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LETTER

Reducing Carbon Emissions from Forest Conversion for Oil Palm Agriculture in Gabon

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Abstract

Growing demand for palm oil is driving its expansion into the African tropics, potentially leading to significant carbon emissions if tropical forest is converted to palm monoculture. In this first study of a Central African oil palm concession (31,800 ha), we predict that the conversion of 11,500 ha of logged forest to a palm plantation in Gabon will release 1.50 Tg C (95% CI = [1.29, 1.76]). These emissions could be completely offset over 25 years through sequestration in planned forest set-asides given a 2.6:1 ratio of logged to converted forest. Using an agricultural suitability model, we find that careful national land-use planning could largely avoid high carbon emissions while meeting goals for palm oil production. We recommend that Gabon adopts a national carbon threshold for land conversion and requires concession-level set-aside ratios that meet no-net emissions criteria as mechanisms for steering plantations away from high carbon forests.

Introduction

Worldwide demand for agricultural products drives the conversion of tropical forest to croplands (Gibbs *et al*. 2010). Oil palm, which yields more than 30% of the world's vegetable oil, is grown on 17 million hectares of tropical lands and is rapidly expanding (Phalan *et al*. 2013; FAO 2014). On the one hand, the oil palm industry can create jobs, expand the corporate tax base, and increase social investment in rural communities (Koh & Wilcove 2007; UNEP 2011). On the other hand, without appropriate restrictions, the conversion of tropical forest to oil palm plantations results in broad-scale environmental degradation, including biodiversity and habitat loss, reduction in ecosystem services, and emission of greenhouse gases (e.g., Fitzherbert *et al*. 2008; Megevand 2013; Wich *et al*. 2014). The challenge then is to determine conditions for oil palm production that best reconcile agricultural development with minimizing environmental degradation.

The conversion of carbon-dense tropical forests to agriculture palm threatens to perturb carbon cycling (Laurance *et al*. 2014). Between 1980 and 2000, the conversion of intact and disturbed forests accounted for 55% and 28% of new agricultural land in the tropics (Gibbs *et al*. 2010). The level of emissions from forest conversion is at least partially dependent on land-use history, with intact forest generally releasing more carbon than disturbed forest (Morel *et al*. 2011; Carlson *et al*. 2013). Currently, the net impacts of palm plantations on forest carbon emissions are uncertain, particularly for Central Africa where there are relatively few industrial palm plantations. Over 88% of palm plantations occur in Asia (FAO 2014), but the crop is expanding in the Neotropics and Africa (Amigun *et al*. 2011; Paoli *et al*. 2011; Phalan *et al*. 2013).

One approach to reconciling agricultural production with climate stability is to steer agricultural expansion away from intact forests toward low carbon landscapes (Dinerstein *et al*. 2015). While intuitive, this approach poses challenges to highly forested countries with low deforestation rates. Gabon is the second most forested country in the world with a deforestation rate near zero (Sannier *et al*. 2014) and ambitions of becoming a leading palm oil exporter by increasing production from 13,000 to 280,000 tons year^{-1} by 2025 (République Gabonaise 2011, 2012). In 2010, the Government entered a joint venture with Olam International Ltd, a multinational agri-business (Versi 2012; Olam 2014), for the first phase (50,000 ha) of Roundtable on Sustainable Palm Oil (RSPO)-certified oil palm development (Gabon 2014). With less than 7% nonforested land (excluding urban and protected areas), some of which fail to meet biophysical and economic criteria for plantation development, deforestation is likely necessary to meet production goals. This raises questions concerning the expected emissions with conversion of forests to plantations and the steps necessary for Gabon to grow its oil palm sector in a way consistent with low-emissions development.

The RSPO currently calls for voluntary minimization of net greenhouse gas emissions, calculated over the full crop cycle by adding emissions released during land clearing, crop production and processing, and subtracting carbon sequestration in standing crop and conservation areas (Chase *et al*. 2012). While RSPO encourages development on low carbon stock areas—defined as areas meeting zero emission standards over one crop rotation—it allows clearance of any forest not defined as primary or high conservation value forest (HCVF), thereby falling short of prescriptive standards for limiting carbon emissions (RSPO 2013). Furthermore, it sets neither limits on carbon emissions nor a methodological standard for carbon monitoring. In brief, current RSPO guidelines leave standards of carbon monitoring and decisions for new plantings up to national interpretation, disadvantaging countries without experience in sustainable agricultural development.

Our goal is to inform policy regarding selection and management of oil palm plantations in Central Africa. We first take a case study approach in Gabon, quantifying forest carbon stocks and predicting net emissions relative to a preconversion baseline from a "typical concession," in which previously logged forest is converted to an oil palm plantation. Calibrating LiDAR data with field measurements, we demonstrate that conversion of even degraded forest results in high gross emissions. Building on this result, we develop a simple model to map the suitable areas for palm agriculture nationwide to evaluate whether there is adequate nonforest land for no-net emissions agriculture in Gabon. This multiscale approach gives rise to a two-tiered decision rule—based on a national carbon threshold and a concession-level set-aside ratio —for plantation establishment in an effort to minimize carbon emissions from palm production.

Materials and methods

Jump to...

Approximately 88% of Gabon (23.5 M ha) is covered by tropical rainforest (Sannier *et al*. 2014). Average soil carbon concentration is 162 Mg C ha^{-1} (Wade 2015). Although little is known about the distribution of peatlands in Gabon, they are comparatively rare (Howard-Williams & Thompson 1985). There are currently 130,680 ha of oil palm concessions in the country of which 58,980 ha is plantable, based on environmental, social, and agronomic suitability (M.E.L. & L.J.T.W., National Land Use Plan). The government leased Olam concessions consisting of Mouila Lots 1 and 2 (ML1: 35,300 ha; ML2: 31,800 ha; Figure 1), subject to impact assessment and the free prior and informed consent of local people. Palm agriculture was initiated in ML1 in early 2013, and in ML2 in 2014.

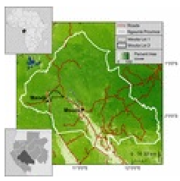

Figure 1. The Mouila concessions, Lot 1 (ML1) and 2 (ML2), in the Ngounié Province of Gabon, Africa. Upper left inset map depicts Gabon within Africa. Lower left inset map shows the Ngounié Province within Gabon. The basemap depicts percent tree cover derived from Landsat imagery (Sexton *et al*. 2013).

ML2 is an old timber concession composed mainly of selectively logged, lowland mixed tropical forest. The lot consists of relatively flat plains to be developed for palm agriculture (11,500 ha), with the remaining plains (4,300 ha) and plateau (15,900 ha) designated as HCVF based on an independent consultation process because they were unsuitable for agriculture (e.g., steep slope), contained mature, biodiverse forest, comprised a river buffer, or were designated for local community use (Proforest 2013; Figure 2).

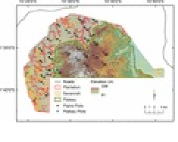

Figure 2. Map of 30 one-hectare plots within ML2 depicting the main habitat types, including the plateau forest and the plains forest and savannah. ML2 is an old timber concession, separated into a relatively flat plain and a rolling, dissected plateau. The plains, where logging was more intense, is dominated by maturing *Aucoumea klaineana* (Okoumé) forests, evidence that historically the area was a savannah colonized by humans. The plains were deemed suitable for palm agriculture and will be planted. The plateau, bounded by steep slopes and dominated by less disturbed, more diverse mature forest, will be conserved as high conservation value forest (HCVF). We did not sample the eastern side of ML2 because it lies within a village use zone, which by agreement between Olam and the villages will not be developed.

Aboveground carbon stocks from field measurements and LiDAR

We estimated forest carbon stocks in ML2 by quantifying aboveground biomass (AGB) (not the other four carbon pools), using a stratified-random design to position 30 one-hectare plots (40 × 250 m) over the study area, with 10 plots on the plateau and 20 plots in the plains (Figure 2). In 2013, technicians inventoried, mapped, and measured each tree with a diameter-at-breast height (DBH) ≥ 10 cm (detailed methods in Appendix S1). We then used a pantropical allometric equation to estimate AGB, AGB_F, and carbon, C_F, both from field data, for each plot (Chave *et al*. 2014), assuming that the carbon content of AGB was 50%.

To map three-dimensional forest structure, we used aerial LiDAR data collected in September 2011 (Appendix S1). The mapping company, SEPRET, produced a 2-m^2 resolution digital terrain model (DTM) from the data using a propriety algorithm to separate ground points from vegetation returns. Combining the DTM with the raw LiDAR data, we calculated vegetation height surfaces at 2-m^2 resolution for each of the four, and cumulative, LiDAR returns (Table S3).

We modeled the relationship between AGB_F and the LiDAR canopy height metrics to predict AGB_L (AGB modeled from LiDAR data) across ML2. To avoid multicollinearity, we evaluated correlations between LiDAR metrics, removing one of the variables from any highly correlated pair ($r \geq 0.7$). We then regressed AGB_F against the remaining LiDAR metrics, employing backward model selection to remove nonsignificant variables to identify the most parsimonious model. To estimate the prediction error from our final model, we used leave-one-out cross-validation, iteratively removing one plot from the dataset, computing the error from the subsequent regression, and then calculating the mean square error from all iterations. To predict AGB_L and carbon densities for the entire concession, we applied the final model across the ML2 landscape using a geographically centered 1-ha (40 × 250 m) focal area, consistent with the scale of the field data.

Estimates of carbon emissions

The carbon map provides a preconversion baseline from which we predict net carbon emissions by accounting for carbon lost through forest conversion and foregone sequestration and gained through sequestration of the oil palm crop and HCVF (see Table 1 for definitions and calculations):

$$\text{Emissions Tg CO}_{2\ \text{eq}} = \left(\begin{matrix}\text{Forest}\\\text{conversion}\end{matrix} + \begin{matrix}\text{Foregone}\\\text{sequestration}\end{matrix} - \begin{matrix}\text{Oil palm}\\\text{sequestration}\end{matrix} - \begin{matrix}\text{HCVF}\\\text{sequestration}\end{matrix}\right) \times \left(\frac{\text{CO}_{2\ \text{eq}}}{\text{Tg C}}\right)$$

Table 1. Description of calculations of carbon emissions and set-aside ratios. (a) Definition of terms used in calculating CO_2 emissions. (b) Carbon emissions of four accounting scenarios. The *Emissions Offset* is the percentage of carbon accumulated in oil palm and HCVF relative to carbon emitted in forest conversion and foregone sequestration. (c) Calculation of set-aside ratios for ML2 and the proposed national carbon threshold for Gabon. The set-aside ratio is the ratio of carbon lost to agriculture relative to carbon gained through conservation on a per ha basis

(a) Definition and calculation of terms	
Forest Conversion	Total carbon, AGB_L, in forested area to be converted to plantation (e.g., carbon lost with deforestation, so savannah not included). For this study, Forest Conversion is 1.29 Tg C for 10,493.5 ha of forested plantation, as estimated from the carbon map (Figure 4).
Foregone Sequestration	Total carbon that would have been sequestered by the forest converted to plantation (e.g., sequestration lost with deforestation, so savannah not included). Calculated as the sequestration rate of logged forest × area of converted forest × length of the crop cycle. $2.41\ \text{Mg C ha}^{-1}\ \text{year}^{-1} \times 10{,}493.5\ \text{ha} \times 25\ \text{year} \times \frac{1\ \text{Tg C}}{1{,}000{,}000\ \text{Mg C}} = 0.63\ \text{Tg C}$ We calculate a second estimate of Foregone Sequestration, used in *HCVF Offsets + Logging*, assuming that in the absence of agriculture, the area would have been selectively logged with an 8% annual loss of AGB. $\sum_{i=1}^{25} 2.41\ \text{Mg C ha}^{-1}\ \text{year}^{-1} \times (10{,}493.5\ \text{ha} \times (1-0.08)^{i-1}) \times \frac{1\ \text{Tg C}}{1{,}000{,}000\ \text{Mg C}} = 0.28\ \text{Tg C}$
Oil Palm Sequestration	Total carbon sequestered by the crop over 25 years (for the entire crop area including both the converted forests and savannah areas). Calculated as the time-averaged sequestration rate for oil palm (Agus *et al*. 2013) × the plantation area. $36\ \text{Mg C ha}^{-1} \times 11{,}548.9\ \text{ha} \times \frac{1\ \text{Tg C}}{1{,}000{,}000\ \text{Mg C}} = 0.42\ \text{Tg C}$
HCVF Sequestration	Total carbon sequestered in the HCVF over one rotation of the oil palm crop. Calculated as sequestration rate of logged forest × HCVF area × length of crop rotation. $2.41\ \text{Mg C ha}^{-1}\ \text{year}^{-1} \times 19{,}853.6\ \text{ha} \times 25\ \text{year} \times \frac{1\ \text{Tg C}}{1{,}000{,}000\ \text{Mg C}} = 1.20\ \text{Tg C}$

(b) Scenarios of oil palm development		
	$\left(\begin{matrix}\text{Forest}\\\text{conversion}\end{matrix} + \begin{matrix}\text{Foregone}\\\text{sequestration}\end{matrix} - \begin{matrix}\text{Oil palm}\\\text{sequestration}\end{matrix} - \begin{matrix}\text{HCVF}\\\text{sequestration}\end{matrix}\right) \times \left(\frac{\text{CO}_{2\ \text{eq}}}{\text{Tg C}}\right) = \text{Emissions Tg CO}_{2\ \text{eq}}$	Emissions Offset
No HCVF Offsets	CO_2 emissions from oil palm development, without crediting for the sequestration of HCVF. $(1.29\ \text{Tg C}_L + 0.63\ \text{Tg C} - 0.42\ \text{Tg C} - 0\ \text{Tg C}) \times \frac{44\ \text{Tg CO}_{2\ \text{eq}}}{12\ \text{Tg C}} = 5.51\ \text{Tg CO}_{2\ \text{eq}}$	21.7%
HCVF Offsets	CO_2 emissions from oil palm development, accounting for sequestration from HCVF. $(1.29\ \text{Tg C}_L + 0.63\ \text{Tg C} - 0.42\ \text{Tg C} - 1.20\ \text{Tg C}) \times \frac{44\ \text{Tg CO}_{2\ \text{eq}}}{12\ \text{Tg C}} = 1.13\ \text{Tg CO}_{2\ \text{eq}}$	84.0%
HCVF Offsets +	CO_2 emissions from oil palm development and sequestration from HCVF, but reducing foregone sequestration by assuming that there would have been an 8% loss of forest AGB	

Logging	(and carbon). $(1.29\ \mathrm{Tg}\ C_L + 0.28\ \mathrm{Tg\ C} - 0.42\ \mathrm{Tg\ C} - 1.20\ \mathrm{Tg\ C}) \times \frac{44\ \mathrm{Tg\ CO_2\ eq}}{12\ \mathrm{Tg\ C}} = -0.17\ \mathrm{Tg\ CO_{2\ eq}}$	102.9%
Full Conservation	CO_2 sequestration if the entire plantation area was conserved from agriculture and logging for 25 years. $(0\ \mathrm{Tg}\ C_L + 0\ \mathrm{Tg\ C} - 0\ \mathrm{Tg\ C} - 1.83\ \mathrm{Tg\ C}) \times \frac{44\ \mathrm{Tg\ CO_2\ eq}}{12\ \mathrm{Tg\ C}} = -6.71\ \mathrm{Tg\ CO_{2\ eq}}$	–

c) Calculation of the set-aside ratios	
	$\left(\begin{matrix}\text{Carbon Density}\\ \text{Mg ha}^{-1}\end{matrix} + \begin{matrix}\text{Foregone}\\ \text{sequestration}\end{matrix} - \begin{matrix}\text{Oil palm}\\ \text{sequestration}\end{matrix}\right) : \begin{matrix}\text{HCVF}\\ \text{sequestration}\end{matrix} = \text{Set} - \text{aside Ratio}$
ML2	For ML2, carbon lost through agriculture includes the mean density of converted forest from our field study (C_F), foregone sequestration, and oil palm sequestration. $(131.1\ \mathrm{Mg\ ha^{-1}} + 60.3\ \mathrm{Mg\ ha^{-1}} - 36\ \mathrm{Mg\ ha^{-1}}) : 60.3\ \mathrm{Mg\ ha^{-1}} = 2.6 : 1$
National threshold	The national set aside ratio is calculated using the recommended 118 Mg C ha^{-1} threshold as the carbon density. $(118\ \mathrm{Mg\ ha^{-1}} + 60.3\ \mathrm{Mg\ ha^{-1}} - 36\ \mathrm{Mg\ ha^{-1}}) : 60.3\ \mathrm{Mg\ ha^{-1}} = 2.4 : 1$

We assume sequestration rates of 2.41 ± 0.61 Mg C ha^{-1} $year^{-1}$ for logged Central African forests (Gourlet-Fleury *et al*. 2013); the High Carbon Stock Science (HCS+) Study recommends a rate of 2.5 C ha^{-1} $year^{-1}$, but this value targets secondary forest and does not include data from Africa (Chave 2015). We use a mean-time-averaged sequestration of 36 Mg C ha^{-1} over a 25-year default oil palm rotation as recommended by RSPO (meta-analysis from Southeast Asia; Agus *et al*. 2013), but note that recent studies have used values of 28 Mg C ha^{-1} (Kho & Jepsen 2015) and 30 Mg C ha^{-1} (Chave 2015). We quantify net emissions for four scenarios: three scenarios of oil palm development with different accounting methods for foregone or HCVF sequestration, and a full conservation scenario with no land-use change (Table 1).

We calculate set-aside ratios as the ratio of net carbon change in the plantation to net carbon change in HCVF (Table 1). Set-aside ratios indicate the proportion of forest area to be conserved to offset losses from agriculture.

Agricultural land suitability

To assess the total area suitable for oil palm agriculture, we constructed a national suitability model based on biophysical constraints: annual precipitation, length of dry season, topographic, soil, and inundation (Appendix S2). We used the resulting map to evaluate the potential for no-net emissions agriculture by quantifying the area of suitable land in savannah or shrubland.

Results

Jump to…

Aboveground carbon stocks from field measurements and LiDAR

We measured 12,821 individual trees from 55 families in the 30 one-hectare plots. We estimated mean plot level C_F to be 149.8 ± 51.3 Mg C ha^{-1} after excluding two plots that straddled savannah and forest, thereby lacking stems ≥10 cm DBH over more than one-third of their areas (Table S2). Plateau plots contained significantly higher C_F than plains plots ($t_{13.5}$ = 2.602, 0.021; Table S1; Figure S1). By multiplying the mean C_F for each forest type by their forest areas, we estimated carbon in ML2 to be 4.81 ± 1.45 Tg C_F. The convertible plains forests account for 1.38 ± 0.40 Tg C_F or gross committed emissions of 5.04 ± 1.45 Tg CO_{2eq}.

Based on LiDAR analysis (Figures S2 and S3), the plateau forest plots had significantly taller mean canopies (28.1 ± 6.58 m) than plains plots (23.0 ± 3.21 m; $t_{11} = -2.294$, $P = 0.042$). The variance in mean LiDAR return heights was significantly higher in plateau than plains forest ($F_{17,9} = 0.231$, $P = 0.009$), suggesting that plateau forests had a more heterogeneous and taller canopy height distribution (Figure S4).

The final model for predicting AGB_L explained 80% of variation in AGB_F ($ln(AGB_F) = 0.3632 + 1.6914\ ln(H_{LiDAR})$; $R^2 = 0.797$; $F_{1,28} = 114.6$, $P < 0.001$; Figure ss="figureLink" title="Link to figure" rel="references:#conl12265-fig-0003">3), with a prediction error of 7.6% (where H_{LiDAR} was the mean height of all LiDAR points). The spatial model predicted that the plains to be converted to plantation 1.29 Tg C_L (95% CI = [1.08, 1.54]), while the HCVF plateau forests contain 2.72 Tg C_L (95% CI = [2.31, 3.20]) and the HCVF plains contain 0.39 Tg C_L (95% CI = [0.32, 0.48]; Figure 4).

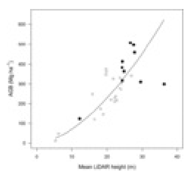

Figure 3. Relationship between AGB_F (Mg ha^{-1}) measured in the field and the mean plot-level tree height (m) estimated from the LiDAR data for the plains forest (gray symbols) and the plateau forest (black symbols). The power law model was used to predict AGB_L from the LiDAR data and to develop the spatial model of carbon density for ML2 (Figure 4).

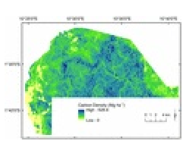

Figure 4. Spatial model of carbon density in ML2 derived from AGB_L. The model predicts that ML2 holds a total of 4.40 Tg C_L (95% CI = [3.71, 5.22]). The plains to be converted to agriculture contain 1.29 Tg C_L (95% CI = [1.08, 1.54]). Conserving HCVF in ML2 avoids the immediate loss of 3.11 Tg C_L. The plateau forests contain 2.72 Tg C_L (95% CI = [2.31, 3.20]) and the HCVF plains contain 0.39 Tg C_L (95% CI = [0.32, 0.48]). Carbon density loosely follows an

accessibility gradient, with areas close to old roads and waterways having relatively low carbon density and areas with high slopes and low accessibility having high carbon density.

Estimates of carbon emissions

With no offsets (*No HCVF Offsets* scenario), development of the convertible plains would result in net emissions of 5.51 Tg CO_{2eq} (Table 1; Figure 5). Only savannah (4% of ML2) could be converted to oil palm under a no-net carbon emissions framework without offset provisions. If ML2 was totally protected (*Full Conservation*) from land use, it would accumulate a net of 6.71 Tg CO_{2eq} (Table 1; Figure 5).

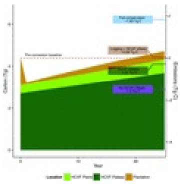

Figure 5. The estimated carbon stocks based on AGB_L of the plantation (11,500 ha), HCVF plains (4,300 ha), and plateau (15,900 ha) and their estimated sequestration over 25 years (year 0 = pre-conversion stocks, year 1 = 1 year after conversion). The dashed red line represents the *pre-conversion* carbon stock baseline as estimated with a combination of field measurements and LiDAR data. The boxes represent carbon emissions under different accounting scenarios after 25 years of agriculture, including: (a) *No HCVF offsets* (purple line): carbon emissions after forest conversion to plantation accounting for foregone sequestration and oil palm sequestration, but without HCVF offsets. (b) *HCVF offsets* (black line): carbon stocks after conversion accounting for foregone sequestration, oil palm sequestration, and conservation of HCVF offsets. (c) *Logging + HCVF offsets* (brown line): carbon stocks calculated as in *HCVF offsets*, but calculating foregone sequestration by assuming an 8% annual loss of AGB from logging —a likely scenario in the absence of a palm plantation or other management. (d) *Full conservation* (blue line): approximately 6.23 Tg C would be conserved if the concession was completely protected over 25 years, assuming no logging and no agriculture, resulting in net sequestration.

Accounting for HCVF sequestration (*HCVF Offsets*) following RSPO methods would result in 1.13 Tg CO_{2eq} (Table 1; Figure 5). The plateau forests would sequester approximately 0.96 ± 0.24 Tg C and the plains HCVF would gain 0.24 ± 0.06 during the 25-year crop rotation. Together, HCVF sequestration and oil palm sequestration account for 84% of the carbon lost from forest conversion (1.29 Tg C_L).

Alternatively, assuming that the convertible forest would have been selectively logged in the absence of agriculture, we factor in an 8% annual loss of AGB (Medjibe *et al*. 2011) in our estimate of foregone sequestration (*HCVF Offsets + Logging*), resulting in net accumulation of 0.17 Tg CO_{2eq} (Table 1; Figure 5). In this scenario, crediting for forest conservation and oil palm sequestration would account for 103% of carbon emissions from ML2 (Table 1). With 64% of ML2 conserved as HCVF, all or nearly all emissions from forest conversion will be successfully offset, depending on the crediting scheme (*HCVF Offsets* and *HCVF Offsets + Logging*).

To meet no-net emissions criteria, 2.6 ha of forest needs to be set aside for every 1 ha of forest converted to plantation under the *HCVF Offset* scenario (Table 1). The set-aside ratio varies with the mean carbon density of the forest, with lower average carbon densities requiring lower set-aside ratios to achieve zero-net emissions.

Agricultural land suitability

According to the suitability model, highly productive areas for oil palm occur on about 4% of land (1.2 M ha), situated in the west of the country, including the Mouila area. Of this land, 8% (~95,000 ha) occurs in savannah or shrubland that might achieve no-net emissions, indicating that Gabon could avoid forest conversion by placing all plantations within these low carbon ecosystems.

Discussion

This article presents the first effort to quantify carbon emissions from oil palm agriculture in Central Africa, and demonstrates that conversion of even previously logged forests will lead to high carbon emissions. Specifically, we found that carbon stocks in ML2 forests are four times greater than the time-averaged density for oil palm over its 25-year life cycle (Agus *et al*. 2013), and would release 155.4 Mg C_F ha^{-1} under the *No HCVF Offsets* scenario. Our results are likely indicative of emissions from other Central African degraded forests, as the carbon density of ML2 is comparable to logged forests across the country and region (Appendix S3).

Our goal is neither to support nor demonize oil palm agriculture, but to outline a path to low-emissions development. Growing demand for palm oil is driving the industry's expansion into Africa (Carter *et al*. 2007; Corley 2009). To minimize the negative environmental effects of expansion, strict criteria for plantation selection, development, and management need to be defined. Although RSPO provides guidelines for environmental sustainability (RSPO 2013), these recommendations lack the specificity necessary to limit carbon emissions in Central Africa. We propose a two-tiered decision rule for plantation establishment, in which: (1) a country-specific carbon threshold first guides the location of plantations at the national level; and then (2) the implementation of a set-aside ratio at the concession or palm estate levels ensures no-net carbon emissions from plantation development. The first rule orients the national government in its designation of plantation areas, while the second rule obliges companies to offset remaining net emissions through spatial planning of set-asides.

Carbon thresholds and national land-use planning

Ideally, forest conversion would be governed by a zero-net emissions threshold, but in highly forested developing nations, exceptions may be necessary to balance social and economic benefits against environmental concerns. Although our agricultural suitability model identified ample nonforested land for palm production in Gabon (95,000 ha of savannah or shrubland, compared to 50–70,000 ha necessary to meet the Government's production goal), carbon emission is just one criterion for plantation development. Considerations of biodiversity, traditional use rights, profitability, and competing land claims could substantially restrict the area of nonforest land available for low-emissions agriculture.

To prohibit the conversion of intact and high carbon forest, we recommend a carbon threshold of 108–118 Mg C ha $^{-1}$ that restricts plantation development to the lower quartile of forest carbon densities, with the lower value based on this study and the upper value based on a nationwide carbon inventory (and equal to the average carbon density of secondary forest; Appendix S3). This threshold is more restrictive than current practices for plantation siting in Gabon (based on ML2), but less restrictive than the 35-75 Mg C ha^{-1} limit recommended by the HCS methods (Raison *et al*. 2015). Both proposed thresholds aim to permit agriculture in previously degraded forests while avoiding deforestation of older secondary and primary forests. Both proposed thresholds also focus solely on aboveground carbon stocks, whereas ideally information on soil carbon stocks should also be incorporated into decisions of plantation siting.

Offsetting carbon emissions

When forest conversion is inevitable, emissions should be offset through set-asides at the concession or palm estate (a company's land holdings) levels to prevent immediate emissions and sequester carbon under proper management. For Gabon, a rule-of-thumb ratio of 2.4 conserved hectare to each converted hectare of forest should be set-aside if the 118 Mg C ha^{-1} threshold is applied, whereas the higher ratio of 2.6:1 for ML2 is due to the C_F exceeding this proposed threshold (Table 1). This ratio will decrease for concessions with mean carbon density below the threshold, incentivizing the selection of low carbon areas for agricultural development. We acknowledge, however, that set-asides can be costly, complicated, and controversial (Walker *et al*. 2009), especially when the respective responsibilities of companies, governments, and communities are poorly defined. Set-asides must be properly designed, managed, and monitored for their intended conservation goals, which may include additional values such as watershed health or biodiversity (Linder 2013; Wich *et al*. 2014).

Challenges to low-emissions development with oil palm agriculture

Managing forest-based carbon emissions while developing oil palm agriculture is challenging, yet possible with careful solutions like our two-tiered decision rule. At the national level, land-use planning could largely avoid forest conversion through strategic identification of productive, low carbon agricultural land. Coarse carbon maps exist for all tropical countries (e.g., Saatchi *et al*. 2011), facilitating a first cut of national-level planning. At the concession level, operators assume the costs of fine-scale carbon mapping as part of plantation development, which should also account for co-benefits such as biodiversity, watershed conservation, and food and income security traditional livelihoods. Land-use planning is challenging in tropical nations because of sparse financial resources, corruption, abstruse land tenure, and limited data, but the tropics are likely to be the epicenter of the agricultural expansion necessary to feed a growing human population (Laurance *et al*. 2014). Our study illustrates that comprehensive land-use planning at both the national and site levels can facilitate low-emissions agricultural development in tropical forest landscapes, providing a model for other countries wishing to develop in a similar context.

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Jump to…

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Supporting Information

Jump to…

Disclaimer: Supplementary materials have been peer-reviewed but not copyedited.

Filename	Format	Size	Description
conl12265-sup-0001-SupInfo.docx		14K	**Appendix S1**. Calculating aboveground carbon stocks with field and LiDAR data. **Appendix S2**. Oil palm suitability model for Gabon, using five variables representing the main geophysical constraints to the crop to identify areas of agricultural productivity. **Appendix S3**. The demonstration that the results from ML2 are representative of forests across Gabon and Central Africa and additional information supporting our proposed forest carbon threshold. **Table S1**. Comparison of forest characteristics between plains plots and plateau plots. **Table S2**. Forest characteristics of the 30 forest plots in ML2, including stem counts, tree heights (H) and diameters (D), basal area (BA), and estimates of AGB using allometric equations from Chave *et al*. (**2014**). **Table S3**. LiDAR height characteristics (in meters) for canopy returns for the 30 plots in plains (Plain) and plateau (Plat) in ML2. **Figure S1**. Comparison of plot characteristics between the plains and plateau forests in ML2, including mean height, stem count, per tree basal area, and per plot basal area. **Figure S2**. The canopy height model for ML2 derived from the LiDAR 1st return dataset. **Figure S3**. Spatial model of all the LiDAR returns for ML2. **Figure S4**. Vertical canopy height profiles from LiDAR for the plains and plateau forest plots.

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