Marginal abatement cost curves for REDD+ in Kalimantan, Indonesia and the potential role of cost-saving plantations

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Abstract
Tackling climate action through REDD+ implementation is a viable option to climate action planning. This study aims to develop a marginal abatement cost (MAC) based process that enables decision-makers to estimate economic cost of emissions abatement and understand the role of cost-saving plantations in climate change planning practices. Our research in Kalimantan, Indonesia shows that cost-saving plantations can contribute to 0.05 million ton CO$_2$ sequestration in research area. Further analysis suggests that cost-effective plantations account for 86% of total carbon emissions. The application of MAC curves for REDD+ in our study provides insights to include the optimization of land utilization in support of leveraging financial resources for the implementation of REDD+ strategies.

1. Introduction

For countries planning to implement UNFCCC policy on Reduced Emissions from Deforestation and forest degradation (REDD+), the economic and financial implications of mitigation options are important. Although the IPCC AR5 analysis of global and regional costs associated with REDD+ demonstrated that forestry-related emission mitigation as a whole represents a cost-effective instrument and produces institutional, economic, social, and environmental benefits in addition, there remain some unresolved fundamental issues regarding costs (Graham et al 2016, Palmer 2011, Leplay et al 2011, Ojea et al 2016, Katani et al 2016).

Meanwhile, there has been a long debate on the role of plantations within REDD+ framework. Plantations differ from natural forests in many ways, such as their biodiversity, the ecosystem services they can provide, and their local livelihood impact. On the one hand, many proponents of REDD+ consider plantations which replace natural forest to represent deforestation, since they usually cause degradation of the soil and reduce biodiversity and carbon stocks, moreover the associated fertilizer and pesticides use may take a heavy social and environmental toll (Adachi et al 2011, Davis et al 2013, Nogueira 2010). On the other hand, some argue that, if plantations are established on degraded areas and in places that are easier to access than remote forests, there may be an overall increase in carbon stocks (Choo et al 2011, Davis et al 2013, Nogueira 2010). Furthermore, the establishment of plantations in degraded forest lands may promote the switch from degradation to responsible forest management, which will then help mitigate global warming while protecting biodiversity and contributing to sustainable development (Sasaki and Putz 2009). Most of these authors are however referring to plantation of forests, often for timber. The situation is a little different when one considers...
plantations of trees for agricultural purposes, such as cocoa, coffee, tea, coconut, bananas, rubber and oil palm. Among these, the cases of rubber and oil palm are particularly important since these are produced on such a large scale, particularly in SE Asia. In the remainder of this paper, the term ‘plantations’ will be exclusively used to refer to rubber and oil palm.

Indonesian officials argue that oil palm plantations could mitigate climate change through carbon sequestration (Creagh 2010), and Malaysia considers that under REDD+, the conversion of natural forest to oil palm and rubber represents degradation, but not deforestation, since these plantations have a lower carbon content than the original forest (Ministry of Natural Resources and Environment Malaysia 2011). The local government in Philippines has adopted a policy under REDD+ to allow the development of tree plantations projects in idle and unproductive lands under public domain (Atty Grizelda 2013). However, while many Parties to the UNFCCC COP have argued that agricultural plantations of these types should not be considered be forest, and that therefore they should be excluded from REDD+, at present the decision on whether to include them or not has been left to the discretion of individual participating countries.

One way in which this conflicted issue could be addressed is by constructing a marginal abatement cost (MAC) curves, to give a succinct and straightforward account of carbon emissions abatement options relative to a baseline (typically a business as usual pathway). A MAC curve provides an easy-to-read visualization of various mitigation options or measures organized by a single, understandable metric—the economic cost of emissions abatement (Sudmant et al 2017, Ibrahim and Kennedy 2016, Calvin et al 2016). Although there are some weaknesses, such as the lack of consideration of correlation between variables in various categories (Ekins et al 2011), it still is an aid for decision making that identifies both the options that are the most cost effective per unit of CO₂ abated and those that offer the greatest abatement potential. At the pan-tropical level it was estimated that emission reduction potential between 1.8 and 2.5 Gt CO₂ emission reductions per year at prices of USD 10–20 per ton CO₂ (Coren et al 2011). At the country level it was estimated that emission reduction potential is 1204 Mt CO₂ emission reductions per year at prices of USD 11 per ton CO₂ in Indonesia (DNPI 2010). At the site-specific level White and Hyman (2009) found that in central Peruvian Amazon for 1990–2007 emission reduction potential is 3.7 ton CO₂ emission reductions per ha per year at prices of USD 2.28 per ton CO₂. In Mpanda and Kigoma districts of Tanzania the mean costs ranged between USD 12.1–13.8 per ton CO₂ (Merger et al 2012). In Malaysian Borneo, Brendan Fisher et al (2011) found that the breakeven carbon payment would be USD 40–42 per ton CO₂, including setup and monitoring costs. These site-specific level studies play important roles for REDD+, while it still is lack of quantitative evaluation at present. For example, information is scarce on how the plantations from different land uses they replace affect the REDD+ payment. Furthermore, it remains unclear how the carbon footprint of plantations help to achieve carbon reduction target of REDD+ policy. The goal of this research is demonstrate how MAC methodology can help decision-makers to estimate the economic cost of emissions abatement for different land use changes, to optimize land resources by compiling and prioritizing mitigation measures, and to recognize and justify the fact that some land use changes result in positive impacts on carbon stock, including the development of plantations in areas which currently have low carbon density vegetation.

2. Methods

2.1. Land changes in research area

We selected north Palangka Raya, Indonesia as the area for examination in our study. This area has been historically surrounded by heath forests; however, since 2000, it has been plagued by large-scale deforestation. A study by Kanninen et al (2007) reported that the remaining forest can be categorized as a ‘forest frontier,’ the clearance of which is likely to reach its maximum level in the next 30 years. We identified land use classes as following: forests, cropland, water, and road. We adopted ‘land spanning more than a canopy cover of more than 10 percent but not include land that is predominantly under agricultural or urban land use’ (FAO 2006) as the definition of a forest. Changes from forests were classified as ‘deforestation’ based on the FAO’s (1995, 2001) position that ‘deforestation refers to a conversion of forest to other land uses such as new agricultural land or unsustainable plantation, or a long-term reduction of the tree canopy cover.’ We used Landsat satellite images to map forests lands with different canopy covers (Hansen et al 2013). We found that there were 28697 ha forests in research area, with 11396.5 ha for forest 80%–100% canopy, 8273.3 ha for forest 60%–80% canopy, 2378.6 ha for forest 40%–60% canopy, 4271.8 ha for forest 30%–40% canopy, 1517.9 ha for forest 20%–30% canopy and 858.9 ha for forest 10%–20% canopy.

We considered these alternative land use classes, denoted by $i$ (forest lands), $j$ (cropland), $k$ (water), and $l$ (road), where $aji$ quantifies gross area converted from forest lands in initial year of 2005 to cropland in final year of 2009; $aji$ quantifies gross area converted from cropland to forest lands over the same interval. $aji$ and $ajj$ represent area in forest lands and cropland that did not change. The net change is the difference between the gross changes $aji$ and $ajj$. We found that cropland increased at the expense of forest lands; this development increased by 9.18% during the period.
2.2. Methodology for constructing MAC curve

A MAC curve is a graph that visualizes the abatement potential of GHG mitigation measures and the relative costs associated with each of these measures. In this study, the MAC curve for REDD+ shows the marginal abatement cost—in USD per ton CO₂—to reduce or offset the emissions—in tons of CO₂—achievable by different land use options at a given point in time. It was constructed using a bottom-up approach that compiles land use options in a step function to enable a prioritization based on cost-effectiveness. Calculating the marginal abatement cost of each land use option in REDD+ requires quantifying two parameters: net present value (USD) and carbon emissions (ton CO₂).

We define MAC as the net present value per unit area (i.e. hectare) divided by the net carbon emission avoided per unit area. The revenue that could have been gained from each area is sacrificed by not logging (or logging more sustainably) or not making the area amenable to agriculture under the conditions of the REDD+ program. Thus, we calculate MAC using the following formula:

\[
MAC_i = \frac{NPV^{FC}_i}{C_i^{FC} * 44/12}
\]  

(1)

where MACᵢ is marginal abatement cost, measured as the net revenues gained per ton of CO₂ emissions per hectare avoided under business-as-usual (BAU) conditions for time t (expressed in USD/tCO₂); NPVᵢ^{FC} represents the net revenues (revenues minus costs) gained from a composite commodity after a forest is converted to land amenable to agriculture (expressed in USD); 44/12 means one ton of carbon equals 3.67 (44/12) tons of CO₂; and Cᵢ^{FC} stands for total emissions of aboveground biomass produced from converting forest (expressed in ton C).

In this study, we used the cellular automaton model to simulate the BAU scenario. This model is based on historical deforestation data gathered using the retrospective method, but offers specific projections related to land use development and changes (Verburg et al. 2006). The cellular automaton model (Kuznetsov 2017, Huang et al. 2017), which is comprised of four elements and one important condition, can be expressed as follows:

\[
BAU^{CA} = \{ X, S, N, R \} \cup DR
\]

(2)

where X represents the individual land use cell; S indicates how the land is being used as per REDD+; N is the cell neighbourhood, which represents the attraction (positive) and repulsion (negative) effects of the various land use cells. Because each cell in a given neighbourhood will be weighted according to its state and distance from the central cell, N can be calculated as:

\[
N_i = \sum_s \sum_d W_{sd} I_{sd}
\]

(3)

where \( W_{sd} \) is the weighting parameter applied to states S at position x in distance zone d of the neighbourhood; \( I_{sd} \) is the Dirac delta function, which equals 1 if the cell is occupied by state S, and 0 otherwise; and R indicates the transition rules that represent a vector of transition potentials for each cell from \( N_i \):

\[
R_i = P\{ j \Rightarrow k | N_1 \cap N_2 ... \cap N_j \}
\]

= Σ \( W^+ / (1 + e^k W^+ ) \)

(4)

where \( W^+ \) is the weight of evidence, which can be calculated as:

\[
\log( D[N_i] ) = \log(D) + W^+
\]

(5)

where D is the event.

\( DR \) indicates the rate of deforestation, which can be calculated using the compound interest law recommended by the Food and Agriculture Organization (FAO 1995); \( DA_1 \) indicates forest area (in hectares) at \( t_1 \); and \( DA_2 \) indicates forest area (in hectares) at \( t_2 \).

As a composite variable, NPVᵢ^{FC} is the net present value (NPV) generated from harvesting one hectare of forest. This composite variable can be modelled as:

\[
NPV_i^{FC} = \sum_{i=1}^{N} \int_0^T \theta_i * A_i(t) e^{-\psi t} dt
\]

(6)

where NPVᵢ^{FC} (t) is the one-time timber harvest value, expressed in USD; \( A_i(t) \) is the annual net revenue of the \( i \)th agricultural activity permitted by the land conversion (expressed in USD); \( R_i(t) \) is the annual revenue of the \( i \)th agricultural activity permitted by the land conversion (expressed in USD). \( C_i(t) \) is the annual costs of the \( i \)th agricultural activity permitted by the land conversion (expressed in USD). \( T \) denotes the period over which the forest is protected (expressed in years). In the study we use 25 years which is an oil palm life span. For the expression \( \psi = \ln(1 + \gamma) \), \( \gamma \) is the discount rate. Finally, \( \theta_i \) is the ratio of \( \gamma \)th agricultural activity area to the total area.

Based on available data and data collection capacities, we used the gain-loss method to measure carbon emissions resulting from forest conversion. Relative to carbon stock inventories, the gain-loss method is more complex. This complexity is due to the development of growth models that incorporate an ecological understanding of how forests and other types of land use grow, as well as information related to natural processes and human actions that result in carbon losses. Ramankutty et al. (2007) suggested that forest emissions can be estimated as:

\[
C_i^{FC} = \int_1^T C_{f, net}^{FC}(t) dt = \int_1^T (C_{f, burn}^{FC}(t) + C_{f, decay}^{FC}(t)) dt
\]

(7)

where \( C_{f, net}^{FC}(t) \) is total flux from forest conversion; \( C_{f, burn}^{FC}(t) \) is burnt flux (figure 2(a)); \( C_{f, decay}^{FC}(t) \) is the fluxes of carbon from decay (figure 2(b)); and \( C_{f, plantations}^{FC}(t) \) is carbon flux from uptake from
Figure 1 shows the predicted future land use changes under the BAU scenario. Deforestation is distributed along rivers and roads, areas where humans can easily access. Moreover, terrestrial areas capable of high carbon storage are found in the East and are at high risk of deforestation. Therefore, meeting the emission reduction targets in these areas is critical and of utmost importance to REDD+. An important factor in anticipating future threats to carbon stocks is information on the rapidity of deforestation in these areas. Identifying, characterizing, and mapping areas not only provides precise information on their vulnerability to deforestation but also helps improve the design of conservation plans and budgets (Wilson et al. 2005).

Figure 2 shows carbon fluxes per unit in the study area derived from equations 7–16. Initial biomass values were determined using the values of Rahajoe (2009) from in situ forest inventories and permanent plantations (figures 2(c) and (d)). They are expressed in tC yr$^{-1}$.

Burnt flux is calculated as:

$$C_{f,burn}^{FC}(t) = \text{Bio}_{clear}(t) \times 0.2$$

where $\text{Bio}_{clear}(t)$ is the total biomass from deforestation and the biomass from cleared secondary vegetation (expressed in tC yr$^{-1}$). This can be calculated with the following formula:

$$\text{Bio}_{clear}(t) = \text{Bio}_{defore}(t) + \text{Bio}_{SF,clear}(t)$$

where $\text{Bio}_{defore}(t)$ is:

$$\text{Bio}_{SF,clear}(t) = \int_{t}^{t_{1}} \text{C}_{veg} \times 0.7 \times \tau / T \times A_{SF,clear}(t, \tau) d \tau$$

and $A_{SF}(t, \tau)$ represents the area of secondary forest for age-cohort $\tau$ at time $t$.

The fluxes of carbon from decay are determined by three pools that experience exponential decay: slash, product, and elemental pools. The dynamics of the carbon flux from the slash, product, and elemental pools can be expressed using the differential equation:

$$\frac{dC}{dt} = C_{in} - \lambda C$$

where $C_{in}$ is the transfer of carbon from deforestation, and $\lambda$ is the decay rate. The respective carbon dynamics for the various pools can be calculated using:

$$C_{\text{slash}}(t) = (1 - \lambda_{\text{slash}}) \times C_{\text{slash}}(t - 1) + C_{in,\text{slash}}(t)$$

$$C_{\text{prod}}(t) = (1 - \lambda_{\text{prod}}) \times C_{\text{prod}}(t - 1) + C_{in,\text{prod}}(t)$$

and the fluxes of carbon from the decay of these pools are calculated as:

$$C_{f,\text{decay}}^{FC}(t) = \lambda_{\text{slash}} C_{\text{slash}}(t - 1) + \lambda_{\text{prod}} C_{\text{prod}}(t - 1) + \lambda_{\text{elem}} C_{\text{elem}}(t - 1)$$

where $\lambda_{\text{slash}} = 0.1$, $\lambda_{\text{prod}} = 0.1$, and $\lambda_{\text{elem}} = 0.001$.

Over the course of period $T$, the carbon flux from uptake from plantation agriculture is:

$$C_{f,\text{plantations}}^{FC}(t) = \sum_{i=1}^{N} \theta_{i} \times C_{f,i}^{FC}(t)$$

where $\theta_{i}$ is the ratio of $i$th agricultural activity area to the total area.

### 3. Results

#### 3.1. Carbon emissions and net present values

Figure 1 shows predicted future land use changes under BAU scenario. Deforestation is distributed along rivers and roads, areas where humans can easily access. Moreover, terrestrial areas capable of high carbon storage are found in the East and are at high risk of deforestation. Therefore, meeting the emission reduction targets in these areas is critical and of utmost importance to REDD+. An important factor in anticipating future threats to carbon stocks is information on the rapidity of deforestation in these areas. Identifying, characterizing, and mapping areas not only provide precise information on their vulnerability to deforestation but also helps improve the design of conservation plans and budgets (Wilson et al. 2005).

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burnt flux from deforestation
regrowth flux from oil palm plantation
regrowth flux from rubber plantation
decay flux from deforestation

Figure 2. Carbon fluxes per unit in the study area.

sampling plots. Annual carbon stock changes in rubber plantations are derived from the work of Wauters et al. (2008) since the elevation, climate condition, soil, and management are very similar. Khasanah et al. (2015) conducted a study for the above ground carbon stock derived from 180 measurement plots from 25 plantations across all the major settings in which oil palm is found in Indonesia. Based on the largest data set available for Indonesian oil palm so far, this study provides recent and reliable data for our research. Ramankutty et al. (2007) indicate a slower release of carbon from the decay of slash, product, and elemental carbon pools, where the fraction of the initial amount of carbon in the pool decayed at a rate of 10%, 10%, and 0.1% per year, respectively. Based on field surveys, the total area used for rubber and oil palm plantations in the expanding agricultural land is 32.7% and 51%, respectively. According to Robert J Zomer’s study (2016) there is a linear relationship between density and percent canopy.

We collected the percentages of rice, rubber and oil palm in expanding agricultural land via field survey in 2010 in research area. Yamamoto and Takeuchi (2012) collected socioeconomic data via a field survey in 2010 and 2011 by visiting 211 households, including one-time net revenue from logging per hectare, net revenue from rubber plantations per hectare, price of rice and rubber. Net revenue from oil palm plantations per hectare is from the work by Fairhurst and McLaughlin in 2010. In this area, oil palm plantations produce yield from the 3rd year and are mature in the 10th year, and rubber plantations produce yield from the 11th year. Costs for plantations include labour force wages, transport fees, factory processing fees, and committed overhead costs (farm, factory, and general). One-time net revenue from logging per hectare is USD 830.

The projections of net present values gained from oil palm plantations, rice cultivation, rubber plantations, and logging using equation 6 indicate that oil palm plantations would produce USD 1.57 million in revenue over six years over 2693 ha, increasing to USD 15.2 million in 25 years over 11222 ha. We project that rubber plantations will produce USD 10.5 million after 25 years. Clearly, the cultivation of oil palm and rubber trees represents the most profitable set of activities for farmers. This has been the case in Indonesia for many years, as farmers first shifted from rice cultivation to rubber agroforests, followed by mono-crop plantations of rubber and oil palm trees (Feintrenie et al. 2010). Papenfus (2000) has shown that high returns combined with relatively low labour requirements for oil palm cultivation make it an attractive option for land use among famers.

3.2. MAC curves
MAC curves are broken into discrete ‘blocks;’ each block represents a type of land use option. For each
block (or land use option), the width indicates the amount of potential carbon emissions abatement, while the height estimates the marginal abatement cost per ton of the carbon emissions abatement. The blocks are ordered such that the lowest cost options are shown first on the left with subsequent higher cost options proceeding to the right. Aggregating these measures in the form of a cost curve allows for analysis of the potential for emissions reductions. The MAC curves for REDD+ we developed show estimates of the annual marginal abatement cost in USD per ton of avoided emissions of CO\(_2\), as well as the abatement potential of these approaches in tons of CO\(_2\).

Figure 3 is MAC curves of oil palm over 11222 ha. Abatement costs and potential abatement in MAC curves are calculated from the dynamic prediction land use model based on formula 1–16. In the model the percent canopy cover affects carbon density but does not affect potential agricultural area. From MAC curves in figure 3, we note that the first land use option A (from forest 30%–40% canopy to oil palm) offsets a very small volume of emissions (0.007 million ton CO\(_2\)) at a cost of abatement of USD 38.9 per ton of CO\(_2\). This is a very expensive option per ton of CO\(_2\) saved but it abates very little emissions, as is evidenced by the narrow width of the bar on the chart. The second land use option B (from forest 40%–60% canopy to oil palm) offsets a much larger volume of 0.03 million ton CO\(_2\) at a cost of USD 14.3 per ton CO\(_2\) abated. Implementation of this kind of land use option is less expensive; that is, the cost of this implementation will be USD 24.6 less than that offset by the resulting reduction from 'forest 30%–40% canopy to oil palm.' The third land use option C (from forest 60%–80% canopy to oil palm) is the next least-cost option, but requires an investment of USD 7.4 per ton CO\(_2\) abated. As we continue to move left along the MAC curve, we find that land use option D (from forest 80%–100% canopy to oil palm) has the maximum abatement potential among all options, which amounts to 0.35 million ton CO\(_2\) at USD 5.34 per ton CO\(_2\) abated. This is because the timber harvest plays a large part in the calculation of carbon emissions. Finally, options K, L and M on the other hand have negative costs per ton CO\(_2\), since these land use changes result in increases in carbon stocks, although the

| Land use change | Initial land use | Final land use |
|-----------------|------------------|----------------|
| A               | Forest 30%–40% canopy | Oil palm       |
| B               | Forest 40%–60% canopy | Oil palm       |
| C               | Forest 60%–80% canopy | Oil palm       |
| D               | Forest 80%–100% canopy | Oil palm       |
| E               | Forest 80%–100% canopy | Forest 40%–60% canopy |
| F               | Forest 60%–80% canopy | Forest 30%–40% canopy |
| H               | Forest 80%–100% canopy | Forest 10%–20% canopy |
| K               | Forest 10%–20% canopy | Oil palm       |
| L               | Rice              | Oil palm       |
| M               | Forest 20%–30% canopy | Oil palm       |

Figure 3. MAC curves of oil palm through combining various land use change options.
potential areas over which they could apply, and therefore their potential to contribute to overall carbon mitigation, are limited.

Similarly, from the MAC curve of rubber (figure 4), we note that land use option A (from forest 20%–30% canopy to rubber) at the rightmost is at a cost of abatement of USD 18.7 per ton of CO\textsubscript{2}—only about half of that from oil palm. Land use options B (from forest 30%–40% canopy to rubber) has less cost of abatement than that of from forest 20%–30% canopy to rubber, accounting for USD 8.64 per ton of CO\textsubscript{2}. The maximum abatement potential of the land use options included in rubber analysis amount to 0.41 million ton CO\textsubscript{2} from forest 80%–100% canopy to rubber plantation, at a cost of abatement of USD 3.22 per ton of CO\textsubscript{2}. Similarly, timber harvest plays a large part in the calculation of carbon emissions. The second ranking abatement potential is from forest 60%–80% canopy to rubber, accounting for 0.2 million ton CO\textsubscript{2}.

Figure 5 illustrates information in this study and from different sources of abatement costs.

### 3.3. Comprehensive analysis of MAC curves for cost-saving plantations

We use comprehensive analysis of MAC curves by combining price of international carbon credits, oil palm, rubber, and rice to model the overall economic implications of the results presented above. The price of international carbon credits was assumed to be USD 5.8 per ton CO\textsubscript{2}, adopted from voluntary carbon market (Molly P-S 2015). Our comprehensive MAC curves produce three categories of mitigation measures that are shown first negatively on the bottom with subsequent positively higher costs proceeding to the top; that is, cost-saving plantations, cost-effective plantations, and cost-prohibitive plantations.

The category of cost-saving plantations is shown in figure 6 below the x-axis on the left-hand side of the graph. The negative abatements costs are due to higher carbon density of the plantation crops compared to the original land use. In this study, we find that land use option from forest 10%–20% canopy to oil palm, from forest 20%–30% canopy to oil palm, and from forest 10%–20% canopy to rubber fit into this category. For example, abatement potential is −0.013 million ton CO\textsubscript{2} and −0.008 million ton CO\textsubscript{2}.

| Land use change | Initial land use | Final land use |
|----------------|-----------------|----------------|
| A              | Forest 20%–30% canopy | Rubber         |
| B              | Forest 30%–40% canopy | Rubber         |
| C              | Forest 40%–60% canopy | Rubber         |
| D              | Forest 60%–80% canopy | Rubber         |
| E              | Forest 80%–100% canopy | Rubber         |
| F              | Forest 80%–100% canopy | Forest 40%–60% canopy |
| G              | Forest 60%–80% canopy | Forest 30%–40% canopy |
| H              | Forest 80%–100% canopy | Forest 10%–20% canopy |
| I              | Rice             | Rubber         |
| J              | Forest 10%–20% canopy | Rubber         |

Figure 4. MAC curves of rubber through combining various land use change options.
Figure 5. Abatement costs from different sources.

Figure 6. Comprehensive analysis of MAC curves for cost-saving plantations.

From forest 10%–20% canopy and forest 20%–30% canopy to oil palm, with abatement costs of USD −5.16 per ton of CO₂ and USD −19.6 per ton of CO₂, respectively. For land use change from forest 10%–20% canopy to rubber, the abatement potential is only one-third of that from oil palm, with abatement costs of USD −12.03 per ton of CO₂.

For some land use options, the abatement costs per ton of carbon are less than the international price of carbon, and these are therefore called ‘cost-effective plantations’. This category includes land use options from forest 80%–100% canopy to oil palm, from forest 60%–80% canopy to rubber, from forest 80%–100% canopy to rubber, from forest 30%–40% canopy to rice, from forest 40%–60% canopy to rice, and from forest 60%–80% canopy to rice.

The category of cost-prohibitive plantations refers to those land use change options for which the abatement cost is higher than the price of international carbon credits, on the right-hand side of the graph. We find that land use option from forest 30%–40% canopy to oil palm, from forest 40%–60% canopy to oil palm, from forest 60%–80% canopy to oil palm, from forest 80%–100% canopy to oil palm, from forest 20%–30% canopy to rubber, from forest 30%–40% canopy to rubber and from forest 40%–60% canopy to rubber fit into this category.

In the comprehensive MAC curves above, cost-saving plantations and cost-effective plantations account for an abatement potential of −0.05 and 1.65 million ton CO₂, over 1144 ha and 18878 ha respectively. The remaining 0.26 million ton CO₂ of abatement potential over 1983 ha is associated with costs in excess of the price of carbon credits, and hence, deemed cost-prohibitive plantations. The three categories together give a total abatement potential of 1.91 million ton CO₂ per annum which means that there is 1.86 million tons of abatement potential.
from avoiding forest transitions and 0.05 million tons of abatement from maintaining transitions that are already occurring/will occur (or, that would be lost if the transitions were to cease).

3.4. Sensitivity analysis using different discount rates
The discount rate measures time preference and, thus, a higher discount rate will result in lower future REDD+ benefits. Since REDD+ projects have a certain oil palm life span in this study, economic calculations for plantations with such long payback are especially sensitive to discount rate. A discount rate of 10%, which is based on the real interest inflation rate currently available in Indonesia, is used to compare costs incurred at different discount rates. We calculate NPVs using lower discount rates of 2.5% and 5%, and higher discount rates of 15% and 20%. We find that the changes of NPV slow down as discount rates increase. For example, NPV decreases by 47% when the discount rate increases from 5% to 10%. In contrast, it decreases by 23% as the discount rate increase from 15% to 20%.

4. Policy remarks
In this study, we developed a methodology for constructing MAC curves for REDD+ to demonstrate a quantitative visualization of land use options. More specifically, we identified three categories of mitigation measures using a comprehensive analysis of MAC curves: cost-saving plantations, cost-effective plantations, and cost-prohibitive plantations. A careful assessment in Central Kalimantan, Indonesia provided significant insights into abatement costs and potential from tree crop plantations for developing countries. Our study has the following implications.

1. Tree crop plantations and their expansion in Southeast Asia are regarded as the direct cause of a host of ecological problems, such as significant carbon reduction from deforestation (Carlson et al 2012, McCarthy 2010). Carefully and thoroughly—judging the sustainability of agroecosystem development requires calculating the carbon footprint of plantations. Carbon debt is incurred where plantations result in lower carbon densities than the land uses they replace. Moreover, the effect of plantations depends on the local situation. For example, it is negative when plantations are grown on deeply drained peat soils converted from forest (Adachi et al 2011, Davis et al 2013), but positive when they are grown on lands already deforested (Choo et al 2011, George and Cowie 2011, Hassan et al 2011). In this study, the MAC curve analysis implies that implementing some land use options—such as from forest 10%–20% canopy to oil palm, from forest 20%–30% canopy to oil palm, and from forest 10%–20% canopy to rubber—can contribute to carbon sequestration. Therefore, careful land use planning based on MAC curves analysis could help to reduce carbon emissions. A carbon threshold for forest land conversion, which meets zero or low carbon emissions criteria as mechanisms for steering plantations away from high carbon forests, should be developed for achieving carbon reduction target of REDD+ policy.

2. Within the REDD+ framework, forest carbon can provide attractive investment opportunities from a financial perspective. Our analysis supports this by showing that implementing land use options below the price of international carbon credits could annually reduce 1.65 million ton CO₂ emissions over 18878 ha. Our finding implies that avoiding emissions from deforestation in research area may provide cost effective land use options for climate mitigation. Our estimate is in good agreement with other on-the-ground empirical estimates (Graham et al 2016, Venter et al 2009). The estimate here is lower than the abatement costs of REDD+ from a number of other studies, since these studies are based on global partial equilibrium models (McKinsey and Company 2010, UNFCCC 2007) which consider effects of leakage.

Moreover, we also find that there is wide range of land use options in cost effective category, compared to the cost prohibitive category. It includes land use options from forest 80%–100% canopy to oil palm, from forest 60%–80% canopy to rubber, from forest 80%–100% canopy to rubber, from forest 30%–40% canopy to rice, from forest 40%–60% canopy to rice, and from forest 60%–80% canopy to rice. This means that there appear to be significant opportunities for tree plantation farmers to avoid the emissions that result from clearing forest for such activities, by participating in the REDD+ compensation mechanism.

Finally, MAC curves for REDD+ may differ from one area to another area because economic costs and savings, and emission from different sources are very different in vast geographic and socioeconomic background. Therefore, they do not reflect generalized land use options for different areas. MAC curves for REDD+ is unique to each area. The emissions profile, costs, and benefits are contextualized, for example, population, emission target, and land change patterns. Thus, there is no universal solution for REDD+ policy. However, the application of MAC curves for REDD+ in our study provides insights to include the optimization of land utilization in support of leveraging financial resources for the implementation of REDD+ strategies. In doing so, in other forest areas of the world, MAC curves for REDD+ could drive climate policy discussions for forest-related mitigation actions.
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