The Potential of REDD+ for Carbon Sequestration in Tropical Forests: Supply Curves for carbon storage for East-Kalimantan*

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PRELIMINARY VERSION

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ABSTRACT

We study the potential of tropical multi-age multi-species forests for sequestering carbon in response to the financial incentives from REDD+. This paper is the first to develop a Hartman model with selective cutting in this setting that takes additionality of carbon sequestration explicitly into account. The use of reduced impact logging techniques (RIL) allows a forest owner to apply for carbon credits whereas the use of conventional logging techniques (CL) does not. We apply the model using data for East Kalimantan. RIL leads to less damages on the residual stand than CL and has lower variable but higher fixed costs. We present forest carbon supply curves that show that at low carbon prices, carbon storage can increase by 17%. Depending on the interpretation of our steady state model, it can be optimal not to harvest either already at modest carbon prices or only when carbon prices are quite high. We also find that awarding carbon credits for carbon stored in end-use wood products may be harmful for forest owners.

Keywords: REDD+, climate policy, carbon sequestration, sustainable forest management, reduced impact logging, optimal forest management, carbon price

1. INTRODUCTION

Forests play an important role in the carbon cycle and may be a low cost option to offset carbon emissions (Richards and Stokes, 2004; van Kooten and Sohngen, 2007; Kindermann *et al.*, 2008). At the 16th Conference of the Parties (CoP 16) of the UNFCCC in Cancun forestry practices have been acknowledged as a means to offset carbon emissions. It has been agreed to consider reduced emissions from deforestation and forest degradation (REDD), including reduced emissions through conservation of forest carbon stocks combined with sustainable management of forests (SFM), and the enhancement of forest carbon stocks (so-called REDD+).

Through intensively planned and carefully controlled timber harvesting, conducted by trained workers, reduced impact logging (RIL) practices (Zimmerman and Kormos, 2012) decrease the deleterious impacts of logging on the residual stand and, ceteris paribus, retain a larger growing stock and therefore additional carbon in the remaining forest stand as compared to conventional logging (CL) practices (Putz and Pinard, 1993; Pinard and Putz, 1996; Putz *et al.*, 2008). While previous literature has studied the effects of carbon storage and biodiversity constraints on optimal cutting cycles (Ingram and Buongiorno, 1996; Boscolo and Buongiorno, 1997), the potential of carbon financing through REDD+ on forest carbon sequestration in tropical forests has not been studied systematically.

In this paper, we analyze the potential of REDD+ to induce carbon sequestration and present supply curves for carbon storage in a tropical multi-age, multi-species forest; that is, fora range of prices of carbon credits we show the corresponding amount of carbon stored in above-ground biomass. It is the first paper that develops a Hartman model for multi-age, multi-species forests and analyzes the tradeoffs between timber revenues and income from carbon credits for a tropical forest. Carbon credits are only granted under RIL while the amount of carbon stored under CL practices in the absence of carbon financing serves as a benchmark. Hence we take additionality explicitly into account. We also explicitly consider the case where no harvesting takes place. We use detailed data on the characteristics of a multi-age, multi-species forest in East-Kalimantan, Indonesia, and solve the model for a range of carbon prices. Our data allow us to develop a detailed model in which the damage from harvesting on the residual stand depends on harvest intensity, forest density and logging technique, and differs across diameter classes (Macpherson et al. 2010). Furthermore we have detailed data on fixed and variable harvest costs according to which RIL has slightly lower variable costs than CL but higher fixed costs. Following the rules of existing voluntary schemes for forest carbon sequestration an additional novel element of our paper is the study of the effect of payments for carbon stored in end-use wood products such as building materials. As we will show, additionality plays a crucial role in determining whether receiving credits for carbon stored in end-use wood products is beneficial for land owners, while explicit modeling of the 'no harvest' case has important ramifications for the interpretation of supply curves for carbon storage. Our carbon supply curves can be used in simulation models for mitigation policies (see e.g. (Bosetti et al., 2011; Rose and Sohngen, 2011; Sohngen and Mendelsohn (2003))).

The effects of carbon payments on timber harvesting regimes have been studied extensively for plantation forests. Van Kooten et al. (1995) analyze the effect of carbon payments on the optimal management of boreal and coastal forest in Canada. Galinato and Uchida (2011) and Olschewski and Benitez (2010) study the effects of the temporary and long term credits under the Clean Development Mechanism (CDM) in plantation forest in tropical countries while Köthke and Dieter (2010) study the effects of various carbon crediting schemes on forest management for an even-aged spruce stand in Germany. Boscolo et al. (1997) and Buongiorno *et al.* (2012) study carbon storage in un-even aged multi-species forests, but neither allows for optimizing behavior of forest owners. In addition, Buongiorno *et al.* (2012) study a forest in the northern hemisphere dominated by Norway spruce. The common finding is that an increasing carbon price leads to larger amounts of carbon stored in forests. However, none of these papers studies the incentives stemming from REDD+ where payments are received only for additional carbon stored as compared to a baseline, nor do they take into account payments for carbon stored in end-use wood products.

The remainder of this paper is organized as follows. We first describe the forest growth model and the economic optimization model. Next we parameterize the model in section 3. We present our results in section 4 and conclude in section 5.

2. MODEL

2.1. Forest Growth Model

To describe the forest dynamics we use a matrix stand growth model. Such models are extensions of population growth models applied to forest stands (Buongiorno and Michie, 1980) and have been applied to tropical forest stands to study management strategies for maximizing economic returns (Ingram and Buongiorno, 1996; Boscolo and Buongiorno, 1997; Boscolo and Vincent, 2000).

At time t a forest stand is represented by column vector $\mathbf{y}_t = [y_{ijt}]$, where y_{ijt} is the number of trees per ha of species (or species group) $i, k \in \{1, \dots, m\}$ and diameter class $j \in \{1, \dots, n\}$. The harvest is represented by vector $\mathbf{h}_t = [h_{ijt}]$. A tree that lives in species group i and diameter class j at time t will at time $t + \theta$ either: (1) die, which happens with probability o_{ij}, (2) stay alive and move up from class j to class $j + 1$, which happens with probability b_{ij}, or (3) stay alive in the same diameter class j, which happens with probability $a_{ij} = 1 - b_{ij} - o_{ij}$. Parameter θ represents the growth interval, i.e. the length of growth period in years.

We use I_{it} to denote the expected ingrowth, i.e. the number of trees entering the smallest size class of species groups i during interval θ. The stand state at time $t + \theta$ is determined by the stand at time t, the harvest at time t, and the ingrowth during interval θ. Ignoring damages from harvesting at the moment, each species in the stand is represented by the following n equations:

$$y_{i\,1\,t+\theta} = I_{it} + a_{i1}(y_{i1t} - h_{i1t}) \tag{1}$$

$$y_{i2t+\theta} = b_{i1}(y_{i1t} - h_{i1t}) + a_{i2}(y_{i2t} - h_{i2t})$$

$$\dots$$

$$y_{i\,n\,t+\theta} = b_{i\,n-1}(y_{i\,n-1\,t} - h_{i\,n-1\,t}) + a_{in}(y_{int} - h_{int})$$

Ingrowth I_{it} is affected by the conditions of the stand (i.e. basal area and number of trees). The ingrowth function is a function of basal area B_{ij}, the initial stand and the harvest:

$$I_{it} = \beta_{0i} - \beta_{1i}\sum_{j=1}^{n} B_{ij}\left(y_{ijt} - h_{ijt}\right) + \beta_{2i}\ \sum_{j=1}^{n}\left(y_{ijt} - h_{ijt}\right), \tag{2}$$

$\beta_{0i}, \beta_{1i}, \beta_{2i} > 0$. Substituting Eq. (2) into the first equation of (1) gives:

$$y_{i\,1\,t+\theta} = \beta_{0i} + e_{i1}(y_{i1t} - h_{i1t}) + \cdots + e_{in}(y_{int} - h_{int}) \tag{3}$$

where:

$$e_{i1} = a_{i1} + \beta_{1i}B_{i1} + \beta_{2i} \tag{4}$$

$$e_{ij} = \beta_{1i}B_{ij} + \beta_{2i} \text{ for } j > 1 \tag{5}$$

Ignoring damage for the time being, the stand state after harvest is:

$$\mathbf{y}_{t+\theta} = \mathbf{G}(\mathbf{y}_t - \mathbf{h}_t) + \mathbf{c} \tag{6}$$

where

$$\mathbf{G} = \mathbf{A} + \mathbf{R} \tag{7}$$

and

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}_1 & 0 & \dots & 0 \\ 0 & \mathbf{A}_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \mathbf{A}_m \end{bmatrix};\ \ \mathbf{A}_i = \begin{bmatrix} a_{i1} & & & 0 \\ b_{i2} & a_{i2} & & \\ & \ddots & \ddots & \\ 0 & & b_{in} & a_{in} \end{bmatrix} \tag{8}$$

$$\mathbf{R} = \begin{bmatrix} \mathbf{R}_{11} & \mathbf{R}_{12} & \dots & \mathbf{R}_{1m} \\ \mathbf{R}_{21} & \mathbf{R}_{22} & \dots & \mathbf{R}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{R}_{m1} & \mathbf{R}_{m2} & \dots & \mathbf{R}_{mm} \end{bmatrix};\ \ \mathbf{R}_{ik} = \begin{bmatrix} e_{i1} & e_{i2} & \dots & e_{in} \\ 0 & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 0 \end{bmatrix} \tag{9}$$

$$\mathbf{c} = \begin{bmatrix} \mathbf{c}_1 \\ \mathbf{c}_2 \\ \vdots \\ \mathbf{c}_m \end{bmatrix};\ \ \mathbf{c}_i = \begin{bmatrix} \beta_{i0} \\ 0 \\ \vdots \\ 0 \end{bmatrix} \tag{10}$$

Matrix $\mathbf{G}$ is the growth matrix. $\mathbf{A}$ is an mn x mn matrix consisting of upgrowth matrices $\mathbf{A}_i$ for species i. It represents the probability of a tree to stay alive in the same diameter class j, move up the next diameter class $j+1$, or die. Ingrowth matrix $\mathbf{R}$ is an mn x mn matrix representing the effect of stand structure on the probability of a tree entering the smallest diameter class in one growth period. Vector $\mathbf{c}$ contains the ingrowth constants representing the number of trees exogenously entering the smallest diameter class for each species.

2.2. Maximizing Timber Revenues

The unit of analysis in this study is one hectare of a forest stand. The economic harvesting decision involves three variables: (i) the type of harvesting practice, i.e. CL or RIL (Dwiprabowo *et al.*, 2002; Boltz *et al.*, 2003), (ii) the length of the cutting cycle (Chang, 1981), and (iii). For a given cutting cycle T we can formulate the problem of maximizing the land expectation value (LEV) over an infinite horizon subject to damage, harvest and steady state equilibrium constraints:

$$\max_{\mathbf{y}_T,\mathbf{h}_T} LEV = \frac{\mathbf{v}_s{}'\mathbf{h}_T - F_s}{(1+r)^T - 1} - \mathbf{v}_s{}'\mathbf{z}_T \tag{11}$$

subject to

$$\mathbf{z}_T = (\mathbf{y}_T - \mathbf{h}_T - \mathbf{d}_{sT}) \tag{12}$$

$$\mathbf{d}_{sT} = f_s(h_{ijT}, y_{ijT}) \tag{13}$$

$$\mathbf{y}_{t+\theta} = \mathbf{G}\mathbf{z}_t + \mathbf{c} \tag{14}$$

$$\mathbf{y}_{t+2\theta} = \mathbf{G}(\mathbf{y}_{t+\theta}) + \mathbf{c} \tag{15}$$

$$\ldots$$

$$\mathbf{y}_{t+\gamma\theta} = \mathbf{G}(\mathbf{y}_{t+\theta(\gamma-1)}) + \mathbf{c} \tag{16}$$

$$\mathbf{y}_T \geq \mathbf{h}_T + \mathbf{d}_{sT} \tag{17}$$

$$\mathbf{h}_T, \mathbf{y}_T, \mathbf{z}_T \geq 0 \tag{18}$$

$$h_{ij} = 0 \text{ for all } j < \eta \tag{19}$$

$$\mathbf{y}_t = \mathbf{y}_{t+\gamma\theta} \text{ for all } t = 1, \ldots, \infty \tag{20}$$

Vector $\mathbf{v}_s$ represents the value of the trees (i.e. price minus variable costs and taxes) under logging practice $s \in \{\text{CL}, \text{RIL}\}$, where v_{ij} is the value of a tree of species i in diameter class j. F_s represents the fixed costs per ha of harvesting using harvesting practice s; r represents the real discount rate; $\mathbf{z}_t$ represents residual stand after harvest, where z_{ij} is the number of trees of species *i* that remain in diameter class j after harvest; and γ is the number of growth periods θ within the harvesting cycle *T*. Equation (11) represents the value of the land, that is, the net present value of all projected revenues and costs over an infinite time horizon of identical forest rotations net of the opportunity cost of not harvesting the remaining stand. Equation (13) represents the damage on the residual stand caused by harvesting activities. The damage to the residual stand is a function of overall harvest intensity and is represented by the mn x 1 vector, $\mathbf{d}_{sT}$. Equations (14)-(16) represent the growth of the forest. Equations (17) and (18) are the harvest and non-negativity constraints. In Equation (19), the harvesting policy constraint, η is the minimum diameter eligible for cutting as set by government regulation. Equation (20) shows the equilibrium steady state constraint.

2.3. Maximizing Timber and Carbon Revenues

Forests can simultaneously produce timber and sequester carbon from the atmosphere. Hartman (1976) was the first to study non-timber benefits in an infinite rotation model. Hartman's model has been applied to timber production and carbon sequestration in plantation forests (Köthke and Dieter, 2010; Olschewski and Benitez, 2010; Galinato and Uchida, 2011). Buongiorno *et al.* (2012) applied it to an uneven-aged multi-species forest, implicitly assuming linear growth in stored carbon and ignoring the fact that carbon credits are usually only awarded for carbon stored beyond the amount of carbon stored in a business-as-usual scenario (that is, ignoring the additionality criterion for carbon financing). Here we use Hartman's model in a multi-age multi-species tropical forest with selective cutting in Indonesia. We follow the REDD+ scheme where carbon stored in the forest (or in end-use wood products) can only be credited when it exceeds the baseline level.

2.3.1. Carbon Revenues from Tree Biomass

In the recent forest economics literature that considers carbon revenues it is commonly assumed that the forest owner is periodically paid for the carbon uptake of trees, and taxed when carbon is released through harvest or decay (Köthke and Dieter, 2010). Whereas carbon storage grows through tree growth and biomass accumulation, it decreases with harvest. Revenues from payments for retaining carbon stored in forest biomass can change the optimal harvesting intensity, the cutting cycle, and the type of logging technique. We use a baseline to determine additionality of carbon storage. The baseline is the average amount of greenhouse gases that is stored in above ground biomass under CL calculated over one rotation. Although trees store carbon, not CO_2, we report quantities of greenhouse gases stored in tons of CO_2 throughout the paper as we express the price of carbon credits in USD/tCO_2. This allows for comparison with observed market prices for carbon credits. We assume that verification and payments for carbon storage take place every θ years and carbon credits are awarded for the amount of CO_2 stored at the instant of verification. The carbon credits expire after θ years and are hence temporary credits (cf. the tCERs for afforestation or reforestation project activities under the CDM).[i] Forest owners get paid for carbon stored above the amount stored under a baseline and hence we subtract the value of the carbon stored in the case of optimal forest management when the forest owner uses conventional logging techniques and does not receive carbon credits (cf. equation (11) with $s = \mathrm{CL}$). The LEV maximization problem under this payment scheme is written as follows:

$$\max_{\mathbf{y}_T,\mathbf{h}_T} LEV = \frac{\mathbf{v}'_{RIL}\mathbf{h}_{T_{RIL}} - F_{RIL}}{(1+r)^{T_{RIL}}-1} - \mathbf{v}'_{RIL}\mathbf{z}_{T_{RIL}} + \frac{p\boldsymbol{\chi}'\sum_{t=\theta}^{T_{RIL}}\mathbf{y}_{RIL,t}(1+r)^{T_{RIL}-t}}{(1+r)^{T_{RIL}}-1} - \frac{p\boldsymbol{\chi}'\sum_{t=\theta}^{T_{CL}}\bar{\mathbf{y}}_{CL,t}(1+r)^{T_{CL}-t}}{(1+r)^{T_{CL}}-1} + p\boldsymbol{\chi}'\left(\mathbf{z}_{T_{RIL}} - \bar{\mathbf{z}}_{T_{CL}}\right) \tag{21}$$

The first two terms in Equation (21) are the same as the terms in Equation (11) and denote the net present value of profits from timber sales over an infinite time horizon net of the opportunity costs of not harvesting the remaining stand. The third term denotes the value of the carbon stored over an

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[i] The relation between the price of carbon credits from temporary carbon projects where payment starts at $t = \theta$ and takes place every θ years, p, and the price of permanent projects, such as the price in the EU ETS, p_∞, can be expressed as follows: $p = p_\infty\left((1+r)^\theta - 1\right)$

infinite horizon, where vector $\boldsymbol{\chi}$ represents the amount of CO_2 stored in above-ground forest biomass (AGB) per tree of species *i* and diameter class *j*. The fourth term denotes the value of the carbon stored under the baseline (indicated by a bar over the vector denoting the stand): it is subtracted from the value of the carbon stored in the presence of a carbon credit scheme to take additionality of the project into account. The final term denotes the benefit from carbon stored in the remaining stand.

Equation (21) applies to cases with positive harvest (i.e. $h_{ij} > 0$ for some i and *j*). However, when carbon prices are sufficiently high it may be preferable not to harvest at all ($\mathbf{h} = \mathbf{0}$). In this case the LEV is given by

$$LEV = \frac{p\boldsymbol{\chi}'\mathbf{y}_{climax}(1+r)}{(1+r)-1} - \mathbf{v}'_{RIL}\mathbf{z}_{T_{RIL}} - \frac{p\boldsymbol{\chi}'\sum_{t=\theta}^{T_{CL}}\bar{\mathbf{y}}_{CL,t}(1+r)^{T_{CL}-t}}{(1+r)^{T_{CL}}-1} \tag{22}$$

The first term of Equation (22) is the value of CO_2 stored in the forest over an infinite time horizon. The second term of Equation (22) reflects the opportunity costs: the value of timber in the stand which is the value of timber in the climax forest, because there is no harvest. The last term of Equation (22) is the value of CO_2 stored under CL, our baseline.

2.3.2. Carbon Revenues from Tree Biomass and End Use Wood Products

As carbon is not only stored in trees but also in end-use wood products (EWP) for some period of time, we model the additional income from payment of carbon from EWP. Under the same payment scheme, the LEV maximization problem with additional income from EWP is written as follows:

$$\max_{\mathbf{y}_T,\mathbf{h}_T} LEV = \frac{\mathbf{v}'_{RIL}\mathbf{h}_{T_{RIL}} - F_{RIL}}{(1+r)^{T_{RIL}}-1} - \mathbf{v}'_{RIL}\mathbf{z}_{T_{RIL}} + \frac{p\boldsymbol{\chi}'\sum_{t=\theta}^{T_{RIL}}\mathbf{y}_{RIL,t}(1+r)^{T_{RIL}-t}}{(1+r)^{T_{RIL}}-1} - \frac{p\boldsymbol{\chi}'\sum_{t=\theta}^{T_{CL}}\bar{\mathbf{y}}_{CL,t}(1+r)^{T_{CL}-t}}{(1+r)^{T_{CL}}-1} + p\boldsymbol{\chi}'\left(\mathbf{z}_{T_{RIL}} - \bar{\mathbf{z}}_{T_{CL}}\right) + \frac{p\boldsymbol{\chi}'\omega\zeta(1+\delta)(1+r)}{[(1+\delta)(1+r)-1]}\left(\frac{\mathbf{h}_{T_{RIL}}(1-u_{RIL})}{(1+r)^{T_{RIL}}-1} - \frac{\bar{\mathbf{h}}_{T_{CL}}(1-u_{CL})}{[(1+r)^{T_{CL}}-1]}\right) \tag{23}$$

The first five terms are equal to the terms in Equation (21). The last term in Equation (23) denotes the value of CO_2 stored in EWP in RIL minus the value of CO_2 stored in EWP under the baseline.

Note that $\bar{\mathbf{h}}_{T_{CL}}$ is the number of the trees harvested under CL at time T when the LEV from timber revenues only is maximized.

Phat *et al.* (2004) point out that not all harvested timber will be used in EWP, but a proportion u_s will be wasted due to logging, skidding, and transportation activities. From the remaining timber arriving at the sawmill, only a proportion ω is used in EWP. We assume that the carbon stored in logging waste u_s and end-use wood waste $(1-\omega)$ is released immediately after harvesting and wood processing. Winjum *et al.* (1998) suggest that from total EWP, a proportion of ζ will be oxidized annually with the oxidation rate of δ, and the remaining fraction (i.e. $1-\zeta$) will completely oxidize in year 0.

3. PARAMETERIZATION OF THE MODEL

3.1. Forest Growth Data

We use the growth matrix developed by Krisnawati *et al.* (2008) for lowland dipterocarp forest in Kalimantan. The data from Krisnawati *et al.* (2008) were collected 190 – 225 m above sea level. The soil type is dominated by podzolic soils. The climate is classified as type A (Schmidt and Ferguson classification) with an annual precipitation rate of 3,520 mm (Samsoedin et al., 2009). The highest and lowest average monthly temperatures are 27.4^{o}C and 24.3^{o}C respectively. The forest is dominated by dipterocarp species including *Shorea sp* and *Dipterocarpus sp.* We use a growth period of 2 years ($\theta = 2$) because observations by Krisnawati *et al.* (2008) were conducted in 1 and 2 years, and the authors found that the observation period of 2 years could produce more accurate data for the increment of tree diameter and volume. We consider three species groups in the growth matrix with $i = 1$ for commercial dipterocarp, $i = 2$ for commercial non-dipterocarp, and $i = 3$ for non-commercial species. Each species group consists of 13 5-centimeter diameter classes ($j = 1$ for 10-14 cm, up to $j = 13$ for $>$ 70 cm).[ii] The complete growth matrices are presented in Appendix 1. Short term validation of the growth model was done by Krisnawati *et al.*

[ii] Diameters are measured at breast height (DBH).

(2008), who concluded that the predicted number of trees in each species and diameter class are not significantly different from the observed values. Following Bollandsas *et al.* (2008), we conduct the long term validation by simulating the matrix growth model without harvesting for 1000 years starting from bare land. Figure 1 shows the development of basal areas of the forest. The climax forest is reached around year 300 and has a basal area of 26.4 m^2/ha with a volume of 330 m^3/ha and 661 tons of CO_2 (251 tons of carbon) stored per ha in above-ground biomass. This predicted climax forest is similar to the basal area of 25 m^2/ha and the 214 ton/ha of carbon stored in above-ground biomass in the climax forest resulting from the growth matrix used in Boscolo and Buongiorno (1997) and Boscolo and Vincent (2000) and slightly thinner than the virgin forest measured in Kalimantan by Sist *et al.* (2003b) and Sist *et al.* (2003a), which has a basal area of ± 30 m^2/ha.

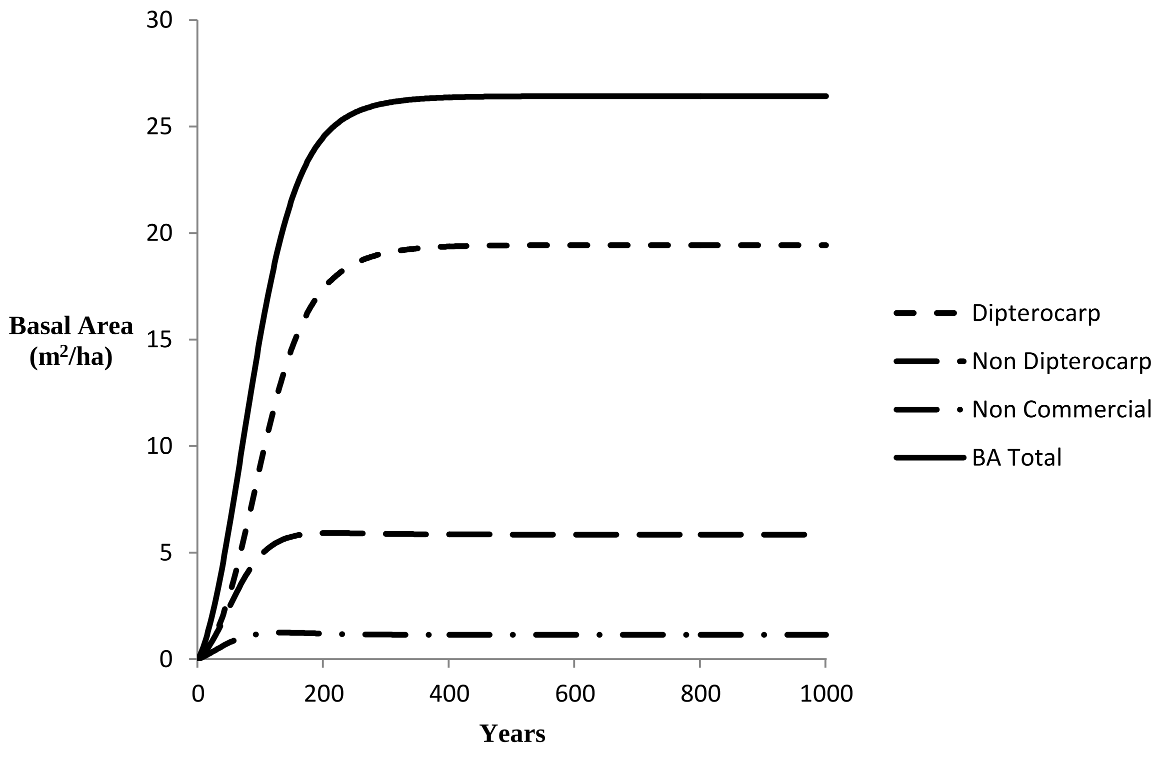

Figure 1. Predicted basal area (BA) of commercial dipterocarp, commercial non-dipterocarp and non-commercial species without harvest.

The dipterocarp species dominates the stand of the climax forest with a basal area of 19.4 m^2/ha (74%), whereas the basal areas of the commercial non-dipterocarp and non-commercial species are 5.8 m^2/ha (22%) and 1.1 m^2/ha (4%) respectively. The growth matrix of Krisnawati *et al.* (2008) was developed in a logged-over forest with high felling intensity. Since the growth rate of dipterocarp is faster than non-dipterocarp species (Vanclay, 1994; Priyadi *et al.*, 2007), the number of trees from dipterocarp species will dominate the stand composition of the climax forest.

3.2. Harvest Damage Relation

Following the approach by Macpherson *et al.* (2010), the number of trees damaged because of harvesting activities is $\mathbf{d}_{sT} = \left(\sum_i \sum_j h_{ijt}\right)\mathbf{D}_s\mathbf{y}_t$, where $\mathbf{D}_s$, a damage matrix, is an mn x mn matrix where the diagonal contains the logging damage coefficients under logging practice s. The damage coefficients represent the proportion of trees killed per tree harvested within each species group i and size class j. Matrix $\mathbf{D}_s$ consists of damage coefficient matrices $\mathbf{E}_s$ and null matrices:

$$\mathbf{D}_s = \begin{bmatrix} \mathbf{E}_s & & 0 \\ & \mathbf{E}_s & \\ 0 & & \mathbf{E}_s \end{bmatrix}$$

According to the CIFOR data (Priyadi *et al.*, 2007) we used to generate $\mathbf{D}_s$, RIL reduces damages per tree harvested as compared to conventional logging with 17% on average over all diameter classes, and with 25% on average for all trees of 50 cm diameter and larger. The matrices $\mathbf{E}_s$ are presented in Appendix 1. The data from Priyadi *et al.* (2007) come from experimental plots in Kalimantan, where different logging practices have been applied. In their study, the minimum-diameter harvested is 50 cm, based on the Indonesian selective logging system (TPTI) that was applied until 2009. For our simulations we follow the new Indonesian selective logging system, effective since 2009 and set the minimum diameter for harvest at $\eta = 40$ cm (Ministry of Forestry, 2009b).

3.3. Economic Parameters

We use production cost parameters reported by Dwiprabowo *et al.* (2002) for CL and RIL for a tropical forest concession on East-Kalimantan.[iii] The investment and administration costs data were collected from a technical proposal of a company in Kalimantan (PT Sumalindo Lestari Jaya, 2008).[iv] The gross prices of timber per m^3 are based on standard prices determined by the Indonesian government in which commercial species are sorted into two groups: dipterocarp and non-dipterocarp.[v] The net price $\mathbf{v}_s$ is the gross price of timber minus the variable costs, fees, and taxes per cubic meter. Total variable costs are slightly lower for RIL than for CL (46.4 USD/m^3 vs 44.8 USD/m^3) due to lower skidding costs (Dwiprabowo et al., 2002). The resulting net price (standard price minus variable costs and taxes) is 59 USD/m^3 for dipterocarp and 32 USD/m^3 for non-dipterocarp for CL, and 61 USD/m^3 for dipterocarp and 34 USD/m^3 for non-dipterocarp for RIL. The fixed costs per harvest for RIL are substantially higher than those for CL (390 and 297 USD/ha per harvest respectively). The fixed costs differ as a result of different machines used and additional pre-harvesting activities with RIL such as data checking and mapping, skid trail marking and checking, software purchasing, vine cutting, and improved timber inventory and contour survey (Dwiprabowo et al., 2002). Our data are similar to data from Boltz *et al.* (2001) in that the variable costs are higher for CL and the fixed costs are higher for RIL. The details of the cost parameters and taxes used in this study are presented in Appendix 2. We use a discount rate of 4% for our main analyses, based on the average real interest rate for Indonesia for the past 20 years.[vi]

3.4. Timber Volume and Carbon Stored in Tree Biomass

We estimate wood volume based on the formula developed by Enggelina (1998) for dipterocarp and non-dipterocarp species in Kalimantan. Because there are no data for wood volume

[iii] We express values in USD of 2012, using an average inflation rate of 7.6% for 2002-2012 and an exchange rate of 1 USD = 9.387 IDR for 2012 (World Bank World Development Indicators).
[iv] We express values in USD of 2012, using an average inflation rate of 4.9% for 2009-2012 and an exchange rate of 1 USD = 9.387 IDR for 2012 (World Bank World Development Indicators).
[v] Ministry of Trade Decree No 22/M-DAG/PER/4/2012. The dipterocarp species price used is 1.270.000 IDR/m^3 and the price for commercial non-dipterocarp is 953.000 IDR/m^3.
[vi] Source: World Bank World Development Indicators.

estimation for non-commercial species, we assume that the formula for wood volume estimation for non-dipterocarp can also be applied for non-commercial species.

The amount of greenhouse gases stored in AGB is calculated as follows: $\boldsymbol{\chi} = \mathbf{AGB} \times \sigma \times 44/12$, where vector $\mathbf{AGB}$ is the vector of above-ground biomass weight, σ is the fraction of total weight stemming from carbon, and $44/12$ is the ratio of molecular mass of CO_2 to the atomic mass of carbon. To estimate the amount of above-ground biomass for diameter class j of each species, we take the middle point of the respective diameter class and use the following allometric equation (Chave *et al.*, 2005) where DBH refers to the diameter at breast height:

$$AGB_j = \rho \exp\left(\alpha_0 + \alpha_1 \ln\overline{DBH_j} + \alpha_2 \ln\overline{DBH_j}^2 + \alpha_3 \ln\overline{DBH_j}^3\right) \tag{24}$$

where $\alpha_0, \alpha_1, \alpha_2,$ and α_3 are coefficients, $\overline{DBH_j}$ represents the middle point of the diameter values in diameter class j, and ρ represents the wood density.

Above-ground dry weight biomass is estimated using equation (24) with parameter values α_0 = -1.499, α_1 = 2.148, α_2 = 0.207, α_3 = -0.0281 (Chave *et al.*, 2005), and ρ = 0.68 (Rahayu *et al.*, 2006). In equations (21) and (23), we take u_s equal to 0.262 and 0.462 for RIL and CL respectively (Sist and Saridan, 1998). Wood processing efficiency ω is assumed to be 50% (Ministry of Forestry, 2009a). Because wood from dipterocarp trees has a relatively high density (Basuki *et al.*, 2009), end-use wood is assumed to be 100% for sawn wood. The proportion of EWP that is oxidized immediately $(1-\zeta)$ is 0.2 while the remainder oxidizes with an annual rate δ of 0.02 (Winjum *et al.*, 1998). The proportion of carbon stored in tree biomass, σ, is 0.47 (IPCC, 2006).

3.5. Solving the Model

Depending on the context (maximize LEV from timber revenues only; include payments for carbon stored in AGB; include payments for carbon stored in EWP), we solve Equations (11), (21), or (23) with equations (12) - (20) as constraints for $\gamma \in \{1,2,\dots,51\}$ using the Excel Solver. We use the Generalized Reduced Gradient (GRG) nonlinear solving method, and find the value of γ that maximizes the land expectation value by non-linear programming. The solver uses a multi-start method using different starting points to avoid local optima.

4. RESULTS AND DISCUSSION

In this section, we first present the results of an optimal harvesting regime for conventional logging in the absence of carbon payments, our baseline case. Next, we introduce carbon pricing and determine the amount of carbon stored for different carbon prices. We conclude this section with a discussion of the carbon supply curves in the context of our steady state model.

4.1. Conventional Logging Without Carbon Prices

We define logging to be conventional when it is done unplanned and uncontrolled. Table 1 presents the key results for the optimal management with conventional logging techniques in the absence of carbon pricing, and compare them with the results for reduced impact logging in the absence of carbon pricing. With conventional logging, the optimal cutting cycle is 26 years with a LEV of 239 USD/ha. This cutting cycle is shorter than that of the new Indonesian selective logging system introduced in 2009 (new TPTI), which is 30 years. Basal areas before and after logging are 8.2 and 4.3 m^2/ha respectively. The number of trees before harvest is 185 trees/ha and the harvest is 7 trees/ha (all commercial trees with diameter larger than 40 cm.) with a volume of 16.4 m^3/ha and a value of 721 USD/ha. This harvesting activity leads to damages on the residual stand with a value of 376 USD/ha. The total number of trees after harvest is 119 trees/ha implying that 59 trees/ha are fatally damaged. The average amount of CO_2 stored in one management cycle in above ground biomass is 120 ton/ha and in end-use wood products is 5 ton/ha.

The LEV for CL in our study is lower than that found studied by Boscolo and Buongiorno (1997). Our damage matrix takes allows for damages on all diameter classes (see Appendix 1), while in Boscolo and Buongiorno (1997) the harvest damages only low diameter classes. In addition, the climax forest in Boscolo and Buongiorno (1997) is dominated by non-commercial trees which have no value, while the forest in our study is dominated by commercial trees.

Table 1. Results for optimal management under CL and RIL

	CL	RIL
Land Expectation Value (USD/ha)	239.1	248.1
Cutting cycle (years)	26	30
Total number of trees before harvest (trees/ha)	185	193
Total number of trees after harvest (trees/ha)	119	120
Basal Area before harvest (m^2/ha)	8.2	9.0
Basal Area after harvest (m^2/ha)	4.3	4.4
Extracted volume (m^3/ha)	16.4	20.8
Harvest revenue (USD/ha)	720.7	945.4
Volume damaged (m^3/ha)	26.7	30.2
Average amount of CO_2 stored in AGB (ton/ha)	119.7	131.1
Average amount of CO_2 stored in EWP (ton/ha)	5.4	9.0

The LEV of RIL is slightly higher than that of CL (248 USD/ha and 239 USD/ha respectively). The lower variable costs and lower damages with the use of RIL apparently offset the higher fixed costs of RIL. Still, CL is widely applied in Indonesia because of a misperception regarding its costs and benefits (Dwiprabowo *et al.*, 2002). However, Putz *et al.* (2000) argue that the costs and benefits of using RIL may not accrue to the same persons, and that RIL may not be suitable for all plots.

The optimal cutting cycle for RIL is 30 years, which is the same as the felling cycle under the new Indonesian selective logging policy TPTI. The cutting cycle is longer than under CL because of the higher fixed cost under RIL.

4.2. Optimal Forest Management in Presence of Carbon Payment

We solve the model for prices for temporary (2-year) carbon credits of 0.2-3 USD per ton of CO_2 This is equivalent to prices for permanent credits of 2.5 - 36.8 USD per ton CO_2, which is in line with the historic minimum and maximum values for permanent permits in the European Union Emissions Trading System (EU-ETS). We set the results for conventional logging at the steady state in which the LEV is maximized from timber only (see Table 1) as our baseline. Forest owners only obtain credits for carbon stored in addition to the amount stored under the baseline.

4.2.1. Carbon Payment from Additional Carbon in Tree Biomass

In this section, we analyze the effect of carbon payment on optimal management where the additional carbon stored is only calculated from tree biomass, i.e. when Equation 21 is the objective function.

Table 2. Results for optimal management using RIL with carbon credits for carbon stored in AGB only

Price temporary credit (USD/tCO_2)	0	0.2	0.4	0.6	0.8	1	1.2	1.8	2	3
Equivalent price permanent credit (USD/tCO_2)	0	2.5	4.9	7.4	9.8	12.3	14.7	22.1	24.5	36.8
LEV with harvest (USD/ha)	248	274	315	385	478	601	800	2136	20252	36054
Cutting cycle (years)	30	34	42	50	56	58	60	74	-	-
Extracted volume (m^3/ha)	21	23	28	33	37	41	44	42	0	0
Harvest revenue (USD/ha)	945	1067	1305	1582	1778	1989	2150	2035	0	0
Value of remaining stand (USD/ha)	0	0	0	49	105	403	782	3964	11351	11351
Volume of damaged trees (m^3/ha)	30	35	45	55	62	64	65	57	0	0
Value of damages (USD/ha)	503	627	902	1193	1413	1557	1664	1714	0	0
Value of additional carbon stored (NPV of acquired carbon credits, USD/ha)	0	32	96	238	409	821	1397	6005	31451	47176
Average amount of CO_2 stored in AGB (tCO_2/ha)	140	147	162	183	199	227	257	422	661	661
Value of CO_2 stored in AGB (USD/ha)	0	307	647	1060	1498	2164	2982	8087	34362	51543
Value of CO_2 stored in EWP (USD/ha)										
Value of CO_2 stored in remaining stand (USD/ha)	0	16	32	52	75	113	162	538	34362	51543
Value of CO_2 stored in AGB in baseline (USD/ha)	0	276	552	828	1103	1379	1655	2483	2758	4138
Value of CO_2 stored in EWP in baseline (USD/ha)	0	14	28	41	55	69	83	124	138	206
Value of CO_2 stored in remaining stand (USD/ha)	0	15	31	46	61	76	92	137	153	229

Under REDD+, logged over tropical forests may apply for carbon credits for carbon that is stored above what is stored under a baseline. Without a price for carbon sequestration, switching CL practice to RIL increases 12% of carbon storage, from 125 to 140 tCO_2. At a CO_2 price of 0.4 USD for 2-year temporary credits (comparable with the current price of permanent carbon credits in the EU ETS) this amount increases to 162 tons, which shows the large potential for increasing carbon storage through improved forest management under REDD+.

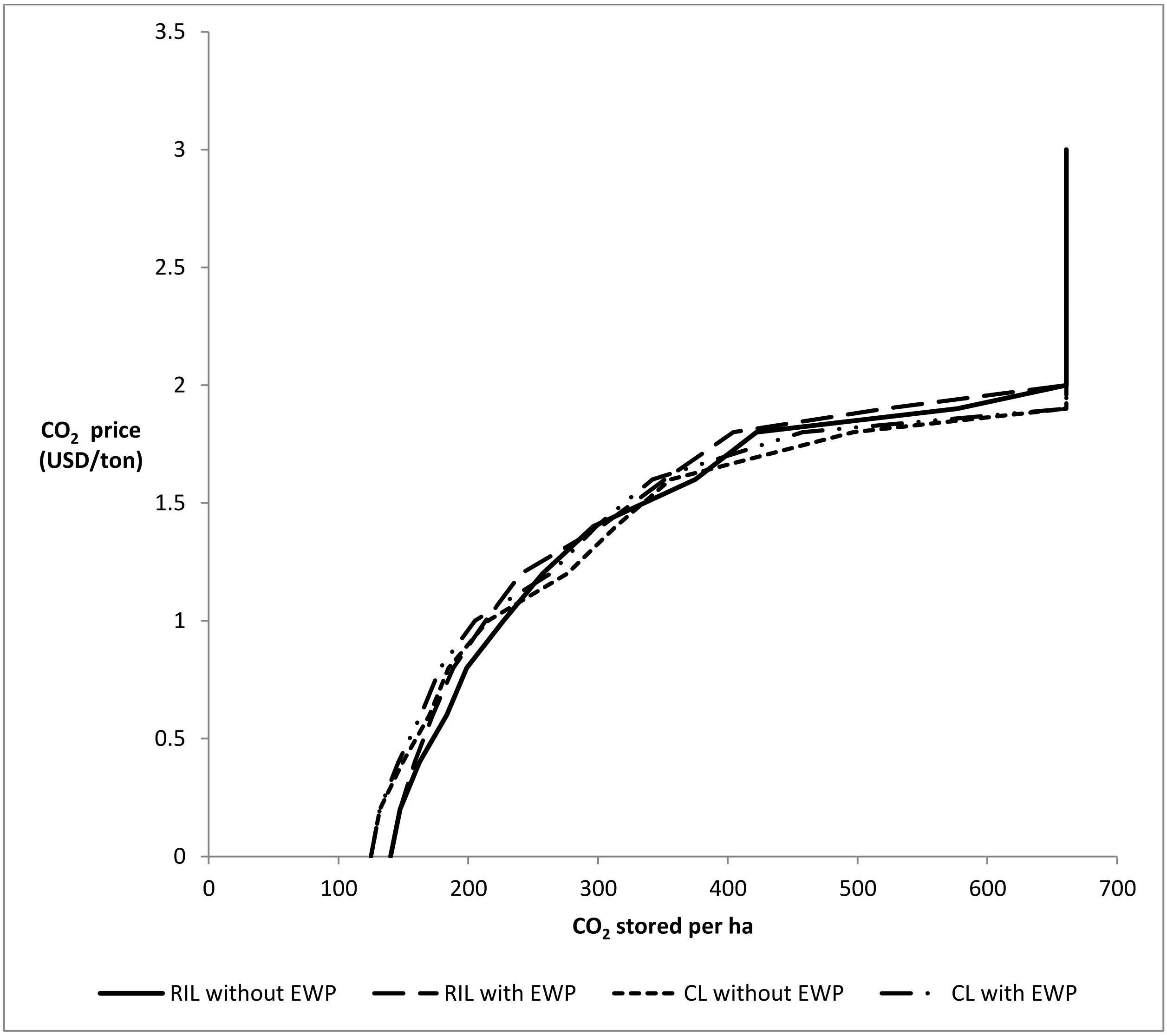

Figure 2. Supply curves for carbon storage for a managed tropical forest in East-Kalimantan for RIL and CL

Figure 2 presents supply curves for carbon storage for a managed tropical forest in East-Kalimantan. The solid line represents the amount of CO_2 stored under RIL when credits are issued for carbon stored in above-ground biomass. Initially, the curve has a concave shape: as the price increases, progressively more carbon becomes stored as the cutting cycle becomes longer and the harvest (and damages) become smaller. This concave shape is different from the convex supply curves presented by Boscolo et al. (1997) and Buongiorno *et al.* (2012). The reason is that we allow for profit maximizing behavior with endogenous adjustment of the cutting cycle as the carbon price increases. Boscolo et al. (1997) do not derive their supply curve from profit maximizing behavior but from imposing exogenous restrictions on forest management, such as lengthening the cutting cycle. Buongiorno *et al.* (2012) keep the cutting cycle fixed: for a given cutting cycle it becomes progressively harder to store more carbon since the only instrument available to the forest owner is the number of trees harvested.

As the carbon price increases from 1.9 USD/tCO_2 to 2 USD/tCO_2 (temporary, 2-year credit) it becomes optimal for a forest owner not to harvest and leave the forest untouched.[vii] In that case, the resulting forest is the climax forest (see Figure 1) with a total amount of CO_2 stored in above-ground biomass of 661 tons and the amount of carbon stored does not increase as the carbon price increases (vertical section of the supply curve).

Table 3. Forest characteristics at the maximum LEV under different carbon prices of CL without end use wood products

Price temporary credit (USD/tCO_2)	0	0.2	0.4	0.6	0.8	1	1.2	1.8	2	3
Equivalent price permanent credit (USD/tCO_2)	0	2.5	4.9	7.4	9.8	12.3	14.7	22.1	24.5	36.8
LEV with harvest (USD/ha)	239	243	264	320	398	526	741	2160	20558	36360
Cutting cycle (years)	26	30	36	46	54	56	58	74	-	-
Extracted volume (m^3/ha)	16	19	22	27	31	35	40	24	0	0
Harvest revenue (USD/ha)	721	821	1004	1268	1462	1462	1888	1117	0	0
Value of remaining stand (USD/ha)	0	0	47	81	98	407	1253	6221	11045	11045
Volume of damaged trees (m^3/ha)	27	32	39	53	64	66	65	44	0	0
Value of damages (USD/ha)	376	494	696	1067	1387	1561	1698	1328	0	0
Value of additional carbon stored (NPV of acquired carbon credits, USD/ha)	0	9	83	209	337	762	1812	8333	31451	47176
Average amount of CO_2 stored in AGB (tCO_2/ha)	125	132	149	170	185	215	276	497	661	661
Value of CO_2 stored in AGB (USD/ha)	0	285	632	1030	1431	2108	3367	10202	34362	51543
Value of CO_2 stored in EWP (USD/ha)	0	12	21	24	25	33	41	19	0	0
Value of CO_2 stored in remaining stand project (USD/ha)	0	15	33	52	71	109	191	751	34362	51543
Value of CO_2 stored in AGB in baseline (USD/ha)	0	276	552	828	1103	1379	1655	2483	2758	4138
Value of CO_2 stored in EWP in baseline (USD/ha)	0	14	28	41	55	69	83	124	138	206
Value of CO_2 stored in remaining stand baseline (USD/ha)	0	15	31	46	61	76	92	137	153	229

For comparison, Table 3 and Figure 2 include the results for various carbon prices when CL is used instead of RIL. Note that CL may not qualify for carbon payments under a REDD+ scheme. Our baseline is the use of conventional logging in the absence of carbon pricing, i.e. the results for CL in Table 1. For low carbon prices (up to 1 USD/tCO_2), more carbon is stored per hectare with

[vii] For prices higher than 1.9 USD/tCO_2 we use equation (22) instead of equation (21) to calculate the LEV.

RIL than with CL. However, for high carbon prices, more carbon in stored under CL while the LEV is higher as well.

4.2.2. Carbon Payments from Additional Carbon in Tree Biomass and Wood Products

In this section we present the results of the optimal management when carbon payments are from additional carbon stored in tree biomass and wood product. Tables 4 and 5 present the results for the case of the effect of carbon payment on CL and RIL respectively.

Table 4. Forest characteristics at the maximum LEV under different carbon prices including EWP under RIL

Price temporary credit (USD/tCO_2)	0	0.2	0.4	0.6	0.8	1	1.2	1.8	2	3
Equivalent price permanent credit (USD/tCO_2)	0	2.5	4.9	7.4	9.8	12.3	14.7	22.1	24.5	36.8
With EWP										
LEV with harvest (USD/ha)	248	278	316	379	463	585	781	2069	20252	36054
Cutting cycle (years)	30	34	40	44	50	50	50	60	-	-
Extracted volume (m^3/ha)	21	23	27	30	33	36	38	37	0	0
Average amount of CO_2 stored in AGB (tCO_2/ha)	140	147	159	173	189	214	240	404	661	661
Value of CO_2 stored in EWP project (USD/ha)	0	17	29	39	44	60	77	73	0	0
Value of CO_2 stored in EWP baseline (USD/ha)	0.0	14	28	41	55	69	83	124	138	206
Without EWP										
LEV with harvest (USD/ha)	248	274	315	385	478	601	800	2136	20252	36054
Cutting cycle (years)	30	34	42	50	56	58	60	74	-	-
Extracted volume (m^3/ha)	21	23	28	33	37	41	44	42	0	0
Average amount of CO_2 stored in AGB (tCO_2/ha)	140	147	162	183	199	227	257	422	661	661

Table 5. Forest characteristics at the maximum LEV under different carbon prices including EWP under CL

Price temporary credit (USD/tCO_2)	0	0.2	0.4	0.6	0.8	1	1.2	1.8	2	3
Equivalent price permanent credit (USD/tCO_2)	0	2.5	4.9	7.4	9.8	12.3	14.7	22.1	24.5	36.8
With EWP										
LEV with harvest (USD/ha)	239	241	258	303	369	492	706	2060	20558	36360
Cutting cycle (years)	26	30	34	42	50	50	50	66	-	-
Extracted volume (m^3/ha)	16	19	21	25	29	32	36	27	0	0
Average amount of CO_2 stored in AGB (tCO_2/ha)	125	132	146	163	178	205	263	458	661	661
Value of CO_2 stored in EWP project (USD/ha)	0	12	22	26	28	39	53	30	0	0
Value of CO_2 stored in EWP baseline (USD/ha)	0	14	28	41	55	69	83	124	138	206
Without EWP										
LEV with harvest (USD/ha)	239	243	264	320	398	526	741	2160	20558	36360
Cutting cycle (years)	26	30	36	46	54	56	58	74	-	-
Extracted volume (m^3/ha)	16	19	22	27	31	35	40	24	0	0
Average amount of CO_2 stored in AGB (tCO_2/ha)	125	132	149	170	185	215	276	497	661	661

Tables 4 and 5 show that the LEVs for CL are lower as compared to RIL for low carbon prices (i.e. p < 1.9 USD/tCO_2). However, for high carbon prices, LEVs are higher for CL than for

RIL. For low carbon price (i.e. $p \leq 0.4$ USD/tCO_2) the LEVs are slightly higher for RIL with EWP with similar optimal cutting cycles. However, for higher carbon prices (i.e. > 0.4 USD/tCO_2), the LEVs are higher for RIL without EWP with shorter cutting cycles. Because the proportion of the amount of carbon stored in EWP is small as compared to amount of carbon stored in trees, the effect of considering the amount of carbon stored in EWP for carbon payment is also minor for LEVs. For high carbon prices, storing more carbon in the trees may lengthen the cutting cycle and as a consequence, the values of carbon stored in EWP have negative effect on LEV's for $p > 0.4$ USD/tCO_2 as it is highly discounted.

In the case of additional income from the amount of carbon stored in EWP, for both RIL and CL, there are positive effects on LEV for low carbon prices (i.e. < 0.6 USD/tCO_2. However, for high carbon prices (i.e. ≥ 0.6 USD/tCO_2) the effect of additional carbon stored in EWP is negative on LEV. For high carbon prices, the additional amounts of carbon stored in EWP are discounted more as the cutting cycles are getting longer. The cutting cycles become longer because it is optimal to store more carbon in trees rather than storage in EWP as the proportion of carbon stored in trees is much higher than that stored in EWP.

Figure 2 shows that positive carbon prices induce the amount of CO_2 stored of more than 125 and 140 ton CO_2 for CL and RIL respectively. Figure 2 also shows that there are still harvest activities at carbon prices lower than 2 and 1.9 USD/tCO_2 for RIL and CL respectively. At higher carbon prices it is optimal to leave the forest untouched. Because the variable costs of harvesting timber under RIL are relatively low compared to CL and timber values are higher under RIL than under CL, the carbon price needed to compensate for not harvesting timber is higher for RIL than for CL.

Figure 2 presents the carbon supply curves as the results of maximizing Equation (21). However, these results are local optima in the sense that we did not compare the LEV for a positive harvest with the LEV of not harvesting for each carbon price (maximizing Equation (22)). In order to make sure a global optimum is obtained, we make this comparison in the next subsection.

4.3. To harvest or not to harvest?

Since our analysis employs a steady state model that determines the maximum LEV by considering marginal changes in the stand before harvest, volume harvested and the length of the cutting cycle, we need to check whether the optimal regime with positive harvest is preferred to not harvesting. When the initial stand is a climax forest and assuming that there are no harvesting activities, standing trees have both timber and carbon values. Calculating the tradeoffs between the two at different carbon prices in the case of “no harvest” (Equation (22)) may give lower LEV than the case of positive harvest (Equation (23)). Table 6 reports LEVs for a no harvest regime and compares them with LEVs from finite cutting cycles.

Table 6. LEV of “harvest” and “no harvest” scenario in RIL and CL with and without carbon credits for carbon stored in end-use wood products

Price temporary credit (USD/tCO_2)	0	0.2	0.4	0.6	0.8	1	1.2	1.8	2	3
Equivalent price permanent credit (USD/tCO_2)	0	2.5	4.9	7.4	9.8	12.3	14.7	22.1	24.5	36.8
RIL without EWP										
LEV with harvest (USD/ha)	248	274	315	385	478	601	800	2136	20252	36054
LEV no harvest (USD/ha)	-11351	-8191	-5030	-1870	1290	4451	7611	17092	20252	36054
RIL with EWP										
LEV with harvest (USD/ha)	248	278	316	379	463	585	781	2069	20252	36054
LEV no harvest (USD/ha)	-11351	-8191	-5030	-1870	1290	4451	7611	17092	20252	36054
CL without EWP										
LEV with harvest (USD/ha)	239	243	264	320	398	526	741	2160	20558	36360
LEV no harvest (USD/ha)	-11045	-7885	-4725	-1564	1596	4756	7917	17398	20558	36360
CL with EWP										
LEV with harvest (USD/ha)	239	241	258	303	369	492	706	2060	20558	36360
LEV no harvest (USD/ha)	-11045	-7885	-4725	-1564	1596	4756	7917	17398	20558	36360

Table 6 shows that at low carbon prices (i.e. $p \leq 0.6$ USD/tCO_2) it is optimal to harvest some trees as it gives a higher LEV than managing a climate forest. In contrast, LEVs are higher in the “no harvest” scenario starting from a carbon price of 0.8 USD/tCO_2. This price is lower than the 1.9 USD/tCO_2 found in section 4.2. Figure 3 presents the corresponding carbon storage supply curves. One way to interpret the difference is to consider the results in that section as stemming from the perspective of a forest owner with an infinite planning horizon who has to decide how to adjust his forest management when the carbon price marginally increases. When the price increases marginally, he marginally adjusts the forest stand and his management practices.

The supply curves for forest carbon storage in Figure 3 can be interpreted as resulting from a forest manager with an infinite planning horizon who can discretely adjust his forest stand, or, alternatively, who has to design optimal forest management schedules for different states of the world. That is, for different carbon prices he can choose a different initial forest stand, including the climax forest.

The difference between the carbon supply curves in Figures 2 and 3 is a direct result from the fact that we use a steady state model. That is, our model does not allow for a transition phase from one forest stand before harvest to another. Extending the Buongiorno and Michie (1980) framework with a transition phase for simulating forest carbon supply curves is an important line of future research.

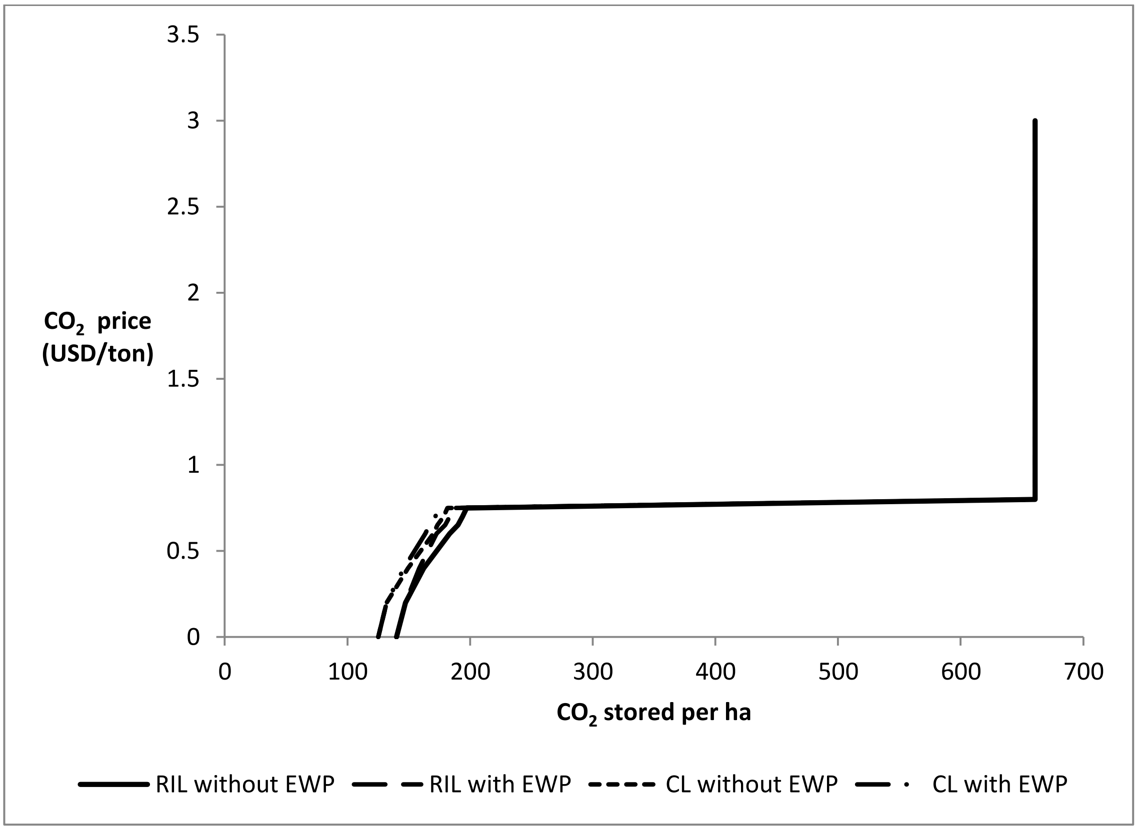

Figure 3. Supply curves for carbon storage for a managed tropical forest in East-Kalimantan for RIL and CL: global solutions

5. CONCLUSIONS

We apply a Hartman model to a tropical forest considering timber values and benefits of carbon sequestration from sustainable forest management (REDD+). We use detailed data from East-Kalimantan. We have presented supply curves for forest carbon sequestration in the context of REDD+. There are three additional interesting findings in our paper. First, for zero carbon prices, reduced impact logging (RIL) is economically more attractive than conventional logging based on our detailed data. Second, already at modest carbon prices (i.e. $p > 0.4$ USD/tCO_2 for a two-year temporary credit, or 4.90 USD/tCO_2 for a permanent credit), the additional income from end-use wood products (EWP) has negative effect on land expectation value. Relative to the baseline scenario, in which there is no compensation for carbon stored in above-ground biomass or end-use wood products, the cutting cycle is lengthened. Hence, the payments for the carbon stored in EWP are discounted more relative to the baseline. As a result, the net present value of the carbon stored in EWP is lower than under the baseline, which leads to a lower LEV. Third, the exact shape of the carbon supply curves depends on the interpretation of our steady state model. If it is assumed that forest owners can immediately adjust the stand of their forest into the climax forest, then it is optimal to switch to a no-harvest policy already at intermediate carbon prices (i.e. p = 0.8 USD/tCO_2 for a two-year temporary credit, or 9.80 USD/tCO_2 for a permanent credit), while if the model is interpreted as representing marginal changes (but without a transition phase) the decision not to harvest is optimal only for a carbon price of 1.90 USD/tCO_2 (23.30 USD/tCO_2 for a permanent credit).

We find that the recent cutting cycle determined by the Ministry of Forestry in Indonesia (i.e. 30 years) is longer than the optimal cutting cycle for conventional logging, but appropriate for reduced impact logging. In addition, our study suggests that switching from conventional logging to reduced impact logging can significantly reduce carbon emissions, even at low carbon prices, while still producing commercial timber – important for employment in the sawmill and manufacturing industries – for low to intermediate carbon prices. There is indeed a win-win situation because RIL is a competitive logging practice even if there are no carbon remunerations.

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Appendix 1. Data for forest growth model

$$A_1 = \begin{bmatrix}
0{,}80 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0{,}16 & 0{,}79 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0{,}17 & 0{,}79 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0{,}18 & 0{,}78 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0{,}19 & 0{,}78 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0{,}19 & 0{,}78 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0{,}20 & 0{,}78 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0{,}19 & 0{,}79 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0{,}19 & 0{,}79 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0{,}18 & 0{,}80 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0{,}17 & 0{,}81 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0{,}16 & 0{,}82 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0{,}14 & 0{,}95
\end{bmatrix}$$

$$A_2 = \begin{bmatrix}
0{,}84 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0{,}14 & 0{,}84 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0{,}13 & 0{,}84 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0{,}13 & 0{,}83 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0{,}12 & 0{,}83 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0{,}11 & 0{,}83 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0{,}11 & 0{,}82 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0{,}10 & 0{,}82 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0{,}09 & 0{,}81 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0{,}08 & 0{,}80 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0{,}07 & 0{,}79 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0{,}06 & 0{,}78 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0{,}05 & 0{,}81
\end{bmatrix}$$

$$A_3 = \begin{bmatrix}
0{,}81 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0{,}13 & 0{,}81 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0{,}13 & 0{,}81 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0{,}12 & 0{,}81 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0{,}12 & 0{,}81 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0{,}11 & 0{,}81 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0{,}11 & 0{,}81 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0{,}10 & 0{,}81 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0{,}10 & 0{,}81 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0{,}09 & 0{,}81 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0{,}09 & 0{,}81 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0{,}08 & 0{,}80 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0{,}08 & 0{,}88
\end{bmatrix}$$

The ingrowth matrices $\mathbf{R}_{ik}$ only contain nonzero values on the first row. For the sake of brevity, we omit the remaining rows.

$$\mathbf{R}_{11}= \begin{bmatrix} 0.0103 & 0.0102 & 0.0099 & 0.0097 & 0.0093 & 0.0090 & 0.0085 & 0.0080 & 0.0075 & 0.0069 & 0.0062 & 0.0055 & 0.0047 \end{bmatrix}$$

$$\mathbf{R}_{12}= \begin{bmatrix} -0.0002 & -0.0003 & -0.0006 & -0.0008 & -0.0012 & -0.0015 & -0.0020 & -0.0025 & -0.0030 & -0.0036 & -0.0043 & -0.0050 & -0.0058 \end{bmatrix}$$

$$\mathbf{R}_{13}= \begin{bmatrix} -0.0002 & -0.0003 & -0.0006 & -0.0008 & -0.0012 & -0.0015 & -0.0020 & -0.0025 & -0.0030 & -0.0036 & -0.0043 & -0.0050 & -0.0058 \end{bmatrix}$$

$$\mathbf{R}_{21} = \begin{bmatrix} -0.0002 & -0.0003 & -0.0006 & -0.0008 & -0.0012 & -0.0015 & -0.0020 & -0.0025 & -0.0030 & -0.0036 & -0.0043 & -0.0050 & -0.0058 \end{bmatrix}$$

$$\mathbf{R}_{22} = \begin{bmatrix} 0.0103 & 0.0102 & 0.0099 & 0.0097 & 0.0093 & 0.0090 & 0.0085 & 0.0080 & 0.0075 & 0.0069 & 0.0062 & 0.0055 & 0.0047 \end{bmatrix}$$

$$\mathbf{R}_{23} = \begin{bmatrix} -0.0002 & -0.0003 & -0.0006 & -0.0008 & -0.0012 & -0.0015 & -0.0020 & -0.0025 & -0.0030 & -0.0036 & -0.0043 & -0.0050 & -0.0058 \end{bmatrix}$$

$$\mathbf{R}_{31} = \begin{bmatrix} -0.0002 & -0.0003 & -0.0006 & -0.0008 & -0.0012 & -0.0015 & -0.0020 & -0.0025 & -0.0030 & -0.0036 & -0.0043 & -0.0050 & -0.0058 \end{bmatrix}$$

$$\mathbf{R}_{32} = \begin{bmatrix} -0.0002 & -0.0003 & -0.0006 & -0.0008 & -0.0012 & -0.0015 & -0.0020 & -0.0025 & -0.0030 & -0.0036 & -0.0043 & -0.0050 & -0.0058 \end{bmatrix}$$

$$\mathbf{R}_{33} = \begin{bmatrix} 0.0103 & 0.0102 & 0.0099 & 0.0097 & 0.0093 & 0.0090 & 0.0085 & 0.0080 & 0.0075 & 0.0069 & 0.0062 & 0.0055 & 0.0047 \end{bmatrix}$$

$$\boldsymbol{c}_1' = [3.89\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0]$$

$$\boldsymbol{c}_2' = [3.88\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0]$$

$$\boldsymbol{c}_3' = [1.87\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0\ \ 0]$$

$$\mathbf{E}_{CL} = \begin{bmatrix} 0.043 &&&&&&&&&&&& \\ & 0.043 &&&&&&&&&&& \\ && 0.043 &&&&&&&&&& \\ &&& 0.043 &&&&&&&&& \\ &&&& 0.046 &&&&&&&& \\ &&&&& 0.046 &&&&&&& \\ &&&&&& 0.046 &&&&&& \\ &&&&&&& 0.046 &&&&& \\ &&&&&&&& 0.051 &&&& \\ &&&&&&&&& 0.051 &&& \\ &&&&&&&&&& 0.045 && \\ &&&&&&&&&&& 0.045 & \\ &&&&&&&&&&&& 0.029 \end{bmatrix}$$

$$\mathbf{E}_{RIL} = \begin{bmatrix} 0.039 &&&&&&&&&&&& \\ & 0.039 &&&&&&&&&&& \\ && 0.039 &&&&&&&&&& \\ &&& 0.039 &&&&&&&&& \\ &&&& 0.034 &&&&&&&& \\ &&&&& 0.034 &&&&&&& \\ &&&&&& 0.044 &&&&&& \\ &&&&&&& 0.044 &&&&& \\ &&&&&&&& 0.036 &&&& \\ &&&&&&&&& 0.036 &&& \\ &&&&&&&&&& 0.034 && \\ &&&&&&&&&&& 0.034 & \\ &&&&&&&&&&&& 0.024 \end{bmatrix}$$

Appendix 2. Additional Tables

Table A2.1. Economic parameters, all values in 2012 US dollars.

	CL	RIL	Source
Fixed costs (in USD/ha)			
Administration and investment			PT Sumalindo Lestari Jaya (2008)
Environmental Impact Assessment (EIA)	0.37	0.37	
Technical Proposal	0.12	0.12	
Working area Definition	0.12	0.12	
Recommendation from Bupati/Gubernur	0.37	0.37	
Building	22.77	22.77	
Forest protection	3.96	3.96	
Transportation	17.76	17.76	
Machineries	218.08	304.19	
Office	2.88	2.88	
Supporting equipment	9.38	9.38	
Pre harvesting			Dwiprabowo et al.(2002)
Timber inventory and contour survey	10.06	13.92	
Data entry and block mapping	1.00	1.31	
Data checking and mapping		0.44	
Skidtrail marking and checking		0.95	
ROADENG software purchase		0.23	
Vine cutting		0.81	
Tax			
Concession license fee (IUPHHK)	5.34	5.34	
Building tax	4.64	4.64	
Total	**297**	**390**	
Variable costs (in USD/m^3)			
Production			
Training		0.47	Dwiprabowo et al. (2002)
Supervision	0.12	0.24	
Felling	0.42	0.42	
Skidding	6.09	4.41	
Log landing opening	0.11	0.08	
Road construction and maintenance	7.90	7.90	
Log transport	31.80	31.80	
Total	**46.4**	**44.8**	

(Table continues on next page)

Table A2.1. Economic parameters, all values in 2012 US dollars (continued).

	CL	RIL	Source
Taxes and prices			
Royalty Tax Dipterocarp*	13.7	13.7	Gov't Regulation No 51/1998
Royalty Tax non Dipterocarp*	10.3	10.3	Gov't Regulation No 51/1998
Reforestation Fund (DR) Dipterocarp	16	16	Presidential Decree No 40/1993
Reforestation Fund (DR) non Dipterocarp	13	13	Presidential Decree No 40/1993
Price Dipterocarp (USD/m^3)	137	137	Min. of Trade Decree No 22/2012
Price non Dipterocarp (USD/m^3)	103	103	Min. of Trade Decree No 22/2012
Net price Dipterocarp (USD/m^3)**	60	61	
Net price Non- Dipterocarp (USD/m^3)**	32	34	
Discount rate	4%	4%	

* Ministry of Trade Decree No 22/2012 (royalty tax is 10% of the standard price determined by the government).

** Price after taxes and variable costs; elements of $\mathbf{v}_s$.

Table A2.2. Predicted stand state in the steady state condition with no harvest

Diameter (cm)	N/ha			Total
	Dipterocarp	Non Dipterocarp	Non Commercial	
10-14	24.85	28.84	9.69	63.4
15-19	18.71	24.57	6.81	50.1
20-24	14.94	20.03	4.60	39.6
25-29	12.47	15.43	2.97	30.9
30-34	10.77	11.09	1.84	23.7
35-39	9.53	7.33	1.09	17.9
40-44	8.57	4.39	0.62	13.6
45-49	7.78	2.35	0.33	10.5
50-54	7.07	1.10	0.17	8.3
55-59	6.39	0.44	0.08	6.9
60-64	5.69	0.15	0.04	5.9
65-69	4.93	0.04	0.02	5.0
≥ 70	14.77	0.01	0.01	14.8
Population (N/ha)	146.4	115.8	28.3	290.5
Basal Area (m^2/ha)	19.4	5.8	1.1	26.4
Volume (m^3/ha)	270	51	9	330
Carbon stored in biomass (ton/ha)	196.02	46.34	8.65	251

Table A2.3. Predicted above ground biomass, root biomass, and carbon stored in biomass in dipterocarp, non-dipterocarp and non-commercial species

Diameter (cm)	Dipterocarp		Non Dipterocarp		Non-commercial	
	AGB (ton /tree)	C stock (ton /tree)	AGB (ton /tree)	C stock (ton /tree)	AGB (ton /tree)	C stock (ton /tree)
10-14	0.082	0.039	0.082	0.039	0.082	0.039
15-19	0.200	0.094	0.200	0.094	0.200	0.094
20-24	0.388	0.183	0.388	0.183	0.388	0.183
25-29	0.655	0.308	0.655	0.308	0.655	0.308
30-34	1.009	0.474	1.009	0.474	1.009	0.474
35-39	1.454	0.683	1.454	0.683	1.454	0.683
40-44	1.995	0.938	1.995	0.938	1.995	0.938
45-49	2.636	1.239	2.636	1.239	2.636	1.239
50-54	3.378	1.587	3.378	1.587	3.378	1.587
55-59	4.222	1.984	4.222	1.984	4.222	1.984
60-64	5.171	2.430	5.171	2.430	5.171	2.430
65-69	6.223	2.925	6.223	2.925	6.223	2.925
≥ 70	7.380	3.469	7.380	3.469	7.380	3.469

Table A2.4. Estimated wood volume and basal area of dipterocarp, non-dipterocarp and non-commercial species

Diameter (cm)	Dipterocarp		Non Dipterocarp		Non-commercial	
	Volume (m^3/tree)	Basal Area (m^2/tree)	Volume (m^3/tree)	Basal Area (m^2/tree)	Volume (m^3/tree)	Basal Area (m^2/tree)
10-14	0.17	0.012	0.06	0.012	0.06	0.012
15-19	0.25	0.024	0.13	0.024	0.13	0.024
20-24	0.41	0.040	0.28	0.040	0.28	0.040
25-29	0.64	0.059	0.49	0.059	0.49	0.059
30-34	0.96	0.083	0.76	0.083	0.76	0.083
35-39	1.35	0.110	1.11	0.110	1.11	0.110
40-44	1.82	0.142	1.51	0.142	1.51	0.142
45-49	2.37	0.177	1.99	0.177	1.99	0.177
50-54	3.00	0.217	2.53	0.217	2.53	0.217
55-59	3.70	0.260	3.13	0.260	3.13	0.260
60-64	4.49	0.307	3.81	0.307	3.81	0.307
65-69	5.35	0.358	4.54	0.358	4.54	0.358
≥ 70	6.29	0.413	5.35	0.413	5.35	0.413

Table A2.5. Value of trees in each species and diameter class

Diameter (cm)	Value of trees					
	Dipterocarp		Non Dipterocarp		Non-commercial	
	CL (USD/tree)	RIL (USD/tree)	CL (USD/tree)	RIL (USD/tree)	CL (USD/tree)	RIL (USD/tree)
10-14	0	0	0	0	0	0
15-19	0	0	0	0	0	0
20-24	0	0	0	0	0	0
25-29	0	0	0	0	0	0
30-34	0	0	0	0	0	0
35-39	0	0	0	0	0	0
40-44	87	89	39	41	0	0
45-49	113	116	51	54	0	0
50-54	143	147	65	68	0	0
55-59	176	181	81	85	0	0
60-64	214	219	98	103	0	0
65-69	255	262	117	123	0	0
≥ 70	299	308	137	144	0	0