LOGGING DAMAGE AND INJURED TREE MORTALITY IN TROPICAL FOREST MANAGEMENT

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ABSTRACT

Selective logging in tropical forests can lead to severe damages on the remaining stand. The use of Reduced Impact Logging (RIL) techniques can reduce these damages relative to Conventional Logging (CL) techniques but comes with higher fixed costs. Injured trees have very low or zero commercial value but negatively affect the growth of other trees. This fact has been ignored in the economic literature on the optimal management of tropical forests. We analyse how logging damage and the presence of injured trees affect key variables for a forest manager using a Faustmann model and data for a tropical forest on Kalimantan.

JEL codes: Q23, Q54, Q57

Keywords: reduced impact logging, conventional logging, logging damage, Faustmann, Kalimantan, sustainable forest management, tree mortality

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1. INTRODUCTION

The extraction of wood from tropical forests using selective logging may contribute to economic development but may also cause forest degradation, especially through the resulting damage on the remaining stand (Medjibe and Putz, 2012). This is particularly the case when conventional logging (CL) techniques are used as workers start cutting ill-trained and ill-prepared. With reduced-impact logging (RIL), harvesting strategies are prepared in advance as (among other things) topography is assessed and skidtrails are planned and opened well in advance, while workers are trained in directional felling. This results in less damage on the remaining stand (Putz and Pinard, 1993, Pinard and Putz, 1996, Bertault and Sist, 1997, Sist et al., 2003). A reduction in logging damage (e.g. snapped stems or uprooting of trees) implies a larger stock of trees for future harvest and, ceteris paribus, a larger stock of carbon in above-ground biomass. However, RIL comes at higher costs due to investment in machineries and training of staff.

Various papers have studied the effects of differences in the costs and benefits of sustainable forest management through RIL, vis-à-vis CL, on the value of the land of a tropical forest. However, they vary widely in their assumptions on the impact of harvesting on the remaining stand. Some papers ignore damages altogether (e.g. Buongiorno et al., 2012, Ingram and Buongiorno, 1996), some assume logging affects only smaller diameter classes (Boscolo and Buongiorno, 1997, Boscolo et al., 1997, Boscolo and Vincent, 2000), while others have a detailed representation of the harvest-damage relation (Indrajaya et al., 2016). Clearly, this has important consequences for the relative economic performance of RIL and CL as well as for the resulting volumes damaged and amounts of carbon stored in above-ground biomass. Importantly, none of these papers takes the indirect costs of injured trees into account: while these trees typically have zero commercial value, they affect the growth of the rest of the stand as they compete for light and nutrients – notably the ingrowth of new trees. Economic models of optimal management of tropical forests assume that all trees are healthy and that trees that get injured after harvest die and disappear immediately (see e.g. Boscolo and Buongiorno, 1997, Boscolo and Vincent, 2000), thereby assuming away the impact of injured trees on the remaining stand. Again, this assumption has repercussions for the economic outcomes of RIL and CL as well as for volumes of carbon stored.

In this paper we explicitly take the role of damages and the biophysical and economic effects of the presence of injured trees into account when analyzing the economic performance of RIL and CL for a tropical forest. We use detailed data on forest growth and the costs of RIL and CL in a Faustmann model for a forest on Kalimantan. We use a scenario in which logging does not cause any damages as a point of reference to analyse the effects of different assumptions on the role of injured trees (both regarding their presence and their mortality rate) on the Land Expectation Value (LEV) for RIL and CL to find for each scenario which logging technique is preferred. Furthermore, we analyse the size of volumes damaged due to harvesting and the impact of harvesting and damages on stand composition. The latter has implications for the amount of carbon stored.

The remainder of this paper is organized as follows. In the next section, we first describe the economic optimization model and the forest growth model. In section 3 we present the scenarios used for our analysis. Next we present the parameters used. We present our results in section 5 and perform a sensitivity analysis in section 6. We conclude in section 7.

2. ECONOMIC AND FOREST GROWTH MODELS

Our model builds on the matrix stand growth model developed by Buongiorno and Michie (1980) and has been used to analyse the effects of credits for forest carbon sequestration on carbon storage in Kalimantan in Indrajaya et al. (2016). We use one hectare of forest stand as our unit of analysis.

2.1. Forest growth and damage model

Let l indicate the number of species groups. Each species group has a healthy variety and an injured variety. To make a distinction between the healthy varieties and injured varieties of a species group, we order species groups such that the first $l = m/2$ species varieties indicate healthy varieties; that is, $i, k \in [1, \ldots, l]$ indicate healthy varieties and $i, k \in [l + 1, \ldots, m]$ indicate injured varieties of the same species groups.

Forest growth can be described as

$$\mathbf{y}_{T+\theta} = \mathbf{G}_x \mathbf{z}_T + \mathbf{c}; \mathbf{y}_{t+\gamma\theta} = \mathbf{G}_x\left(\mathbf{y}_{t+\theta(\gamma-1)}\right) + \mathbf{c}, \tag{1}$$

where vector $\mathbf{y}_t = [y_{ijt}]$ is a column vector and y_{ijt} is the number of the trees per ha of species variety i and diameter class $j \in [1, \ldots, n]$ at time t. Parameter θ represents the growth period in years and γ is the number of growth periods θ within the harvesting cycle (T). Vector $\mathbf{z}_T = [z_{ijT}]$ denotes the residual stand after harvest, where z_{ijT} is the number of trees that remain in diameter class j of variety i after harvest. Matrix $\mathbf{G}_x$ is the $nm \times nm$ forest growth matrix where x indicates that its composition depends on the scenario at hand. It consists of an upgrowth matrix and an ingrowth matrix:

$$\mathbf{G}_x = \mathbf{A}_x + \mathbf{R}. \tag{2}$$

Matrix $\mathbf{A}_x$ is an upgrowth matrix representing the probabilities of a tree in each species group and diameter class to stay in the same diameter class (a_{ij}), die (o_{xij}), or move to a larger diameter class ($b_{xij} = 1 - a_{ij} - o_{xij}$). Among other things, we analyse the effect of a lower growth rate of injured varieties. Hence, the mortality rate o_{xij} and the probability to move to a larger diameter class b_{xij} depend on the scenario at hand, x:

$$\mathbf{A}_x = \begin{bmatrix} \mathbf{A}_{x,1} & 0 & \dots & 0 \\ 0 & \mathbf{A}_{x,2} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \mathbf{A}_{x,m} \end{bmatrix}; \ \mathbf{A}_{x,i} = \begin{bmatrix} a_{i1} & & & 0 \\ b_{xi2} & a_{i2} & & \\ & \ddots & \ddots & \\ 0 & & b_{xin} & a_{in} \end{bmatrix} \tag{3}$$

Matrix **R** represents the effects of the stand state on ingrowth. It is based on the hypothesis that ingrowth for a species is positively affected by the number of trees of that species, and negatively affected by the total stand density (Buongiorno and Michie, 1980; Buongiorno et al., 1995; Lu and Buongiorno, 1993). We assume that there is no ingrowth in injured species varieties: trees enter these varieties only when being injured after harvest. That is,

$$\mathbf{R} = \begin{bmatrix} \mathbf{R}_{11} & \mathbf{R}_{12} & \dots & \mathbf{R}_{1m} \\ \mathbf{R}_{21} & \mathbf{R}_{22} & \dots & \mathbf{R}_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{R}_{m1} & \mathbf{R}_{m2} & \dots & \mathbf{R}_{mm} \end{bmatrix}; \ \mathbf{R}_{ik} = \begin{bmatrix} e_{i1} & e_{i2} & \dots & e_{in} \\ 0 & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 0 \end{bmatrix} \text{ for } i \le l; \ \mathbf{R}_{ik} = \mathbf{0} \text{ for } i > l. \tag{4}$$

Finally, vector **c** contains the ingrowth constants representing the number of trees exogenously entering the smallest diameter class for each variety. There is no exogenous ingrowth in injured species varieties:

$$\mathbf{c} = \begin{bmatrix} \mathbf{c}_1 \\ \mathbf{c}_2 \\ \vdots \\ \mathbf{c}_m \end{bmatrix}; \mathbf{c}_i = \begin{bmatrix} \beta_{i0} \\ 0 \\ \vdots \\ 0 \end{bmatrix} \text{ for } i \le l; \ \mathbf{c}_i = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \text{ for } i > l. \tag{5}$$

Harvest at the end of the cutting cycle is represented by vector $\mathbf{h}_T = [h_{ijT}]$, where h_{ijT} is the number of trees harvested of variety i and DBH (diameter at breast height) class j. The damage to the residual stand $\mathbf{d}_{xsT}$ is a function of overall logging intensity and this function depends on the scenario at hand, x, and the harvesting practice $s \in \{CL, RIL\}$. We will provide more details below. Equation (6) represents the stand immediately after harvest:

$$\mathbf{z}_T = \mathbf{y}_T - \mathbf{h}_T - \mathbf{\Gamma}_{xs}\mathbf{d}_{xsT}. \tag{6}$$

A novelty in our model is the introduction of matrix $\mathbf{\Gamma}_{xs}$. After harvest, this transition matrix moves a fraction of the trees that got damaged during harvest from ‘healthy’ species varieties to ‘injured’ species varieties. The rest of the damaged trees are considered dead and no longer affect the growth rate of living trees through competition for light and nutrients. In our model this means that they disappear immediately from the plot. The exact design of this matrix depends on the scenario at hand and will be explained below. Note that the transition matrix differs for the two logging techniques: following Pinard and Putz (1996), Bertault and Sist (1997) and Sist et al. (2003) we allow for a larger fraction of injured trees with conventional logging relative to RIL.

2.2. Economic model

Optimal management of a multi-age multi-species tropical forest concerns the choice of three variables: (i) type of logging practice (CL or RIL), (ii) length of the cutting cycle T, and (iii) harvest intensity $\mathbf{h}_T$ (i.e. number of trees harvested for each variety and diameter class per ha). The economic model for maximizing land expectation value (LEV) over an infinite horizon subject to logging damage, harvest and steady state equilibrium constraints for a given cutting cycle looks as follows:

$$\max_{\mathbf{y}_T,\mathbf{h}_T} LEV = \frac{\mathbf{v}_s{}' \, \mathbf{h}_T - F_s}{(1+r)^T - 1} - \mathbf{v}_s{}' \boldsymbol{z}_{\boldsymbol{T}} \qquad (7)$$

subject to equations (1), (6) and

$$\mathbf{y}_T \geq \mathbf{h}_T + \mathbf{d}_{xsT} \qquad (8)$$

$$\mathbf{h}_T, \mathbf{y}_T, \mathbf{z}_T \geq 0 \qquad (9)$$

$$h_{ij} = 0 \text{ for all } j < \eta \qquad (10)$$

$$\mathbf{y}_t = \mathbf{y}_{t+T} \text{ for all } t = 1, \ldots, \infty. \qquad (11)$$

Vector $\mathbf{v}_s$ denotes the net revenue per tree (i.e. price minus variable costs and taxes) under logging practice s (where s = CL represents conventional logging and s = RIL represents reduced impact logging), F_s represents the fixed costs per ha of harvesting using logging practice s and r represents the discount rate. Equations (8) and (9) are the harvest and non-negativity constraints. Equation (10) represents the minimum diameter harvested, where η is the minimum diameter harvested as restricted by government regulation. Equation (11) shows the equilibrium steady state constraint. We solve the model for different values of $\gamma \geq 1$ and then find the value of γ that maximizes the land expectation value.

3. LOGGING DAMAGE AND GROWTH OF INJURED TREES

Our focus in this paper is on the economic performance of RIL and CL under various assumptions regarding the role of trees that get injured during harvest. We proceed to describe our scenarios. For each of our scenarios we will assess the performance of conventional logging practices and reduced impact logging. For each scenario, we make assumptions on the following model characteristics:

1. The effect of harvesting on the stand through damages: $\mathbf{d}_{xsT}$;
2. The effect of damages on stand composition, i.e. whether some damaged trees move from healthy species varieties to injured species varieties: $\mathbf{\Gamma}_{xs}$;
3. The effect of injured trees on the ingrowth of healthy trees: $\mathbf{R}_{ik}$;
4. The growth parameter and mortality rate for injured trees for $i > l$: b_{xij} and o_{xij}.

3.1 Scenario A: No damage

Our first scenario is a reference scenario in which we make the extreme assumption that logging does not result in damages and, consequently, there are no injured or dead trees (e.g. Buongiorno et al., 2012, Ingram and Buongiorno, 1996). This allows us to examine the effects of the differences in fixed and variable costs for RIL and CL on the corresponding

LEV and optimal cutting cycle. In subsequent scenarios we will introduce more realistic assumptions about damaged trees.

We denote this scenario *scenario A*, i.e. $x = A$ in which we assume

$$\mathbf{d}_{AsT} = \mathbf{0} \tag{12}$$

and since no trees need to be moved from healthy to injured species varieties

$$\boldsymbol{\Gamma}_{As} = \mathbf{I}_{\boldsymbol{nm}\times\boldsymbol{nm}}. \tag{13}$$

Furthermore, since there is no distinction between healthy and injured trees,

$$o_{Aij} = o_{ij}. \tag{14}$$

3.2 Scenario B: Damage occurs but does not affect growth of the remaining stand

For *scenario B* we follow Macpherson et al. (2010) and Indrajaya et al. (2016) and assume that harvest intensity and stand composition affect damages in the following way:

$$\mathbf{d}_{BsT} = \left(\sum_{\mathrm{i}} \sum_{\mathrm{j}} \mathrm{h}_{\mathrm{ijT}}\right)\mathbf{D}_{s}\mathbf{y}_{\mathrm{T}} \tag{12'}$$

where $\mathbf{D}_{\mathrm{s}}$, 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 damaged, per tree harvested, within each species group i and size j. Matrix $\mathbf{D}_{s}$ consists of damage coefficient matrices $\mathbf{E}_{\mathrm{s}}$ and null matrices:

$$\mathbf{D}_{s} = \begin{bmatrix} \mathbf{E}_{s} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{E}_{s} & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{E}_{s} \end{bmatrix}. \tag{15}$$

In this scenario, we assume that all damaged trees disappear immediately and do not affect growth of the remaining stand, irrespective whether they are injured but still alive (for example due to a bark or crown injury) or immediately die during harvest (for example due to a broken trunk). This is a common assumption in the literature on the optimal management of multi-age multi-species forests (e.g. Boscolo et al., 1997, Boscolo and Vincent, 2000, 2003, Indrajaya et al., 2016). As a result, as in scenario *A*, no trees need to be moved from healthy to injured species varieties so,

$$\mathbf{\Gamma}_{Bs} = \mathbf{I}_{nm\times nm} \tag{13'}$$

and

$$o_{Bij} = o_{ij}. \tag{14'}$$

Comparing the results of this scenario with those of scenario *A* allows us to disentangle the effects of differences in costs and the effects of differences in damages between CL and RIL on various variables.

3.3 Scenario C: Damage occurs and injured trees affect growth

In *scenario C* we assume harvest causes damages to the remaining stand, as in scenario *B*:

$$\mathbf{d}_{CsT} = \left(\sum_{\mathrm{i}} \sum_{\mathrm{j}} \mathrm{h}_{\mathrm{ijT}}\right)\mathbf{D}_{\mathrm{s}}\mathbf{y}_{\mathrm{T}}. \tag{12''}$$

However, in the current scenario we divide damaged trees into two groups: injured trees and dead trees. We assume that while dead trees *de facto* disappear as they no longer affect the growth rate of the other trees, injured trees stay on the plot. Mathematically, for each species group and each diameter class a fraction of the damaged trees that disappeared after harvest in scenario *B* now stays on the plot and moves from the 'healthy' species variety to the corresponding 'injured' species variety. Let $\omega_{i,j,s}$ denote the proportion of damaged trees in diameter class j of 'healthy' species variety $i \leq l$ that moves to diameter class j of its corresponding 'injured' species variety $k > l$ after harvest. In scenario *C* we assume

$$\mathbf{\Gamma}_{Cs} = \begin{bmatrix} \mathbf{W}_{1,1,s} & \cdots & \mathbf{W}_{1,m,s} \\ \vdots & \ddots & \vdots \\ \mathbf{W}_{m,1,s} & \cdots & \mathbf{W}_{m,m,s} \end{bmatrix} \tag{13''}$$

where $\mathbf{W}_{i,k,s} = \mathbf{I}_{n\times n}$ for $i, k \leq l$ so all previously healthy trees that got damaged during harvest move out of the 'healthy' species variety; $\mathbf{W}_{i,k,s} = \mathbf{0}$ for $i \leq l$ and $k > l$ as after harvest previously injured trees do not suddenly become healthy; $\mathbf{W}_{i,k,s} = -\mathbf{I}_{n\times n}\omega_{i,j,s}$ for $i > l$ and $k \leq l$ (that is, a fraction $\omega_{i,j,s}$ of previously healthy trees that got damaged during harvest moves to the injured variety; the remainder dies and disappears), and $\mathbf{W}_{i,k,s} = \mathbf{I}_{n\times n}(\mathbf{1} - \omega_{i,j,s})$ for $i, k > l$ (i.e., all trees that were previously injured had time to recover – although with zero commercial value – and simply get damaged again).

Injured trees compete with other trees for light and nutrients. In our growth model, the upgrowth of trees (the fraction of trees within a diameter class moving up to a larger diameter class) is unaffected by the density and composition of the stand. However, the ingrowth of new trees is positively affected by the basal area of the own species and negatively affected by the basal area of other species. In this scenario we compare two different examples regarding the effect of injured trees on ingrowth of the own species. First, we assume that injured trees positively contribute to ingrowth of healthy trees of the own species, just like healthy trees. We subsequently analyse the effects of assuming that injured trees negatively affect the ingrowth of healthy trees of the own species, just like healthy trees negatively affect the ingrowth of trees in other species groups.

As in scenario *B*, we assume that injured trees and healthy trees have the same growth and mortality rates:

$$o_{Cij} = o_{ij} \text{ for all } i. \qquad (14'')$$

Comparing the results for this scenario with those for scenario *B* allows us to analyse the effect of the presence of injured trees that have zero commercial value but may affect the ingrowth of new trees due to competition for light and nutrients.

3.4 Scenario D: Damage occurs and injured trees have higher mortality rate

For *scenario D* we make the same assumptions regarding damages and injured species varieties as in scenario *C*:

$$\mathbf{d}_{DsT} = \left(\sum_{\mathrm{i}} \sum_{\mathrm{j}} \mathrm{h}_{\mathrm{ijT}}\right)\mathbf{D}_{\mathrm{s}}\mathbf{y}_{\mathrm{T}} \quad (12''')$$

and

$$\boldsymbol{\Gamma}_{Ds} = \begin{bmatrix} \mathbf{W}_{1,1,s} & \cdots & \mathbf{W}_{1,m,s} \\ \vdots & \ddots & \vdots \\ \mathbf{W}_{m,1,s} & \cdots & \mathbf{W}_{m,m,s} \end{bmatrix}. \quad (13''')$$

As in scenario *C*, we also compare two different examples regarding the effect of injured trees on ingrowth of the own species.

Sist and Nguyen-Thé (2002) have shown that injured trees have a higher mortality rate than trees that are undamaged. Hence in scenario *D* we assume that

$$o_{Dij} = o_{ij} + \kappa \text{ for } i > l. \quad (14''')$$

That is, injured trees have a higher mortality rate and a lower probability to move up to a larger diameter class than healthy trees. Hence, with this scenario we can assess the effect of higher tree mortality of injured trees.

4. PARAMETERIZATION OF THE MODEL

4.1. Forest Growth Parameters

We apply the forest growth model described in Indrajaya et al. (2016), which is based on the growth matrix developed by Krisnawati *et al.* (2008) for lowland dipterocarp forest in Central Kalimantan. The forest is dominated by dipterocarp species including *Shorea* spp. and *Dipterocarpus* spp. We use a growth period θ of 2 years. There are three (healthy) species groups i in the growth matrix with $i = 1$ for commercial dipterocarp, $i = 2$ for commercial non-dipterocarp, and $i = 3$ for non-commercial species. Correspondingly, $i \in \{4, 5, 6\}$ indicates the respective injured variety of each species group. Each species group i consists of 13 5-centimeter diameter classes ($j = 1$ for 10-14 cm DBH, and $j = 13$ for > 70 cm DBH). Following current Indonesian policy, we apply a diameter cutting limit of 40 cm (i.e. $\eta = 40$). Larger trees are only harvested when it is commercially attractive to do so. The complete growth matrices and model validation are presented in Indrajaya et al. (2016).

Damage parameters of matrix $\mathbf{D}_s$ scenarios *B*-*D* are as in Indrajaya et al. (2016) and are based on Priyadi et al. (2007). Damaged trees can further be classified into dead trees and injured trees. Bertault and Sist (1997) and Sist et al. (2003) compare tree injuries and mortalities after harvests based on conventional logging techniques with those after harvests based on reduced impact logging techniques in East Kalimantan, and Pinard and Putz (1996) do so for Sabah, Malaysia. From these papers, we calculate the average fraction (over all diameter classes over all three papers) of damaged trees that dies after harvest to be 53% for CL and 43% for RIL. Next, we use findings from Pinard and Putz (1996) to calculate the parameters $\omega_{i,j,s}$ of transition matrix $\mathbf{\Gamma}_{xs}$, i.e. the proportion of damaged trees in diameter class j of 'healthy' species variety $i \leq l$ that moves to diameter class j of its corresponding 'injured' species variety $k > l$ after harvest, for scenarios *C* and *D*. The details and the values of the elements of the matrix can be found in Appendix A.

In scenario *D* we use an increased mortality rate for injured trees as compared to healthy trees. We increase the annualised mortality rate of injured trees by 3.1 percentage points relative to that of healthy trees, based on the mean mortality rates of 1.8% and 4.9% for undamaged and injured trees respectively in that Sist and Nguyen-Thé (2002). Since our model is based on two-year growth periods we use $\kappa = 0.059923$. Sist and Nguyen-Thé (2002) report that four years after harvest they do not find statistically significant differences between mortality rates of the two groups, but the authors admit that "[t]his decrease of mortality in comparison to that recorded 2 years after logging was likely to be the result of the removal of the most badly damaged stems [through cutting or poisoning], eliminating by this way the most vulnerable trees in terms of survival." (p.89). In our model, and in most managed tropical forests, badly damaged stems are not removed.

In scenarios C and D we analyse the effects of two different examples regarding the effect of injured trees on ingrowth of the own species. First, we assume that injured trees positively contribute to ingrowth of healthy trees of the own species, just like healthy trees. In this case the elements of the ingrowth matrix $\mathbf{R}$ used in Indrajaya et al. (2016) are used for both healthy and injured species groups. Alternatively we assume that injured trees negatively affect the ingrowth of healthy trees of the own species, just like healthy trees negatively affect the ingrowth of trees in other species groups. That is, $\mathbf{R}_{i\,i+3} = \mathbf{R}_{ij}$ for $i \neq j$ and $j < l$.

We estimate the weight of Above Ground Biomass (AGB) in metric tons per tree with the allometric equation developed by Chave et al. (2005): $AGB_j = \rho \times \exp\left(-1.499 + 2.148 \ln \overline{DBH}_j + 0.207 \ln \overline{DBH}_j^{\,2} - 0.0281 \ln \overline{DBH}_j^{\,3}\right)/1000$, where $\overline{DBH}_j$ represents the middle point of the diameter values in diameter class j, and ρ represents the wood density (i.e. 0.68 based on Rahayu et al., 2006). The proportion of carbon stored in forest biomass is 0.47 (IPCC, 2006). The amount of carbon stored in AGB at time t is $\boldsymbol{\chi}_t = \mathbf{AGB}'\mathbf{y}_t$. The average amount of carbon stored in AGB in one cutting cycle is therefore: $\bar{\boldsymbol{\chi}} = \sum_{t=\theta}^{T} \boldsymbol{\chi}_t / \gamma$, where γ is the number of growth periods within a cutting cycle.

4.2. Economic Parameters

The production cost parameters for CL and RIL used in our study are those reported by Dwiprabowo et al. (2002) for a forest concession on East-Kalimantan and used in Indrajaya et al. (2016).[5] We use the investment and administration costs data from a technical proposal of a company in Kalimantan (PT Sumalindo Lestari Jaya, 2008).[6] The standard prices determined by the Indonesian government are used for gross prices of timber per m^3 are in which commercial species are sorted into two groups: dipterocarp and non-dipterocarp.[7] The net price $\mathbf{v}_s$ is the gross price of timber minus the variable costs and taxes per cubic meter and is positive for healthy trees and zero for injured trees. Total variable costs are slightly lower for RIL than for CL (46.4 USD/m^3 vs 44.8 USD/m^3), whereas the fixed costs per harvest for RIL are substantially higher than those for CL (389 and 297 USD/ha per harvest respectively). The different machines used and additional pre-harvesting activities with RIL such as data checking and mapping, skidtrail marking and checking, software purchasing, vine cutting, and improved timber inventory and contour survey cause higher fixed costs for RIL (Dwiprabowo et al., 2002). Our data are similar to data from Boltz et al. (2001) in that the variable costs are higher for CL than that for RIL and the fixed costs are higher for RIL than those for CL. Regarding variable costs, additional activities with RIL, such as training and supervision, also imply higher costs. However, this is more than offset by higher skidding costs with CL (Dwiprabowo et al., 2002). The resulting net price (standard price minus variable costs) is 59 USD/m^3 for dipterocarp and 32 USD/m^3 for non-dipterocarp in CL and 61 USD/m^3 for dipterocarp and 34 USD/m^3 for non-dipterocarp in RIL.

Since 96% of managed tropical forests in Indonesia are managed by private companies (Hutan-Aceh, 2014), we use a discount rate of 12% for our main analyses. For

[5] 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).
[6] 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).
[7] 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.

sensitivity analysis, we use a discount rate of 4% based on the average real interest rate for Indonesia for the past 20 years.[8]

5. RESULTS

In this section, we first present the results for the different scenarios. We present results on Land Expectation Value (LEV), cutting cycles, stand composition, timber volumes, and carbon stored in Above-Ground Biomass (AGB).

5.1. Scenario A: No damage

In scenario *A*, we assume that logging activities do not cause damage to the residual stand. The results of the scenario *A* for CL and RIL are presented in Table 1.

Table 1. Results for optimal management under CL and RIL without damage to residual stand

	CL	RIL
Land Expectation Value (USD/ha)	305	274
Cutting cycle (years)	10	10
Basal Area before harvest (m^2/ha)	11	11
Basal Area after harvest (m^2/ha)	9	9
Extracted volume (m^3/ha)	23	23
Net harvest revenue (USD/ha)	938	967
Volume damaged (m^3/ha)	0	0
Average amount of C stored in AGB (t/ha)	55	55

When harvests do not cause damage to the residual stand, the only difference between CL and RIL is in their costs, with CL having higher variable costs but RIL having higher fixed costs. Table 1 shows that the stand state of the forest and volumes harvested are the

[8] Source: World Bank World Development Indicators.

same for CL and RIL. With lower variable cost per m^3 timber harvested, RIL gives higher harvest revenue than CL. However, the higher variable cost cannot offset the much higher fixed costs in RIL, so LEV is higher in CL than in RIL. Hence, in the reference scenario, in which logging does not result in damages, profit-maximizing forest managers prefer CL over RIL.

The cutting cycle for CL and RIL is 10 years. The difference in fixed costs is not sufficiently large to induce a longer cutting cycle for RIL.[9] This 10 year cutting cycle is much shorter than the current cutting cycles determined by the Indonesian government (i.e. 30 years) but longer than the five-year cutting cycle found by Ingram and Buongiorno (1996) for the case of absence of logging damages when using CL for Malaysia. The average amount of carbon (C) stored in Above Ground Biomass (AGB) is the same for both CL and RIL (i.e. 55 ton C per ha).

5.2. Scenario B: Damage occurs but does not affect growth of the remaining stand

In scenario *B*, we assume that logging activities do cause damages to the residual stand, yet damaged trees do not affect the growth of the remaining stand. The results of scenario *B* are presented in Table 2.

With the assumption that all damaged trees die and disappear immediately from the plot, the cutting cycles for both CL and RIL are longer than those in scenario *A*: 18 and 20 years for CL and RIL respectively in scenario *B* as compared to 10 years for both CL and RIL in scenario *A*. In scenario *B*, the number of trees, basal areas, and extracted volumes are lower than those in scenario A, due to the damage on residual stand. The LEV’s are lower for

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[9] Note that our model uses a growth period of two years. The current difference in fixed costs is probably sufficient to induce a difference in cutting cycles of one year but this cannot be shown with our model. As a check we have run the model with larger differences in fixed costs and find that when fixed costs for RIL are 425 USD/ha or higher, the cutting cycle for RIL becomes longer than that for CL. In this paper, we use fixed cost for RIL of 389 USD/ha.

both CL and RIL in scenario *B* than those in scenario *A* due to smaller volumes, longer cutting cycles and lower extracted volumes.

Table 2. Results for optimal management under CL and RIL when damage occurs but does not affect growth of the remaining stand

	CL	RIL
Land Expectation Value (USD/ha)	32	29
Cutting cycle (years)	18	20
Total number of trees before harvest (trees/ha)	171	176
Total Basal Area before harvest (m^2/ha)	7	7
Basal Area after harvest (m^2/ha)	4	5
Extracted volume (m^3/ha)	12	14
Net harvest revenue (USD/ha)	512	638
Volume damaged (m^3/ha)	17	18
Average amount of C stored in AGB (t/ha)	29.3	31.4

As has been shown in the literature, application of reduced impact logging techniques results in less damage on the remaining stand as compared to conventional logging (Putz and Pinard, 1993, Pinard and Putz, 1996, Bertault and Sist, 1997, Sist et al., 2003). This results in a larger residual stand (ceteris paribus) and hence more potential for future harvests. Still, we find, as in scenario *A*, that CL gives a higher LEV than RIL. Apparently the gain in the size of the residual stand and the larger harvest size (14 vs 12 m^3/ha) and higher revenues (638 vs 512 USD/ha) are insufficient to offset the higher fixed costs and longer cutting cycle (and hence more discounting of harvest revenues) that come with the use of RIL (cf. Boscolo et al., 1997).

As shown in the last row of Table 2, when logging causes damage to the residual stand, the average amount of carbon stored in AGB is considerably lower as compared to that in scenario *A* even though the cutting cycles are longer in scenario *B*.

5.3. Scenario C: Damage occurs and injured trees affect growth

In scenario C, we assume that harvesting activities cause damage: while dead trees disappear immediately from the plot, injured trees become zero commercial value but stay on the plot. We analyse two different ways in which injured trees affect the ingrowth in the own (healthy) species group: 'positive effect' where injured trees still produce seedlings as if they are healthy and 'negative effect' where the they negatively affect ingrowth due to competition for light and nutrients just like trees from rival species groups. The results for scenario *C* are presented in Table 3.

Table 3. Results for optimal management under CL and RIL when damage occurs and injured trees affect growth of the remaining stand

Effect injured trees on ingrowth own species	Positive		Negative	
	CL	RIL	CL	RIL
Land Expectation Value (USD/ha)	35.1	32.3	31.1	27.2
Cutting cycle (years)	16.0	18.0	18.0	20.0
Total number of trees before harvest (trees/ha)	204.8	223.4	191.9	204.6
Basal Area before harvest (m^2/ha)	11.3	14.3	10.7	13.0
Basal Area after harvest (m^2/ha)	9.2	12.3	8.5	11.1
Extracted volume (m^3/ha)	11.0	13.6	11.8	14.2
Net harvest revenue (USD/ha)	477.0	604.9	504.8	624.9
Volume damaged (m^3/ha)	28.8	37.0	28.5	34.4
Average amount of C stored in AGB (t/ha)	61.2	83.2	57.2	74.8

With the assumption that some damaged trees move from healthy varieties to injured varieties rather than disappear immediately from the plot (as in scenario *B*), there could be more trees that produce seeds for ingrowth ('Positive' effect in Table 3) or, alternatively more trees that compete for light and nutrient with the healthy trees ('Negative' effect). When there are more trees producing seeds, the growth rate of healthy trees will be higher than that in scenario *B* because more trees will enter the smallest diameter class. With relatively faster growth rate in scenario *C*, the cutting cycle for both CL and RIL are shorter than those in scenario *B* (i.e. 16 and 18 vs 18 and 20 years for CL and RIL respectively). The LEVs are higher than those in scenario *B* (i.e. 35 and 32 vs 32 and 29 USD/ha for CL and RIL respectively).

In contrast, when the injured trees could not produce seeds, their existence will only impede the growth of healthy trees due to light and nutrients competition. With relatively slower growth rate of healthy trees than that in scenario *B*, the cutting cycles are the same as that in scenario *B* (i.e. 18 and 20 years for Cl and RIL respectively), but with lower LEVs (i.e. 31 and 27 vs 32 and 29 USD/ha for CL and RIL respectively).

In scenario *C*, the number of the trees and basal area are higher than those in scenario *B*, and hence the average amount of carbon stored in AGB in scenario *C* is larger than that in scenario *B*.

5.4. Scenario D: Damage occurs and injured trees have higher mortality rate

Relative to scenario *C,* we assume in scenario *D* that injured trees have a lower growth rate than healthy trees. The results for scenario *D* are presented in Table 4.

Table 4. Results for optimal management under CL and RIL when damage occurs and injured trees have higher mortality rate

	Positive		Negative	
	CL	RIL	CL	RIL
Land Expectation Value (USD/ha)	34.6	31.5	31.8	28.3
Cutting cycle (years)	18.0	20.0	18.0	20.0
Total number of trees before harvest (trees/ha)	189.5	198.9	178.3	185.6
Total number of trees after harvest (trees/ha)	158.7	171.8	150.0	160.8
Basal Area before harvest (m^2/ha)	8.3	9.2	7.8	8.6
Basal Area after harvest (m^2/ha)	6.3	7.4	5.9	6.8
Extracted volume (m^3/ha)	12.2	14.8	11.8	14.2
Net harvest revenue (USD/ha)	528.5	662.0	510.6	634.4
Volume damaged (m^3/ha)	21.5	24.2	19.5	21.6
Average amount of C stored in AGB (t/ha)	38.6	44.5	36.1	41.1

The lower growth rate for injured trees implies fewer seedlings for the case of the 'positive effect' assumption on own ingrowth. In contrast, with 'negative effect', there will be fewer trees competing for light and nutrients with healthy trees and hence the ingrowth of healthy species will be larger as compared to scenario *B*.

With the 'positive effect' assumption, cutting cycles is longer in scenario *D* than that in scenario *C* for CL (18 vs 16 years) and the same for RIL (i.e. 20 years), while with 'negative effect' assumption, the cutting cycles are the same in scenario *D* and *C* for both CL and RIL. With the 'positive effect' assumption, the LEVs are slightly higher for both CL and RIL in scenario *D* than those in scenario *C*. In contrary, with the 'negative effect' assumption the LEVs are higher for both CL and RIL in scenario *D* than those in scenario *C*.

In scenario *D*, there are fewer trees (healthy and injured) and a smaller basal area than in scenario *C*. Thus, the average amount of carbon stored in AGB for scenario *D* is less than in scenario *C* for both CL and RIL and both assumptions 'positive' and 'negative' effect.

6. CONCLUSIONS

Harvesting a managed tropical forest causes damage to the residual stand which, ceteris paribus, is lower when sustainable logging practices such as reduced impact logging (RIL) is used. Injured trees affect the growth of healthy trees. Thus far, the literature on optimal management of tropical forests ignores injured trees altogether and simply assumes that injured trees disappear from the plot after harvest, just like dead trees. In this paper we analysed four scenarios to identify the effect of various assumptions regarding injured trees on land expectation value (LEV), cutting cycle, basal areas and carbon stored in above-ground biomass (AGB).

We find that allowing injured trees to stay on the plot leads to larger basal areas and more carbon stored in AGB. This has important implications for the potential of managed tropical forests to store carbon in response to carbon management policies such as payments for ecosystem services. Furthermore, explicitly identifying injured trees slightly increases the LEV. The cutting cycle becomes slightly lower, unless lower growth rates for injured trees are taken into account.

Future research should assess the effect of injured trees of upgrowth (in addition to ingrowth) of healthy trees.

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APPENDIX A. ELEMENTS OF TRANSITION MATRIX $\mathbf{\Gamma}_{xs}$

In scenarios *C* and *D* we use transition matrix $\mathbf{\Gamma}_{xs}$ to move trees that got injured during harvest from healthy to injured species groups. From Bertault and Sist (1997), Sist et al. (2003) and Pinard and Putz (1996) we calculate the average fraction of damaged trees that dies after harvest to be 53% for CL and 43% for RIL. In Pinard and Putz (1996) these numbers are 61% and 46% respectively. This is the only paper from which we can derive these parameters for different diameter classes while differentiating between CL and RIL. We scale their numbers for the 10-20, 20-40 and 40-60 cm DBH classes down using the ratios 53/61 and 43/46 for CL and RIL respectively. Our growth model has 5 cm DBH classes with the largest class being 60-70 cm. We assume that all 5 cm classes within each of the broader

10-20, 20-40 and 40-60 DBH classes have the same fraction of damaged trees that dies after harvest. Furthermore, we assume that the numbers for the 60-70 cm class are the same as for the 40-60 cm class. The latter assumption can be justified based on the findings by Bertault and Sist (1997), who report only combined data for CL and RIL. The values for $\omega_{i,j,s}$, the fraction of previously healthy trees that got damaged during harvest and moves to the injured variety, are presented in Table A.1.

Table A.1. The values for $\omega_{i,j,s}$ for CL and RIL

DBH (cm)	CL	RIL
10-14	0.45	0.50
15-19	0.45	0.50
20-24	0.50	0.73
25-29	0.50	0.73
30-34	0.50	0.73
35-39	0.50	0.73
40-44	0.60	0.79
45-49	0.60	0.79
50-54	0.60	0.79
55-60	0.60	0.79
60-64	0.60	0.79
65-69	0.60	0.79
>70	0.60	0.79