stored 123.8 Mg C ha^{-1}, a mean AGC lower than the Gabon average (141.6 Mg C ha^{-1}) but substantially higher than the 75 Mg C ha^{-1} threshold recommended by the High Carbon Stock protocol. Converting secondary forest to plantation might incur high environmental opportunity costs from lost carbon sequestration through forest succession and growth. In this study, we estimate that a rubber plantation can sequester similar amounts of AGC as secondary forest by the end of a 30-year rotation; however, the time-averaged AGC of regenerating secondary forests under no development would be 184% higher than a mature rubber plantation with a 30-year rotation, 169% higher than an extended rubber rotation, and 512% higher than a 30-year oil palm rotation. When degraded forest is developed for agriculture, measures should be taken to avoid emissions and prolong carbon retention. We specifically estimate carbon retention from extended harvest rotations and conserving high carbon value areas as set-asides and highlight recommendations from the literature such as minimizing soil disturbance and creating rubber timber products (e.g. furniture). To minimize carbon emissions from agriculture, crop plantation area should be minimized at national and regional scales in highly forested countries, and new plantations should be coupled explicitly with effective forest restoration actions, through suitable regulation and planning, to mitigate or compensate for their climate and biodiversity impacts.

1. Introduction

Tackling climate change requires understanding options to reduce greenhouse gas emissions from agriculture while still providing consumer products, especially in tropical forest landscapes. Agriculture is the source of roughly 24% of annual greenhouse gas emissions (EPA, 2017) and the cause of 80% of deforestation globally, with most emissions coming from developing countries (Kissinger et al., 2012). Yet, given current agricultural technology, one billion hectares of additional land needs to be converted to crops by 2050 to support the projected human population of 11 billion by the end of the century (Tilman, 2001; United Nations, 2013). Much of this agricultural expansion is expected to take place in the tropics, especially Sub-Saharan Africa and South America, likely leading to the loss of tropical old growth forests and woodlands and concomitant increases in carbon emissions (DeFries et al., 2002). These anticipated trends raise questions regarding the best way to achieve low emissions agriculture in forested landscapes, including which crops to grow and how and where to grow them (De Pinto et al., 2016; Dinerstein et al., 2015; Laurance et al., 2014).

Rubber is currently undergoing significant commercial expansion in tropical regions (Warren-Thomas et al., 2018; Ziegler et al., 2009). Central Africa was historically an important rubber producer until a

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decline in demand after the 1970s (Ovono Edzang, 2008; Mathews, 2017), whereas Southeast Asia, including Thailand, Indonesia, Vietnam, and Malaysia, currently produces nearly 83% of all natural rubber (Blagodatsky et al., 2016; Food and Agriculture Organization of the United Nations, 2014). Recent demand for rubber from China and India has reignited investment in production in Central African countries, which is expected to steadily increase in the near future (Mathews, 2017). Although rubber plantations can drive deforestation in Southeast Asia and tropical China (Xu et al., 2014; Ziegler et al., 2009), they sequester more carbon by the end of a rotation cycle than other tropical crops like oil palm, cocoa and citrus (Kongsager et al., 2013; Sun et al., 2017). Thus, rubber production could potentially grow the economies of tropical countries with relatively low net carbon emissions.

In addition to growing crops with high carbon storage potential, low emissions development might also be achieved by directing agricultural expansion towards low carbon landscapes, especially if spatial planning of plantations considers previous land use and pre-disturbance carbon storage (Brahma et al., 2018; Dinerstein et al., 2015). The Forest Stewardship Council (FSC), for example, certifies rubber plantations that are not linked to forest degradation or deforestation (Forest Stewardship Council, 2017). Private sector and civil society stakeholders have proposed a High Carbon Stock (HCS) approach to select areas or land cover categories with low carbon stocks for agriculture (Austin et al., 2017; HCS Steering Group Committee, 2017). In nations with high forest cover and carbon density, however, low carbon areas that are suitable for agriculture and meet the requirements of carbon neutral or near neutral agriculture may not exist (Burton et al., 2017).

The Gabonese Republic, a country historically reliant on oil reserves and mining (Chambrier, 1990), aspires to increase its agricultural production, which currently amounts to approximately 5% of GDP (Maganga-Moussavou, 2019), without substantially increasing carbon emissions (Austin et al., 2017). In this study, we evaluate the effects of rubber production on forest carbon stocks and emissions. We estimate carbon stocks in the Olam Rubber Gabon (ORG) concession in northern Gabon to answer the following questions: (1) what is the carbon value of a degraded forest in northwest Gabon? (2) what are the implications of different carbon development thresholds for agricultural development? (3) how will different development scenarios (no development, ND; rubber plantation with a 30 year-rotation, R30; rubber plantation with an extended rotation, R40; oil palm with 30 years rotation, P30) influence the long-term carbon sequestration value of degraded forests? Based on our results, we make management recommendations for reducing and offsetting carbon emissions from land conversion to rubber plantations.

2. Material and methods

2.1. Characteristics of study site

Gabon is one of the most forested countries in the world with 22 million hectares of forest, 88% forest cover, and a deforestation rate near zero (Sannier et al., 2014). Gabon also boasts a mean forest carbon density of 141.6 Mg C ha^{-1} and a carbon density of 166.6 Mg C ha^{-1} in primary, *terra firma* forest (Poulsen et al., 2020), considerably higher than other Sub-Saharan Africa countries (Bombelli et al., 2009; Saatchi et al., 2011). Important carbon stocks also occur in the coarse woody debris, large lianas, and soils (Carlson et al., 2017; Poulsen et al., 2017; Wade et al., 2019).

In this study, we focus on a 7004 ha parcel of degraded forest in northern Gabon, which is part of the 37,529 ha ORG concession acquired by Olam in 2012 in a public–private partnership with the government (Olam Rubber Gabon, 2017). The concession was occupied at least until the mid-1940s by 18 to 20 villages that likely carried out traditional slash-and-burn farming and hunting (Pourtier, 1989). In the 1950s, the colonial and post-colonial governments relocated these villages according to the 'regroupement' policies of the time and the area was logged with conventional techniques (Pourtier, 1989). The concession sits on a dissected plateau with broad, flat hills separated by gentle slopes and seasonally flooded swamps. As a result of previous deforestation, a heterogeneous secondary forest dominates flat areas (including patches of relatively undisturbed forest, extensive rattan-dominated disturbed scrub, and abandoned farms) and older, more diverse forests dominate slopes that presumably suffered less disturbance.

To date, 11,000 ha of the concession have been converted to rubber plantation (Olam Rubber Gabon, 2017) (Fig. 1a). In 2017 ORG halted any further conversion to agriculture to engage in a multi-stakeholder dialogue on responsible agricultural development in Gabon and to contribute to the growing body of comparative methods for forest carbon estimation. The study area, located in the northern part of the ORG concession, is earmarked for future conversion to rubber (Fig. 1b). ORG designated parts of the study area as 'plantable' using its in-house, LiDAR-based forest stratification (Fig. 1b). These 3496 ha of plantable areas deemed appropriate for rubber have not been recently logged or converted to crops and consist of secondary forest regrowth.

2.2. Field data collection

Between March and April 2018, four teams of six technicians from the Gabon Parks Agency (ANPN) sampled aboveground forest carbon (AGC) in the study area using internationally recognized protocols (Matthews et al., 2014). The teams established 19 1-ha tree plots (100 m × 100 m) randomly located throughout the study area. Each tree with a diameter-at-breast height (DBH) $\geq$ 10 cm was mapped, measured and identified to species. Field teams measured DBH at a height of 1.3 m from the ground, or 50 cm above any buttresses, stilt roots, or deformities. They measured tree heights with a laser hypsometer, taking three measurements from different angles of 55 randomly selected trees per site with 10 trees from each of 5 DBH subclasses (10–20 cm, 21–30 cm, 31–40 cm, 41–50 cm, >50 cm) and the five largest trees (Sullivan et al., 2018). The habitat types were also categorized and recorded as *terra firma* (i.e. firm ground), swamp and sloped areas.

2.3. Estimates of carbon stocks at the plot level

Using the measured heights of trees in each plot, we first developed site-wide height-diameter (HD) models using the BIOMASS package in R (Réjou-Méchain et al., 2017). We applied five HD models (log1, log2, log3, Weibull and Michaelis) to the data and selected the log2 model with the lowest residual standard error (RSE) and average bias. We then developed HD models specific to each plot (Beirne et al., 2019), deriving the HD relationship for each of the 19 plots as described above. We predicted tree height for all trees in the 19 plots using both the site-wide and plot-specific HD models.

With field measurements of tree diameters, predicted tree heights and species-specific estimates of wood density from the literature, we derived AGC for each tree using both regional (Fayolle et al., 2018) and pantropical (Chave et al., 2014) allometric equations and employing both site-wide and plot-specific HD predictions. The regional allometric equation (Fayolle et al., 2018) was developed for tropical forests in six Congo Basin countries (Equatorial Guinea, Gabon, Cameroon, Central African Republic, Republic of Congo, Democratic Republic of Congo), whereas the pantropical equation (Chave et al., 2014) was developed with data from 58 sites from 24 countries from all tropical regions. These allometric equations provide estimates of aboveground biomass (AGB). To convert AGB to AGC, we multiplied AGB by the assumed carbon content, 0.471 (Thomas and Martin, 2012). We summed the AGC of all stems within a plot under both the Chave and Fayolle models (with site-wide HD prediction, plot-specific HD prediction and no height), and took a pooled average of the models to obtain the final plot-level AGC.

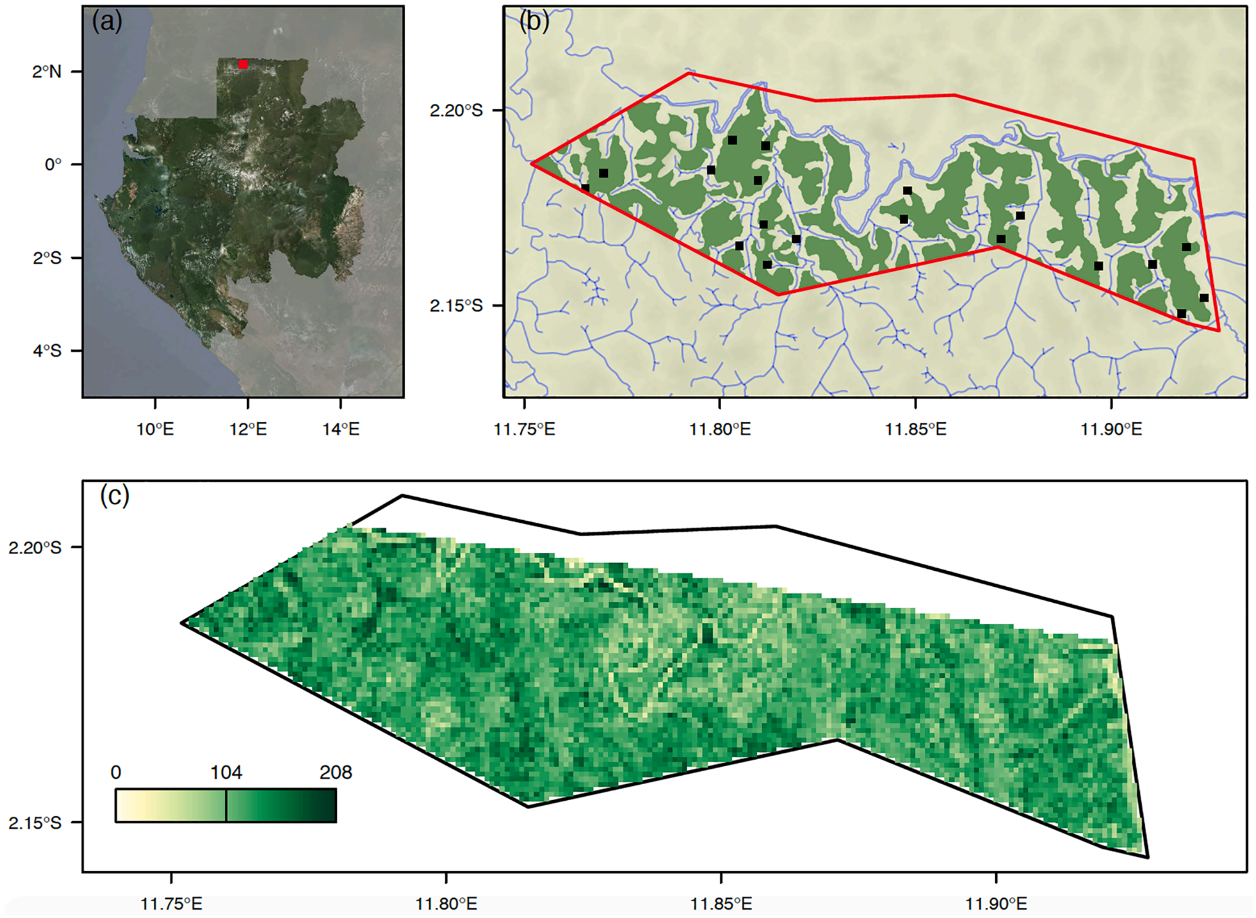

Fig. 1. The study area (a) is located in the ORG rubber concession (red point) in northern Gabon and (b) consists of a 7004 ha parcel designated for rubber production with both plantable (dark green) and non-plantable areas (light green). Black square symbols represent locations of the field plots. (c) Map of forest carbon density in the study area. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.4. Estimates of carbon stocks at the site level

Using airborne raw LiDAR created by SEPRET in 2011 (see details in Burton et al., 2017), we derived a 2 m resolution tree height raster by creating a Digital Surface Model (DSM) and Digital Elevation Model (DEM), and subtracting the DEM from the DSM. Overlaying the tree height raster with the coordinates of the 19 study plots, we then used zonal statistics in ArcGIS Pro to estimate the median canopy height for each plot. To estimate carbon stocks for the entire concession, we regressed plot-level median height versus plot-level AGC and used the resulting equation, $AGB = 0.4488 + 13.0603 \cdot H$, to predict AGC density across the entire study area at 1-ha resolution.

2.5. Carbon balance in four development scenarios

To evaluate the effects of land conversion from forest to plantation, we estimated carbon stocks, losses and gains under four development scenarios (Table 1):

(1) No development (ND): the study area forest is conserved and not cleared for agriculture (rubber or other crops) or other commercial activities.
(2) Rubber plantation with a 30-year rotation (R30): the study area forest is cleared for rubber and carbon stocks are estimated after 30 years of growth.
(3) Rubber plantation with an extended rotation (R40): the study area forest is cleared for rubber, with 50% of the plantation being replanted after 30 years and 50% being replanted after 40 years.
(4) Oil palm plantation with a 30-year rotation (P30): the study area forest is cleared for oil palm with a 30-year rotation (Burton et al., 2017), following the typical rotation length of between 25 and 30 years (FAO, 2001).

To compare results of these scenarios, we use the time averaged AGC, C_{ta}, to determine the average carbon stored during the rotation time (Blagodatsky et al., 2016; Palm et al., 2000), taking into account tree or plant establishment, regrowth and harvesting. This allows the comparison of development scenarios that have different rotation lengths.

2.6. Set-aside ratio

We modified the set-aside calculation from Burton et al. (2017) to estimate set-aside ratios:

$$\frac{\text{Carbon density} + \text{Foregone sequestration} - \text{Plantation sequestration}}{\text{No development forest sequestration}}$$

The set-aside ratio refers to the ratio of carbon loss due to agriculture relative to carbon gain through conservation per hectare and indicates the number of hectares of forest required to be set aside for every hectare of forest converted to plantation. Low carbon density forests require low set-aside ratios to achieve zero-net emissions (Burton et al., 2017).

Table 1

Estimation of carbon stocks under different development scenarios. To estimate (a) total carbon sequestration for each above scenario, we employ published sequestration rates for Sub-Saharan African secondary forests (1.4 Mg C ha^{-1} yr^{-1}) (Silver et al., 2000), rubber trees less than 14 years old (8.67 Mg C ha^{-1} yr^{-1}) and mature rubber trees more than 14 years old (2.65 Mg C ha^{-1} yr^{-1}) (Grieco, 2011), and oil palm trees (2 Mg C ha^{-1} yr^{-1}) (Kongsager et al., 2013). To calculate (b) time averaged carbon stocks (C_{ta}), we sum the starting carbon stock and the maximum carbon stock at time of clearing and divide them by 2, assuming biomass increases linearly (Blagodatsky et al., 2016). To estimate (c) net emissions, we calculate the difference between the C_{ta} of different scenarios and C_{ta} of no development.

Agricultural development scenarios	
No development (ND)	(a) Average forest AGC plus expected carbon sequestration over 30 years of growth: $123.8\ \mathrm{Mg\ C\ ha^{-1}} + 30\ \mathrm{yr} \times 1.4\ \mathrm{Mg\ C\ yr^{-1}} = 165.8\ \mathrm{Mg\ C\ ha^{-1}}$ and 40 years of growth: $123.8\ \mathrm{Mg\ C\ ha^{-1}} + 40\ \mathrm{yr} \times 1.4\ \mathrm{Mg\ C\ yr^{-1}} = 178.4\ \mathrm{Mg\ C\ ha^{-1}}$ (b) $C_{ta} = (178.4\ \mathrm{Mg\ C\ ha^{-1}} + 123.8\ \mathrm{Mg\ C\ ha^{-1}})/2 = 151.1\ \mathrm{Mg\ C\ ha^{-1}}$ (c) Net emissions: 151.1 Mg C ha^{-1} –151.1 Mg C ha^{-1} = 0 Mg C ha^{-1}, i.e. no net emission
30-year rubber rotation (R30)	(a) Clearing reduces AGC to zero. Based on a sequestration rate of 8.67 Mg C yr^{-1}, we assume that AGC of the rubber plantation will reach 121.5 Mg C ha^{-1} after 14-years (Grieco, 2011) with average growth of 2.65 Mg C yr^{-1} for the next 16 years. $0\ \mathrm{Mg\ C\ ha^{-1}} + 121.5\ \mathrm{Mg\ C\ ha^{-1}} + 16\ \mathrm{yr} \times 2.65\ \mathrm{Mg\ C\ yr^{-1}} = 163.9\ \mathrm{Mg\ C\ ha^{-1}}$ (b) $C_{ta} = (163.9\ \mathrm{Mg\ C\ ha^{-1}} + 0\ \mathrm{Mg\ C\ ha^{-1}})/2 = 82.0\ \mathrm{Mg\ C\ ha^{-1}}$ (c) Difference in net emissions compared to ND at year 30: 151.1 Mg C ha^{-1} –82 Mg C ha^{-1} = 69.1 Mg C ha^{-1} (d) Set aside ratio: $(123.8\ \mathrm{Mg\ C\ ha^{-1}} + (1.4\ \mathrm{Mg\ C\ ha^{-1}\ yr^{-1}} \times 30\ \mathrm{yr}) - 163.9\ \mathrm{Mg\ C\ ha^{-1}})/(1.4\ \mathrm{Mg\ C\ ha^{-1}\ yr^{-1}} \times 30\ \mathrm{yr}) = 0.045$
Extended rotation (R40)	(a) Same as R30, but after 30 years 50% of the plantation is cleared and replanted and 50% of the mature trees are left to grow for 10 years. $(163.9\ \mathrm{Mg\ C\ ha^{-1}} - 163.9\ \mathrm{Mg\ C\ ha^{-1}} \times 0.5 + (10\ \mathrm{yr} \times 2.65\ \mathrm{Mg\ C\ yr^{-1}} \times 0.5) + (10\ \mathrm{yr} \times 8.68\ \mathrm{Mg\ C\ yr^{-1}} \times 0.5)) = 138.6\ \mathrm{Mg\ C\ ha^{-1}}$ (b) For years 1–30: $(0\ \mathrm{Mg\ C\ ha^{-1}} + 163.9\ \mathrm{Mg\ C\ ha^{-1}})/2 = 82.0\ \mathrm{Mg\ C\ ha^{-1}}$ For years 30–40: $(82.0\ \mathrm{Mg\ C\ ha^{-1}} + 138.6\ \mathrm{Mg\ C\ ha^{-1}})/2 = 110.2\ \mathrm{Mg\ C\ ha^{-1}}$ C_{ta} weighted average: $(82.0\ \mathrm{Mg\ C\ ha^{-1}}) \times 30/40\ \mathrm{yr} + (110.2\ \mathrm{Mg\ C\ ha^{-1}}) \times 10/40\ \mathrm{yr} = 89.1\ \mathrm{Mg\ C\ ha^{-1}}$ (c) Difference in net emissions compared to ND at year 40: 151.1 Mg C ha^{-1} –89.1 Mg C ha^{-1} = 62 Mg C ha^{-1} (d) Set aside ratio: $(123.8\ \mathrm{Mg\ C\ ha^{-1}} + (1.4\ \mathrm{Mg\ C\ ha^{-1}\ yr^{-1}} \times 40\ \mathrm{yr}) - 138.6\ \mathrm{Mg\ C\ ha^{-1}})/(1.4\ \mathrm{Mg\ C\ ha^{-1}\ yr^{-1}} \times 40\ \mathrm{yr}) = 0.736$
30-year oil palm rotation (P30)	(a) Clearing reduces AGC to zero. Assuming oil palm reaches 45 Mg C ha^{-1} after 23 years with an accumulation rate of 2 Mg C $ha^{-1}yr^{-1}$ thereafter (Kongsager et al., 2013): $0\ \mathrm{Mg\ C} + 45\ \mathrm{Mg\ C} + 7\ \mathrm{yr} \times 2\ \mathrm{Mg\ C\ yr^{-1}} = 59\ \mathrm{Mg\ C}$ (b) $C_{ta} = (59 + 0)/2 = 29.5\ \mathrm{Mg\ C\ ha^{-1}}$ (c) Difference in net emissions compared to ND at year 30: 151.1 Mg C ha^{-1} –29.5 Mg C ha^{-1} = 121.6 Mg C ha^{-1} (d) Set aside ratio: $(123.8\ \mathrm{Mg\ C\ ha^{-1}} + (1.4\ \mathrm{Mg\ C\ ha^{-1}\ yr^{-1}} \times 30\ \mathrm{yr}) - 59\ \mathrm{Mg\ C\ ha^{-1}})/(1.4\ \mathrm{Mg\ C\ ha^{-1}\ yr^{-1}} \times 30\ \mathrm{yr}) = 2.54$

3. Results

3.1. Site-level carbon map and carbon summary using field data

We estimated AGC of 7288 trees from 56 families in 19 1-ha plots. For the field plots, mean AGC was 113.2 Mg C ha^{-1} [95% CI = 79, 147.3]; median height was 23.7 m [95% CI = 10.4, 46.5]; and mean wood density was 0.614 g cm^{-3} [95% CI = 0.43, 0.8]. Using LiDAR to extrapolate across the entire study site, mean AGC was 123.8 Mg C ha^{-1} [95% CI = 74.2, 173.5] with a total forest carbon stock of 0.87 Tg C (Fig. 1c), and mean tree height was 20.6 m [95% CI = 2.1, 39.0]. The 95% confidence intervals for plot- and site-level AGC and median height overlap, indicating that the two scales do not differ significantly in either measure. However, the slightly higher mean AGC and slightly lower median height at the plot-level compared to the site-level is likely attributable to variation in tree density and species composition with variation in elevation and habitat type across the site. This emphasizes the challenge of capturing site-level variation within 19 field plots.

3.2. Developable areas under different carbon thresholds

To reduce deforestation and avoid carbon emissions, thresholds of aboveground carbon stocks have been proposed above which plantation development would be prohibited (Austin et al., 2017; HCS Steering Group Committee, 2017). The High Carbon Stock protocol recommends a threshold of 75 Mg C ha^{-1} (HCS Steering Group Committee, 2017), whereas Burton et al. (2017) proposed a Gabon-specific threshold of 118 Mg C ha^{-1}. We quantified the areas that could be converted to rubber agriculture under both carbon thresholds. The developable area was 5.1% of the plantable area under the HCS threshold and 36.7% under the Gabon-specific threshold.

3.3. Carbon balance under agricultural development scenarios

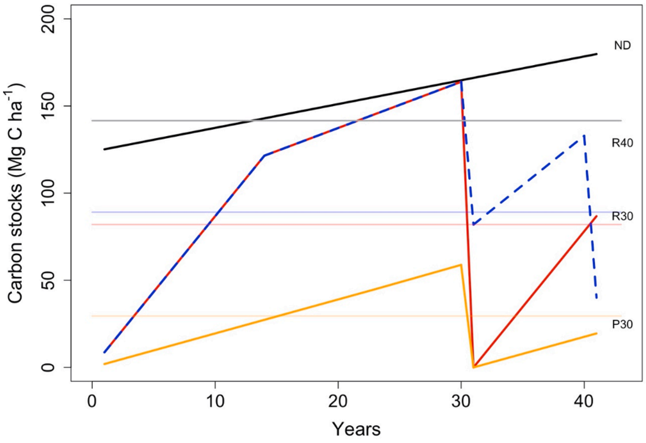

Fig. 2. Carbon balance of the ORG study area under four scenarios, including: (ND) no development, (R30) 30-year rubber rotation, (R40) extended rubber rotation, and (P30) 30-year oil palm rotation with the corresponding C_{ta} (displayed as straight lines with matching color). The light grey line indicates the average AGC in Gabon (Poulsen et al., 2020).

We developed four scenarios of forest management and calculated their expected carbon dynamics (Table 1, Fig. 2), assuming a linear carbon sequestration rate due to lack of longitudinal data on rates of carbon sequestration for rubber trees in Central Africa.

With an initial carbon density of 123.8 Mg C ha^{-1}, under the ND scenario the study area will hold 165.8 Mg C ha^{-1} after 30 years and 178.4 Mg C ha^{-1} after 40 years (assuming a linear growth rate), a 44% increase in AGC that is approximately 26% higher than the mean forest carbon density in Gabon (Fig. 2). Under the R30 scenario, we estimate that the rubber tree plantation would sequester 163.4 Mg C ha^{-1} by year 30 (Fig. 2), a rate of sequestration nearly three times that of the ND scenario. Under the R40 scenario, the rubber tree plantation would sequester 138.6 Mg C ha^{-1} after 40 years. R40 is the only development scenario in which the carbon stock never falls to zero following harvest (Fig. 2). Under P30, a palm oil plantation would attain 58.9 Mg C ha^{-1}

after 30 years and an additional 19.5 Mg C ha^{-1} by year 40 (Fig. 2). The time averaged carbon stocks, C_{ta}, are 151.1 Mg C ha^{-1} (ND), 89.1 Mg C ha^{-1} (R40), 82.0 Mg C ha^{-1} (R30), and 29.5 Mg C ha^{-1} (P30): over 30–40 years, rubber C_{ta} is much lower than non-developed forests, but far exceeds that of oil palm.

AGC in the study area is 123.8 Mg C ha^{-1} and the foregone sequestration (1.4 Mg C ha^{-1} yr^{-1} $\times$ 40 yr = 56 Mg C ha^{-1}) would be the same as the sequestration rate under the ND scenario. Rubber tree sequestration at the end of a 40-year extended rotation (the best agricultural development scenario based on time-average carbon stocks, C_{ta}) would be 138.6 Mg ha^{-1}. Therefore, for each hectare of forest converted to a rubber plantation, 0.74 ha would need to be set aside as an offset for development to be carbon neutral. Supplementary 2 describes net carbon emissions under different planting areas (entire concession, plantable area, HCS, HCS Gabon) and development scenarios.

4. Discussion

One strategy for mitigating climate change is to prohibit land use activities that will result in deforestation in high carbon forests. The High Carbon Stock approach recommends avoiding agricultural development in forests with more than 75 Mg C ha^{-1} (HCS Steering Group Committee, 2017). For a forested country with high carbon stocks like Gabon, Burton et al. (2017) suggested a threshold of 118 Mg C ha^{-1} to allow for some agriculture. Despite being a secondary forest with land-clearing history, the ORG study area has an average carbon storage value (123.8 Mg C ha^{-1}) exceeding both of these thresholds. However, rubber plantations can sequester carbon faster than natural forest, especially at early stages, and reach relatively high carbon values over a few decades. To compare the effects of different scenarios of development on carbon emissions, we employed the time averaged carbon stock, C_{ta}, approach to decrease uncertainties in assessing carbon stocks of scenarios with different rotation lengths (Blagodatsky et al., 2016; Palm et al., 2000). Rubber agriculture with an extended rotation had a higher C_{ta} than rubber with a shorter rotation or oil palm, but natural, regenerating secondary forest had a C_{ta} 1.7 times that of R40 and would be a long-term carbon sink. Therefore, conversion of the study area to agriculture without appropriate mitigation would accrue a sizable carbon deficit.

Our carbon density estimates of 123.8 Mg C ha^{-1} in secondary forest are similar to those from other West and Central African studies. In Cameroon, fallow fields 23 years after cultivation had an average carbon density of 131 ± 37 Mg C ha^{-1} (Palm et al., 2000) and secondary forests had a mean carbon density of about 125 Mg C ha^{-1} (Bombelli et al., 2009; Kotto-Same et al., 1997). Secondary forest in Ghana retained 146.9 ± 5.9 Mg C ha^{-1} (Grieco, 2011). By contrast, carbon density of secondary forest in Gabonese forests are higher than in Panama (100 Mg C ha^{-1}) (Tschakert et al., 2007) and Costa Rica (82.2 Mg C ha^{-1}), though this estimate is limited by the young age of forests (Fonseca et al., 2011).

4.1. Implications of conversion to rubber plantation: carbon balance and other concerns

The growth rates of rubber trees vary widely across different tropical and subtropical regions due to different climate patterns, altitudes and soil types (Brahma et al., 2018; Choudhary et al., 2016; Grieco, 2011; Kongsager et al., 2013; Liu et al., 2017; Maggiotto et al., 2014; Yang et al., 2016). In Ghana, a 14-year old rubber plantation had an AGC stock of 121.5 ± 25.3 Mg C ha^{-1}, whereas a 49-year old plantation stored 214.5 ± 47.7 Mg C ha^{-1} (Grieco, 2011). Agricultural rotation lengths are usually 30–40 years; thus, the latter represents an unusually old plantation with greater AGC than estimated here for secondary forest (123.8 Mg C ha^{-1}) and even mature forest (192.4 Mg C ha^{-1}) after 49 years of sequestration. Given similar climatic conditions, rubber cultivation has the potential to sequester high amounts of carbon and be a significant carbon sink for degraded, secondary forest and degraded fallow lands in Gabon.

The degree to which rubber plantations can serve as long-term carbon sinks is an important consideration for agricultural development. Fast-growing rubber plantations can accumulate carbon more rapidly than slow-growing natural forests up to the time of harvest (Cheng et al., 2007). Nevertheless, natural forests provide longer-term carbon storage through the persistence of large living trees and also preserve biodiversity. Rubber plantations are usually harvested before reaching their maximum biomass; thus, the ability of carbon pools to regain their pre-disturbance levels depends on rotation length (Nizami et al., 2014). Along these lines, if the ORG concession was conserved it would act as a carbon sink for at least four decades and presumably accumulate a carbon density comparable to the mean carbon density in Gabon (Poulsen et al., 2020). In our three development scenarios, the plantation would not reach similarly high levels of carbon density; thus, both rubber and oil palm production would lead to net carbon emissions relative to a conservation baseline. Strict conservation of the plantation might not be a reasonable assumption given that most Central African forests are committed to logging concessions (Bayol et al., 2012; Forêt Ressources Management., 2018). Selective timber harvest would lower the carbon stock of secondary forests (Medjibe et al., 2013), but the time-averaged carbon stock would still be higher than plantations provided logging activities are not excessively exploitative (Supplementary Information 2).

Several factors complicate carbon balance estimations. First, given the uncertainty in soil carbon disruption that typically follows forest clearance, it might take longer than estimated for a rubber plantation to transition from a net carbon source to net carbon sink. Soil releases carbon for several years after disturbance and can lose up to 40% of its organic carbon following plantation development and harvest (de Blécourt et al., 2013; Guillaume et al., 2018; van Straaten et al., 2015). On average, topsoil in Gabon contains about 50 Mg C ha^{-1} of soil carbon (Wade et al., 2019); thus, 3496 ha of plantable area could release up to 0.07 Tg C of soil carbon immediately after clearance, potentially discounting the net carbon sequestration. Second, latex and plant parts harvested from rubber trees can make up 13–20% of sequestered carbon (Kotowska et al., 2015), therefore tapping latex can periodically lower the carbon stock on site. It is important to note that our estimates of AGC in rubber plantations were derived for tapped plantations, therefore latex would be an additional gain in carbon stocks not considered in our calculations. Third, the end-of-life use of rubber wood and latex affects the carbon balance. For example, manufacturing furniture with rubber wood extends its carbon storage. If a portion of rubber biomass was used for furniture at the end of harvest, the AGC stock of R30 would never reach zero, and both scenarios R30 and R40 would demonstrate increasing sequestration following harvest.

4.2. Mitigating negative impacts of forest to rubber plantation conversion

Given our findings above, we make several general recommendations for mitigating the negative impacts of forest conversion and increasing the retention of carbon in the Afrotropics.

(a) Extended rotation

Extended harvest rotations keep the plantation carbon density from reaching zero (Scenario 3). An extended rotation has been recommended in Cameroon because a 10-year shunt gap (the gap between 30 year and 40 year plants) allows newly planted trees to become mature before the other half of the plantation is cleared (Egbe, 2012). The extended rotation also allows plantation owners to acquire income more frequently and is arguably more sustainable (Egbe, 2012). Other studies have recommended extended rotation lengths of 40 years without a shunt gap (Nizami et al., 2014). In this paper, we demonstrate that the R40 scenario has the highest C_{ta} among development scenarios.

(b) Soil management

While this study focuses on AGC, tropical forest soils hold substantial belowground carbon stocks (Wade et al., 2019); minimizing soil disturbance will minimize soil carbon emissions. When forests are disturbed, both aboveground and belowground carbon are released, and low leaf litter input could lead to steep reductions in soil organic carbon stock, which prolongs the time needed for an ecosystem to regain carbon neutrality and turn from a net carbon source into a sink (Bashkin and Binkley, 1998; de Blécourt et al., 2013; Hassler et al., 2015; van Straaten et al., 2015). Keeping leaf litter on site in rubber plantations can significantly increase soil carbon storage (Cheng et al., 2007).

(c) End-of-life use of rubber wood

In addition to latex, rubber trees produce wood that can be made into veneer or furniture (Kusdiana, 2015). The recovery rate of wood from rubber trees ranges from 21 to 47% (Balsiger et al., 2000). The production of wood products grows employment and would reduce carbon emissions because the carbon stored inside the wood is preserved rather than released into the atmosphere. Rubber wood accounts for 35% of exported wood products in Malaysia and 60% of exported wood products in Thailand (Balsiger et al., 2000; Shigematsu et al., 2011). Branches or by-products of rubber trees could also be used as firewood by local communities, potentially reducing the cutting of native trees.

(d) Offsetting carbon emissions

Emissions from plantation conversion can be offset by setting aside other lands to prevent immediate net emissions on a landscape level and to sequester carbon under proper management. For Gabon, a general ratio of 2.4 conserved hectares to each converted hectare of forest should be set aside for oil palm plantation, using a 118 Mg C ha^{-1} carbon threshold (Burton et al., 2017). Given the higher carbon sequestration rate of rubber trees compared to oil palm, we estimate that 0.74 ha should be set aside for each hectare of forest converted to rubber plantation with an extended rotation (R40 scenario). Note that this set aside ratio is based on the secondary forest in the study site and would need to be higher if logged or old growth forest was cleared for agriculture. In the entire 7004 ha ORG plantation, 2978 ha (i.e., 7004 ha × 0.74 ha/1.74) of forest would have to be set aside. Alternatively, if only the 3496 ha plantable area was considered, the set aside would need to encompass 1486 ha (3496 ha × 0.74 ha/1.74). Our set-aside ratio has limitations, including not accounting for soil carbon and being sensitive to carbon sequestered by the crop. For example, when the plantation can achieve similar carbon sequestration levels as secondary forest (because clearing of plantations at their maturation after 30 or 40 years is not taken into account), the set-aside ratio can be very low or even negative, as illustrated in the R30 set-aside estimate of 0.04 ha. Previous studies have demonstrated that weak administrative processes, poor technical design and lax enforcement can also limit the effectiveness of set-asides (Walker et al., 2009).

5. Conclusion

Whereas the impacts of rubber agriculture in Southeast Asia have been relatively well studied, we provide the first estimates of carbon emissions for conversion of secondary forest to rubber plantations in Central Africa. Rubber has much higher carbon sequestration potential than oil palm, but even under the best agricultural development scenario, the time-averaged AGC of a mature rubber plantation at the end of a 40-year extended rotation cycle does not reach that of protected secondary forests regenerating toward old-growth forest. Our results have important implications for the region. Considering only carbon emissions, rubber plantations should be located in low-carbon, severely disturbed shrublands or forest. Because of the relatively high AGC in secondary forests, AGC must be measured and not assumed from land cover type as proposed by HCS (HCS Steering Group Committee, 2017). Although in need of investigation in Central Africa, it is unlikely that biodiversity losses from encroachment of rubber into secondary forests will be offset by rubber agroforestry or management, arguing for the sustainable intensification of tropical agriculture (Edwards et al., 2010; Warren-Thomas et al., 2018). For similar reasons, we advocate the intensification of rubber agriculture – land sparing, not land sharing – to combat climate change. Decisions on new tree crop plantations should balance their economic, environmental and climate trade-offs. Large amounts of carbon can be sequestered through the regeneration of degraded natural forests (Lewis et al., 2019) where they can be effectively protected. But such conservation also bears an economic opportunity cost that may not be fully compensated through climate financing and does not generate the employment that is often a political priority in developing countries. Thus, crop plantation area should be minimized at national and regional scales in highly forested countries, and new plantations should be coupled explicitly with effective forest restoration actions, through suitable regulation and planning, to mitigate or compensate for their climate and biodiversity impacts.

CRediT authorship contribution statement

Ying Wei Jong: Data curation, Writing - original draft, Formal analysis. **Christopher Beirne:** Investigation, Writing - review & editing, Project administration. **Quentin Meunier:** Conceptualization, Writing - review & editing. **Andréana Paola:** Investigation, Writing - review & editing, Project administration. **Alex Ebang Mbélé:** Investigation, Writing - review & editing. **Christopher G. Stewart:** Conceptualization, Writing - review & editing. **John R. Poulsen:** Conceptualization, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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