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Yonky Indrajaya, Environmental Economics and Natural Resources Group, Wageningen University (The Netherlands)
Edwin van der Werf, Environmental Economics and Natural Resources Group, Wageningen University (The Netherlands) and CESifo (Germany)
Hans-Peter Weikard, Environmental Economics and Natural Resources Group, Wageningen University (The Netherlands)
Frits Mohren, Forest Ecology and Forest Management Group, Wageningen University (The Netherlands)
Ekko C. van Ierland, Environmental Economics and Natural Resources Group, Wageningen University (The Netherlands)

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By Yonky Indrajaya, Environmental Economics and Natural Resources Group, Wageningen University (The Netherlands)
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Summary

We study the potential of tropical multi-age multi-species forests for sequestering carbon in response to financial incentives from REDD+. 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. 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. We apply the model using data for Kalimantan, Indonesia. RIL leads to less damages on the residual stand than CL and has lower variable but higher fixed costs. We find that a system of carbon credits through REDD+ has a large potential for carbon storage. Interestingly, awarding carbon credits to carbon stored in end-use wood products does not increase the amount of carbon stored and reduces Land Expectation Value. We also observe that the level of the carbon price at which it becomes optimal not to harvest depends on the interpretation of the steady state model.

Keywords: REDD+, Carbon Credits, Carbon Sequestration, Sustainable Forest Management, Reduced Impact Logging, Optimal Forest Management, Carbon Price
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Address for correspondence
Edwin van der Werf
Environmental Economics and Natural Resources Group
Wageningen University
Hollandseweg 1
6706KN
Wageningen
The Netherlands
Email: edwin.vanderwerf@wur.nl

The Potential of REDD+ for Carbon Sequestration in Tropical Forests: Supply Curves for carbon storage for Kalimantan, Indonesia[i]

Yonky Indrajaya[ii], Edwin van der Werf[iii], Hans-Peter Weikard[iv],
Frits Mohren[v], and Ekko C. van Ierland[vi]

Abstract: We study the potential of tropical multi-age multi-species forests for sequestering carbon in response to financial incentives from REDD+. 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. 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. We apply the model using data for Kalimantan, Indonesia. RIL leads to less damages on the residual stand than CL and has lower variable but higher fixed costs. We find that a system of carbon credits through REDD+ has a large potential for carbon storage. Interestingly, awarding carbon credits to carbon stored in end-use wood products does not increase the amount of carbon stored and reduces Land Expectation Value. We also observe that the level of the carbon price at which it becomes optimal not to harvest depends on the interpretation of the steady state model.

Keywords: REDD+, carbon credits, 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 (REDD+).

The harvest of mature trees in managed tropical forests causes damage on the remaining stand. 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 of managed tropical forests (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, for a 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 (1976) 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 in the absence of carbon credits serves as a benchmark (see for example the methodology for financing forest carbon projects of Verified Carbon Standard, the largest voluntary greenhouse gas reduction program). 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 central 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 to the residual stand depends on harvest intensity, forest density and logging technique, and differs across diameter classes (Macpherson *et al.*, 2010). Furthermore we apply detailed data on fixed and variable harvest costs from a forest company in East Kalimantan, 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 under REDD+ (Dangerfield *et al.*, 2013), 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 Sohngen and Mendelsohn, 2003; Bosetti *et al.*, 2011; Rose and Sohngen, 2011).

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 temporary and long term credits under the Clean Development Mechanism (CDM) in plantation forests in tropical countries while Köthke and Dieter (2010) and Tassone *et al.* (2004) study the effects of carbon crediting schemes on forest management for even-aged forests in Germany and Italy respectively. Boscolo *et al.* (1997) and Buongiorno *et al.* (2012) study carbon storage in un-even aged multi-species forests, but do not allow 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 consider payments for carbon stored in end-use wood products.

In the remainder of this paper we first describe the forest growth model and the economic optimization model. Next, in Section 3, we parameterize the model. 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; Tassone *et al.*, 2004).

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) $i \in \{1, \ldots, m\}$ and diameter class $j \in \{1, \ldots, n\}$. The harvest is represented by vector $\mathbf{h}_t = [h_{ijt}]$. A tree living 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 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 group i during a growth period 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 for the moment, each species in the stand is represented by the following n equations:

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

$$y_{i\,2\,t+\theta} = b_{i1}(y_{i1t} - h_{i1t}) + a_{i2}(y_{i2t} - h_{i2t})$$

$$\ldots$$

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

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:

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

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

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

where:

$$e_{i1} = a_{i1} + \beta_{1i} B_{i1} + \beta_{2i} \quad (4)$$

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

Ignoring damage for now, the stand 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 **G** is the growth matrix. **A** is an mn x mn matrix consisting of species upgrowth matrices $\mathbf{A}_i$. 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 **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 **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 in years (Chang, 1981), and (iii) the intensity of the harvest in trees per ha for each species group. 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 forest management 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 accounting for damage; 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. Here we use Hartman's model in a multi-age multi-species tropical forest with selective cutting in Indonesia. We follow the REDD+ scheme as implemented by Verified Carbon Standard, an existing voluntary greenhouse gas reduction program, where carbon stored in the forest (or in end-use wood products) can only be credited when it exceeds the baseline level (Dangerfield *et al.*, 2013), i.e. we explicitly account for additionality.

2.3.1. Carbon Revenues from Tree Biomass

Payments for carbon stored in forest biomass can change the optimal harvesting intensity, the cutting cycle, and the optimal (steady-state) stand before harvest. We use a baseline to determine additionality of carbon storage. The baseline is based on 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 direct comparison with observed market prices for carbon credits. We assume that verification and payments for carbon storage take place every θ years, starting in year θ of every cycle, and carbon credits are awarded for the amount of carbon stored in commercial and non-commercial trees at the instant of verification. In our application we set $\theta = 2$ years.

Following Verified Carbon Standard (Dangerfield *et al.*, 2013) forest owners receive temporary carbon credits that expire after θ years (cf. the tCERs for afforestation or reforestation projects under the CDM).[vii] 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: $p = p_\infty\left((1+r)^\theta - 1\right)$. For example, for a permanent credit of 7.40 USD/tCO_2 (approximately the current price in the EU ETS) the equivalent two-year credit has a value of 0.6 USD/tCO_2.

Forest owners get paid for carbon stored above the amount stored under a baseline. Hence we subtract the present 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 payments (cf. equation (11) with $s = \mathrm{CL}$). The LEV maximization problem under this payment scheme is written as follows:

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

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 present value of the carbon stored over an infinite horizon in the presence of a carbon payment program under REDD+. To qualify for such a program the forest owner needs to implement sustainable forest management techniques (RIL). Vector $\boldsymbol{\chi}$ represents the amount of CO_2 implicitly stored in above-ground forest biomass (AGB) per tree of species *i* and diameter class *j*. The fourth term denotes the net present 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 account for additionality. 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, 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

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

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

Carbon is not only stored in trees but for some period of time also in end-use wood products (EWP). Following REDD+ as implemented by Verified Carbon Standard (Dangerfield *et al.*, 2013), we allow for credits for carbon stored in EWP. The LEV maximization problem with additional income from carbon in EWP is written as follows:

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

The first five terms are equal to the terms in Equation (21). The last term in Equation (23) denotes the net present value of CO_2 stored in EWP in RIL minus the net present 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 immediately after harvest, for example because it gets burned.

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 central Kalimantan. The soil type of the study area 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 increments 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).[viii] The growth matrices are presented in Appendix 1. Short term validation of the growth model was done by Krisnawati *et al.* (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 (180 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.

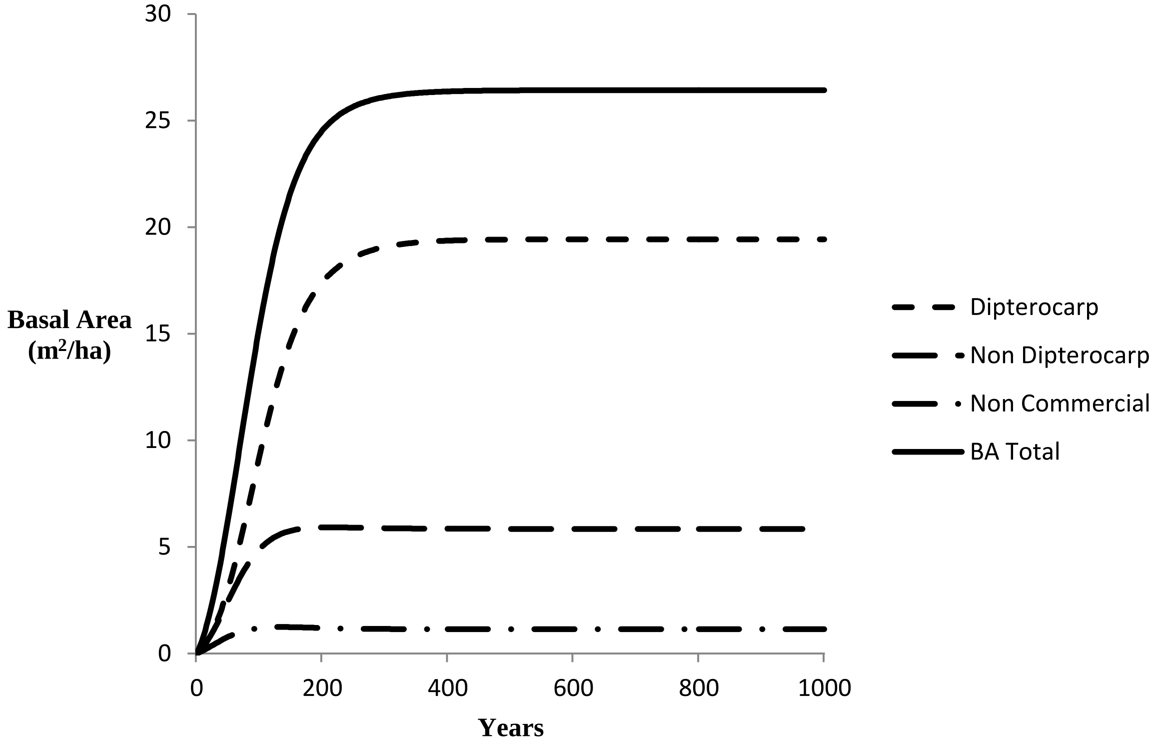

Figure 1. Predicted basal area (BA) of commercial dipterocarp, commercial non-dipterocarp and non-commercial species without harvest.

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 through 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.[ix] The investment and administration costs data were collected from a technical proposal of a company in East-Kalimantan (PT Sumalindo Lestari Jaya, 2008).[x] 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.[xi] 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.[xii]

3.4. Timber Volume and Carbon Stored in Tree Biomass

We estimate timber volume using the formula developed by Enggelina (1998) for dipterocarp and non-dipterocarp species in Kalimantan. Because there are no data for timber volume estimation for non-commercial species, we assume that the formula for timber 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. Following Verified Carbon Standard, the largest existing voluntary carbon standard, we do not allow for credits for carbon stored in below-ground biomass. 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 when forest owners maximize their land expectation value. 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

Table 1 presents the key results for the optimal management with conventional logging techniques together 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. Steady state total 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 (i.e. all commercial trees with diameter larger than 40 cm.) with a harvest volume of 16.4 m^3/ha and 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 commercial and non-commercial trees after harvest is 119 trees/ha implying that 59 trees/ha are fatally damaged. The average implicit amounts of CO_2 stored in above-ground biomass and in end-use wood products over one management cycle are 120 ton/ha and 5 ton/ha respectively.

The LEV for CL in our study is lower than that found in the study by Boscolo and Buongiorno (1997). Our damage matrix accounts for damages on all diameter classes (see Appendix 1), while in Boscolo and Buongiorno (1997) the harvest only damages smaller trees. In addition, the climax forest in Boscolo and Buongiorno (1997) is dominated by non-commercial trees (that have zero value), while the forest in our study is dominated by commercial trees, resulting in a larger value for damages.

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 when using 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). 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. Because of the longer cutting cycle, more carbon is stored in AGB. Since the extracted volume is also larger under RIL, more carbon is stored in EWP as well.

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/tCO_2. This is equivalent to prices for permanent credits of 2.5-36.8 USD/tCO_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 in which the LEV from timber revenues only is maximized (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 payments on optimal management when we only consider carbon stored in 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 (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)	131	138	151	171	186	213	242	409	661	661
Average amount of CO_2 stored in EWP (tCO_2/ha)	9	10	11	12	13	14	15	13	0	0
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)	0	17	28	33	37	48	57	45	0	0
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 in baseline (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 carbon remuneration, switching from CL to RIL increases carbon storage in AGB by 9%, from 120 to 131 tCO_2/ha. At a CO_2 price of 0.6 USD for 2-year temporary credits (equivalent to the current price of permanent carbon credits in the EU ETS of about 7.4 USD/tCO_2) this amount increases to 171 tCO_2/ha. A switch to RIL increases the amount of carbon stored in EWP from 5 to 9 tCO_2/ha for a zero carbon price, and increases further to 12 tCO_2/ha at 0.6 USD/tCO_2. The total amount of carbon stored (AGB + EWP) hence increases by 12% relative to the baseline when the carbon price is zero (i.e. by switching from CL to RIL and adjusting cutting cycle, harvest and initial stand accordingly) and by 46% when it equals 0.6 USD/tCO_2, which shows the large potential for increasing carbon storage through improved forest management under REDD+.

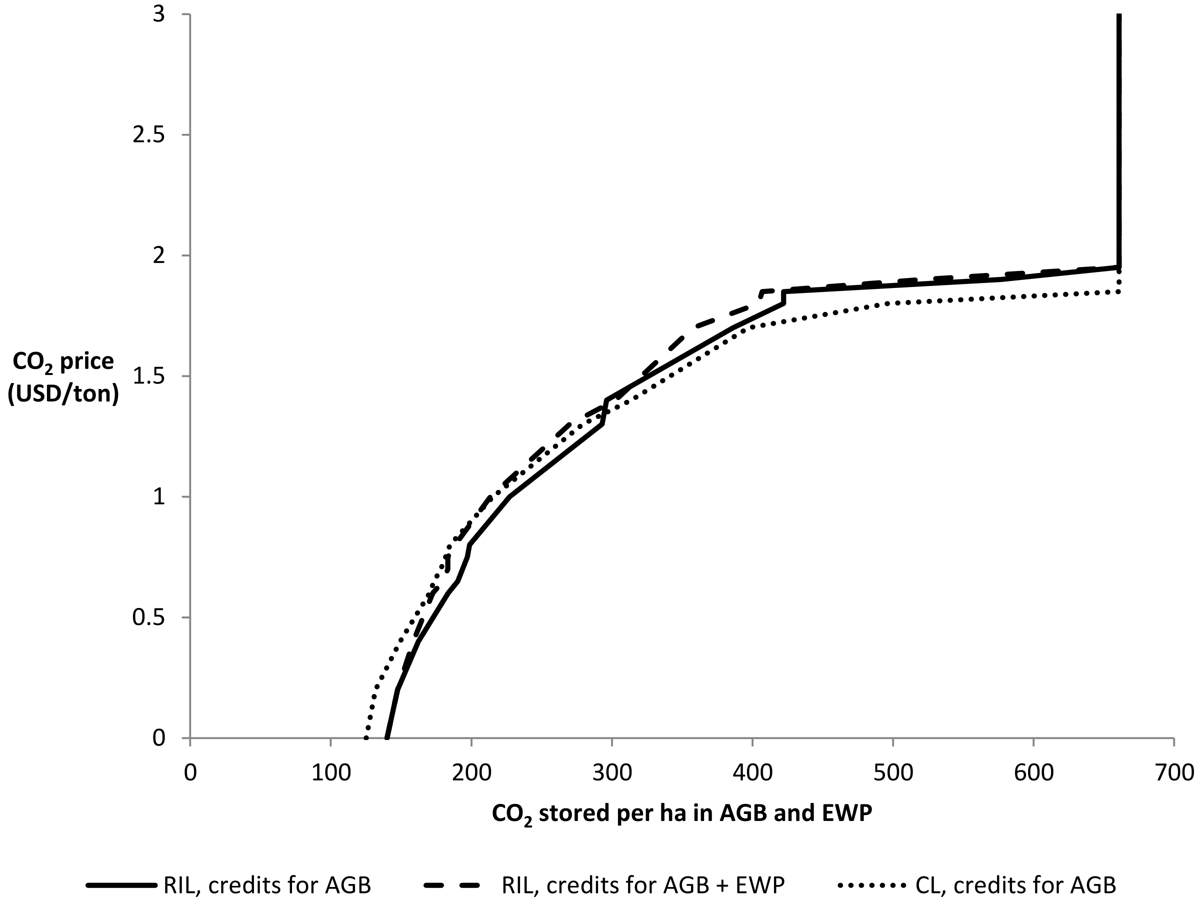

Figure 2. Supply curves for carbon storage for a managed tropical forest on Kalimantan, Indonesia, for RIL and CL

Figure 2 presents supply curves for carbon storage for a managed tropical forest on Kalimantan, Indonesia. The solid line represents the total amount of CO_2 stored (AGB + EWP) 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 since the cutting cycle becomes longer even though damages increase as the CO_2 price increases up to 1.5 USD/tCO_2. Extracted volume also increases up to a price of 1.5 USD/tCO_2 but while this increases the amount of carbon stored in EWP it decreases AGB. 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) take the initial stand as given and do not use a steady state model. They derive their supply curve from imposing exogenous restrictions on forest management, such as lengthening the cutting cycle. Buongiorno *et al.* (2012) use a steady state model with endogenous steady state stand but keep the cutting cycle fixed: for a given cutting cycle it gets harder to store more carbon.

As the carbon price increases beyond 1.9 USD/tCO_2 (temporary, 2-year credit) it is optimal for a forest owner not to harvest and the climax forest is preferred.[xiii] The climax forest (see Figure 1) implicitly stores 661 tCO_2/ha independent of the carbon price. This gives a vertical section of the supply curve.

Table 3. Results for optimal management using CL 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 (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)	120	126	143	163	177	207	266	491	661	661
Average amount of CO_2 stored in EWP (tCO_2/ha)	5	6	7	7	8	9	10	5	0	0
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 (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 in 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 the use of conventional logging techniques may not qualify a forest stand for carbon payments under a REDD+ scheme as CL is not considered to be sustainable. Our baseline is the same as before: CL 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 in AGB per hectare under RIL than under CL because of the longer cutting cycle under RIL. However, for high carbon prices, more carbon in stored under CL. While the optimal cutting cycles for CL and RIL converge as the carbon price increases, fewer trees are harvested under CL leading to less damages and more AGB. For high carbon prices, the LEV under CL is higher as well because the opportunity costs of not harvesting (value of the remaining stand) is lower for CL. Furthermore, under CL it is optimal to not harvest at a carbon price of 1.9 USD/tCO_2 (2 USD/tCO_2 in case of RIL). Because the variable costs of harvesting timber under RIL are lower than under CL, the net price per cubic meter his higher for RIL and the carbon price needed to compensate for not harvesting is higher for RIL than for CL.

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 received for additional carbon stored in both tree biomass and end-use wood products, such as construction wood.

Table 4 presents results for credits for carbon stored in AGB and EWP and compares them with results for key variables for the case without credits for carbon in EWP. The dashed line in Figure 2 presents the corresponding carbon supply curve. Interestingly, allowing for carbon credits for carbon stored in end-use wood products reduces LEV at positive carbon prices. That is, forest owners are worse off when they receive compensation for carbon stored in final products. The reason for this counter-intuitive result is that with RIL and a positive carbon price the cutting cycle is lengthened to 30 years or more (compared to 26 years under the baseline) and hence carbon is stored in end-use wood products at a later date than under the baseline. As a consequence, payments for carbon stored in EWP take place at a later date and are more heavily discounted than under the baseline. As can be seen in the last term of equation (23), for a given amount of carbon stored in EWP the net present value of carbon credits is lower than under the baseline, which reduces LEV. Indeed, the discounting effect more than offsets the higher wood efficiency with RIL ($u_{RIL} > u_{CL}$) and the larger harvested volume compared to the baseline.

Table 4. Results for optimal management using RIL with carbon credits for carbon stored in AGB and EWP

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 credits for CO_2 in EWP										
LEV (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
Value of additional carbon stored (NPV of acquired carbon credits, USD/ha)	0	32	89	211	381	775	1205	5869	31452	47176
Average amount of CO_2 stored in AGB (tCO_2/ha)	131	138	148	161	177	200	227	392	661	661
Average amount of CO_2 stored in EWP (tCO_2/ha)	9	10	11	11	12	13	14	13	0	0
Value of CO_2 stored in EWP (USD/ha)	0	17	29	39	44	60	77	73	0	0
Value of CO_2 stored in EWP baseline (USD/ha)	0	14	28	41	55	69	83	124	138	206
Without credits for CO_2 in 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
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)	131	138	151	171	186	213	242	409	661	661
Average amount of CO_2 stored in EWP (tCO_2/ha)	9	10	11	12	13	14	15	13	0	0

Table 4 also shows that credits for carbon in EWP shorten the cutting cycle and reduces extracted volume at intermediate and higher carbon prices. There are several forces at work here. First, obtaining credits for carbon stored in EWP gives an incentive to shorten the cutting cycle: since payment takes place at the instant of harvest, the shorter the cutting cycle, the earlier payment takes place and the smaller is the effect of discounting. Second, there is an incentive to increase harvested volume to obtain credits for carbon stored in EWP. However, this is more than offset by foregone credits for carbon stored in the remaining stand as AGB is not only reduced by the increased harvest but also by the resulting additional damage. The resulting carbon supply curve in Figure 2 shows that payments for carbon stored in EWP never increase the amount of carbon stored but rather reduces it for most carbon prices.

Figure 2 presents the carbon supply curves resulting from maximizing the LEV in Equation (21) or (23). 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)). Now we turn to this comparison in order to make sure a global optimum is obtained.

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 (Equations (21) and (23)). Table 5 reports LEVs for a no harvest regime and compares them with LEVs from locally optimal cutting cycles.

Table 5. LEV of "harvest" and "no harvest" scenario for 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
Equivalent price permanent credit (USD/tCO_2)	0	2.5	4.9	7.4	9.8	12.3	14.7	22.1	24.5
RIL without EWP									
LEV with harvest (USD/ha)	248	274	315	385	478	601	800	2136	20252
LEV no harvest (USD/ha)	-11351	-8191	-5030	-1870	1290	4451	7611	17092	20252
RIL with EWP									
LEV with harvest (USD/ha)	248	278	316	379	463	585	781	2069	20252
LEV no harvest (USD/ha)	-11351	-8191	-5030	-1870	1290	4451	7611	17092	20252
CL without EWP									
LEV with harvest (USD/ha)	239	243	264	320	398	526	741	2160	20558
LEV no harvest (USD/ha)	-11045	-7885	-4725	-1564	1596	4756	7917	17398	20558

Table 5 shows that at low carbon prices (i.e. $p \leq 0.6$ USD/tCO_2) it is optimal to harvest as it gives a higher LEV than managing a climax 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. To understand the difference between Figures 2 and 3, notice that the supply curve of Figure 2 takesthe perspective of a forest owner with an infinite planning horizon who considers adjustments of forest management when the carbon price changes marginally. In this case adjustments to the steady state forest stand and the management practices will be marginal.

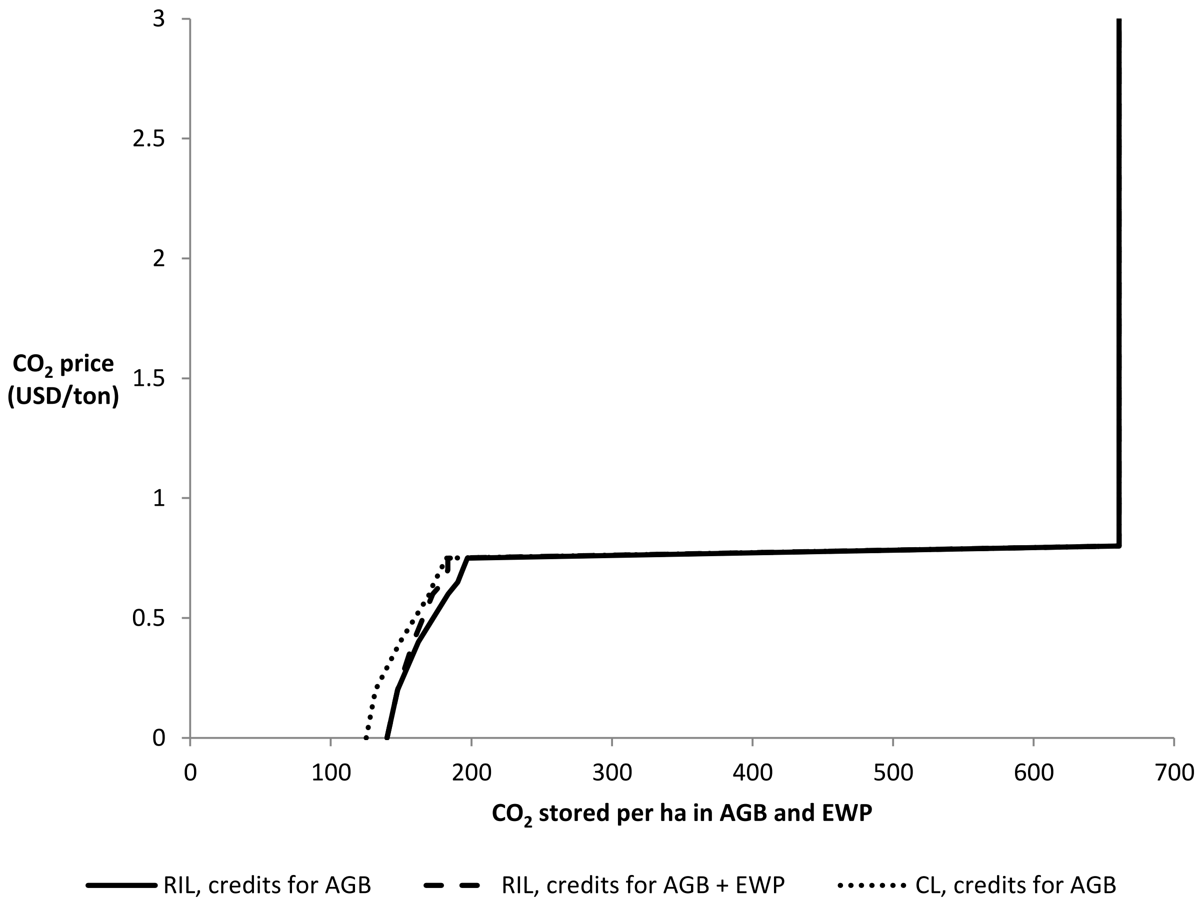

Figure 3. Supply curves for carbon storage for a managed tropical forest on Kalimantan, Indonesia, for RIL and CL: global solutions

By contrast the supply curves for forest carbon storage in Figure 3 come from the perspective of a forest manager with an infinite planning horizon who can chose an optimal steady state forest stand and adopt the associated harvest and management schedule.

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

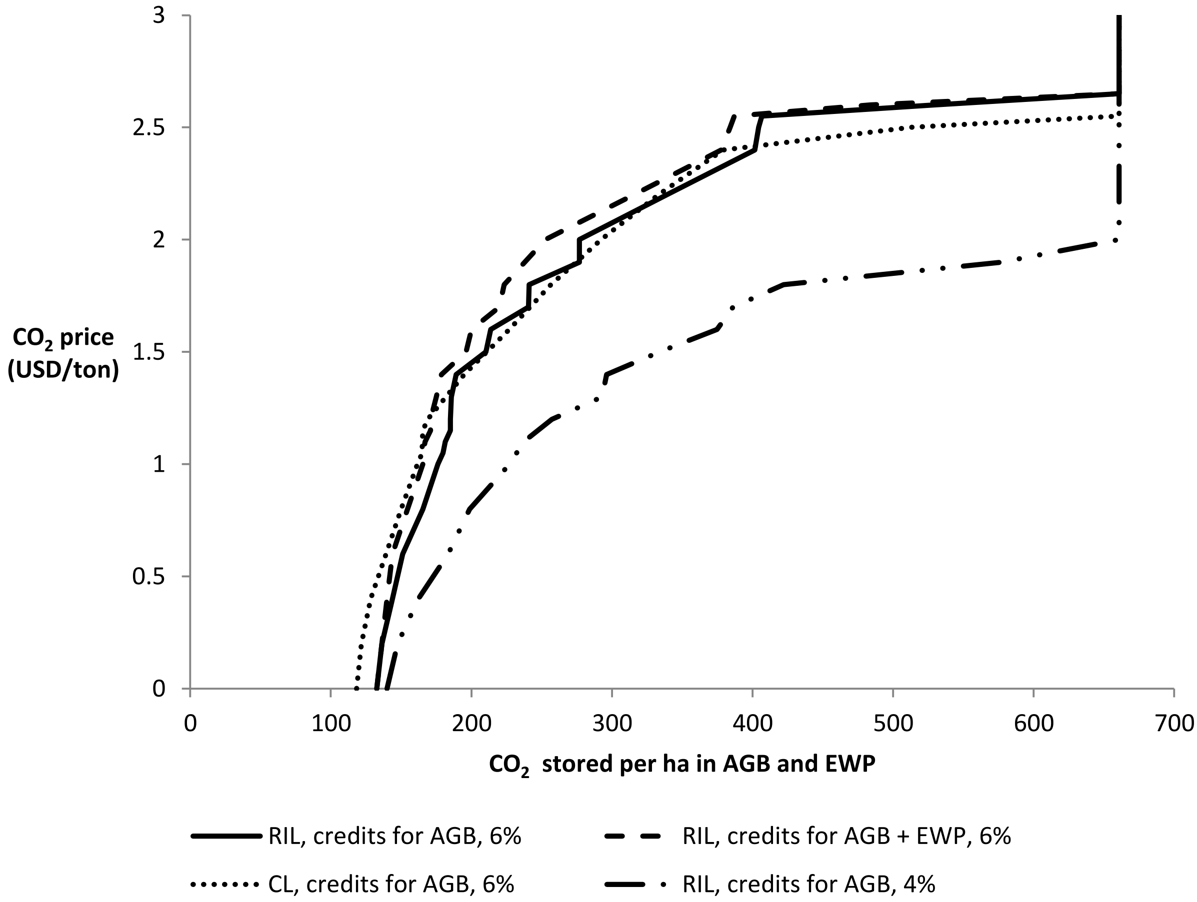

Figure 4. Supply curves for carbon storage for a managed tropical forest on Kalimantan, Indonesia, for RIL and CL for a 6% discount rate

4.4.Sensitivity analysis

To test the sensitivity of our carbon supply curves with respect to the discount rate, we also derived the supply curves using a discount rate of 6%. The corresponding carbon supply curves are presented in Figures 4 (marginal increases in carbon price, as in section 4.2) and 5 (global solutions as in section 4.3), together with the carbon supply curve for RIL with credits for carbon in AGB only with a 4% discount rate. The baseline is the case of RIL without carbon pricing and with a discount rate of 6%.

Generally, higher disount rates imply a shorter optimal cutting cycle as income from timber and carbon credits is more heavily discounted (see Figure 4). As a result, the switch to a zero harvest management policy takes place at a higher carbon price when the discount rate is 6%. As can be seen in Figure 4, there is a large potential for additional carbon storage under REDD+ also with a 6% discount rate. When the carbon price is zero, switching to RIL increases the amount of CO_2 stored on a hectare of forest land from 118 tons to 133 tons (+13%). At a carbon price of 0.6

USD/tCO_2 (7.4 USD/tCO_2 for a permanent credit; comparable with the current price for emission allowances in the EU ETS) this increases to 151 tCO_2/ha (+28%). Figure 5 shows similar results for the case of global optima.

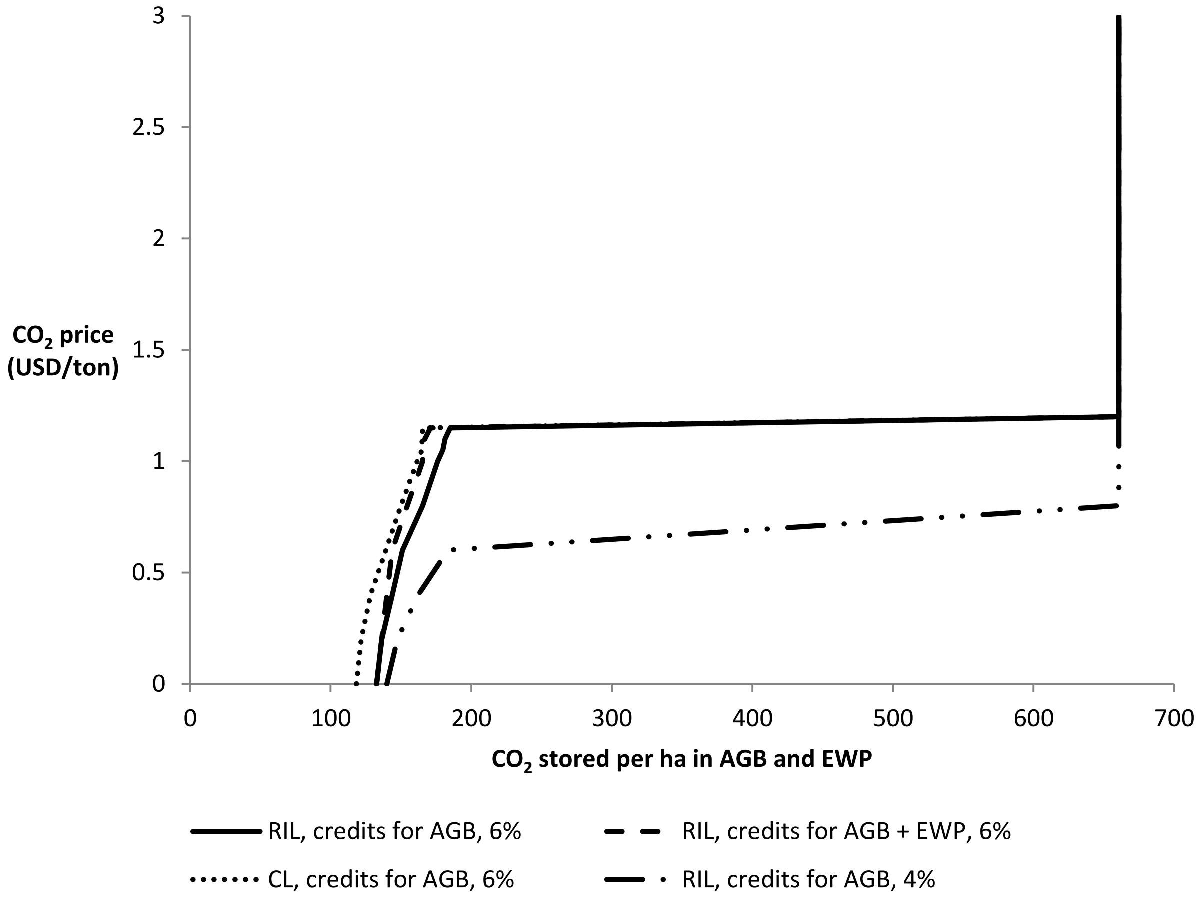

Figure 5. Supply curves for carbon storage for a managed tropical forest on Kalimantan, Indonesia, for RIL and CL: global solutions for a 6% discount rate

5. CONCLUSIONS

We have applied a Hartman model to a tropical forest considering timber values and benefits of carbon sequestration from sustainable forest management (REDD+). We have used detailed data from Kalimantan, Indonesia. We have presented supply curves for forest carbon sequestration in the context of REDD+, both when carbon credits are awarded only for carbon stored in above-ground biomass and when credits are also awarded for carbon end-use wood products. If carbon credits are valued at 0.6 USD/tCO_2 for two-year credits (equivalent to current (mid-2015) prices of permanent credits in the EU ETS), the total amount of CO_2 (implicitly) stored per ha in AGB and EWP could increase by 58 tons or 46%. Assuming that all production forest with selective logging on the

Indonesian part of Kalimantan (10.8 million ha; not including limited production forests, protection forests and plantation forests) is currently managed using conventional logging, this suggests that REDD+ could permanently increase the amount of CO_2 stored by 626 million tCO_2 on Kalimantan. This is equivalent to e.g. about a year's emissions of greenhouse gases from the United Kingdom and Ireland (excluding emissions from land use, land-use change and forestry). Second, the extracted volume of timber increases with the carbon price up to a price of 1.5 USD/tCO_2 (18 USD/ tCO_2 for permanent credits). This shows that sustainable forest management, forest carbon sequestration and production of commercial timber – important for employment in the sawmill and manufacturing industries – can go hand in hand. However, for higher carbon prices it will be beneficial for forest owners to not harvest at all. Third, remuneration for carbon stored in end-use wood products (EWP) has a 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 longer when the carbon price is positive. As a consequence, carbon gets stored in EWP at a later date and the corresponding payments take place later as well and are hence discounted more heavily than under 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. Fourth, credits for carbon stored in EWP do not increase the amount of carbon stored as carbon stored in end-use products is not stored in trees, while cutting more trees for timber increases damages on the remaining stand and reduces revenues from carbon credits for carbon in AGB. Fifth, 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). An interesting line for future research is to extend the current model with a transition phase from an existing initial stand to a new steady state forest and derive supply curves for forest carbon sequestration for the transition phase and for the steady state.

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Appendix 1. Data for forest growth model

***A*$_1$=**

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

***A*$_2$ =**

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

***A*$_3$ =**

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

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

Endnotes

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[ii] Environmental Economics and Natural Resources Group, Wageningen University, Hollandseweg 1, 6706KN, Wageningen, The Netherlands. Email: yonky.indrajaya@wur.nl

[iii] Corresponding author. Environmental Economics and Natural Resources Group, Wageningen University, The Netherlands, and CESifo, Munich, Germany. Email: edwin.vanderwerf@wur.nl

[iv] Environmental Economics and Natural Resources Group, Wageningen University, The Netherlands. Email: hans-peter.weikard@wur.nl

[v] Forest Ecology and Forest Management Group, Wageningen University, The Netherlands. Email: frits.mohren@wur.nl

[vi] Environmental Economics and Natural Resources Group, Wageningen University, The Netherlands. Email: ekko.vanierland@wur.nl

[vii] See also Olschewski and Benitez (2010) and Galinato and Uchida (2011).

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

[ix] 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).

[x] 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).

[xi] 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.

[xii] Source: World Bank World Development Indicators.

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

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