Logging damage and injured tree mortality in tropical forest management

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Abstract
Using insights from the forest ecology literature, we analyze the effect of injured trees on stand composition and carbon stored in above-ground biomass and the implications for forest management decisions. Results from a Faustmann model with data for a tropical forest on Kalimantan show that up to 50% of the basal area of the stand before harvest can consist of injured trees. Considering injured trees leads to an increase in the amount of carbon in above-ground biomass of up to 165%. These effects are larger under reduced impact logging than under conventional logging. The effects on land expectation value and cutting cycle are relatively small. The results suggest that considering injured trees in models for tropical forest management is important for the correct assessment of the potential of financial programs to store carbon and conserve forest ecosystem services in managed tropical forests, such as reducing emissions from deforestation and forest degradation and payment for ecosystem services.

Recommendations for Resource Managers
• Considering the role of injured trees is important for managing tropical forests
These trees can cover up to 50% of basal area and contain more than 50% of the carbon stored in aboveground biomass.

Reduced impact logging leads to a larger basal area of injured trees and more carbon stored in injured trees than conventional logging.

Injured trees play an important role when assessing the potential for carbon storage in the context of payment for forest ecosystem services.

**KEYWORDS**
age-structured model, bioeconomic model, conventional logging, Faustmann, Kalimantan, logging damage, reduced impact logging, sustainable forest management, tree mortality, tropical forest

1 | INTRODUCTION

Limiting global warming to no more than 2°C, and preferably below 1.5°C, has become the target for global climate policy. To achieve this target, it will be necessary to utilize carbon sinks, including forests as a natural sink (Rogelj et al., 2015). The extraction of wood from tropical forests using selective logging causes forest degradation, especially through the resulting damage on the remaining stand (Medjibe & Putz, 2012), and thereby a reduction in the pool of stored carbon. This is particularly the case when conventional logging (CL) techniques are used as workers start cutting ill-trained and ill-prepared. Carbon losses can be reduced with the use of reduced-impact logging (RIL), that is, “intensively planned and carefully controlled timber harvesting conducted by trained workers in ways that minimize the deleterious impacts of logging” (Putz, Sist, Fredericksen, & Dykstra, 2008, p.1,428). Although uniform guidelines for RIL do not exist (Putz et al., 2008), common RIL practices include preharvest planning (block layout, inventory, vine cutting, data processing, and map making), harvest planning (tree marking, road planning, log and deck planning), infrastructure development (road construction, log deck construction, and skidtrail layout), directional felling, and low stumps (Dykstra & Heinrich, 1996; Holmes et al., 2002). Estimates for the fraction of the remaining stand that gets damaged during harvest range from 48% to 65% for CL and from 28% to 38% for RIL (Bertault & Sist, 1997; Pinard & Putz, 1996; Sist, Sheil, Kartawinata, & Priyadi, 2003). Still, a large fraction of damaged trees does not die but rather gets injured (e.g., crown or bark injury) where the survival rate for damaged trees is higher for RIL (54–62%) than for CL (39–52%) (Bertault & Sist, 1997; Pinard & Putz, 1996; Sist et al., 2003). Contrary to decayed dead trees, injured trees contribute to the stock of carbon yet they negatively affect the development of young trees as they take away light and nutrients.

The economic literature on the optimal management of managed tropical forests has dealt with harvest damages in various ways. Some papers ignore damages altogether (e.g., Ingram & Buongiorno, 1996), some assume logging affects only smaller diameter classes (Boscolo & Buongiorno, 1997; Boscolo & Vincent, 2000; Boscolo, Buongiorno, & Panayotou, 1997), whereas others have a detailed representation of the harvest-damage relation (Indrajaya, van der Werf,
Weikard, Mohren, & van Ierland, 2016). Importantly, all papers assume that all damaged trees (whether they are dead or only injured) decay quickly and do not affect the remaining stand. Surprisingly, none of these papers takes the indirect costs of injured trees into account, despite the fact that these trees negatively affect the growth of the rest of the stand – notably the ingrowth of new trees. Ignoring the role of injured trees leads to gross underestimates of the amount of carbon stored in managed tropical forests and affects recommendations regarding optimal management decisions, such as harvest rates and cutting cycle.

In this study, we explicitly take the role of harvest damages and the biophysical and economic effects of the presence of injured trees into account when analyzing the optimal management of a tropical forest. Using findings from the forest ecology literature, we allow for a large fraction of damaged trees to remain on the stand after harvest and thereby to contribute to the carbon pool while negatively affecting the ingrowth of new trees. We use the detailed harvest-damage relation modeled in Indrajaya et al. (2016) together with detailed data on forest growth and management costs for a forest on Kalimantan in a Faustmann model. We use a scenario in which logging does not cause any damages as a point of reference to analyze the effects of different assumptions about the role of injured trees (both regarding their presence and their mortality rate) on stand composition, carbon stored in above-ground biomass, and economic decision variables, such as the cutting cycle. Among other things, we find that ignoring the role of injured trees can lead to underestimates of the amount of carbon stored in above-ground biomass of up to 109% with CL and up to 165% with RIL.

The remainder of this article is organized as follows. In Section 2, we first describe the economic optimization model and the forest growth model. We subsequently present the scenarios and parameters used for our analysis. We present our results in Section 3 and perform sensitivity analysis in Section 4. We conclude in Section 5.

2 | STUDY METHODS AND MATERIALS

Our model builds on the matrix stand growth model developed by Buongiorno and Michie (1980) and has previously been applied in Indrajaya et al. (2016). We use one hectare of forest stand as our unit of analysis.

2.1 | Economic and forest growth models

2.1.1 | 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, \( i, k \in [1,..., l] \) indicate healthy varieties and \( i, k \in [l + 1,..., m] \) indicate injured varieties of the same species groups.

Forest growth can be described as

\[
y_{T+\varphi} = G_x z_T + c; \quad y_{r+\varphi r} = G_x (y_{r+\varphi (y-r-1)}) + c, \quad (1)
\]

where vector \( y_i = [y_{ij}] \) is a column vector, and \( y_{ij} \) is the number of the trees per hectare of species variety \( i \) and diameter class \( j \in [1,..., n] \) at time \( t \). Parameter \( \varphi \) represents the growth
period in years, and $\gamma$ is the number of growth periods $\theta$ within the harvesting cycle ($T$). Vector $z_{T} = [z_{ij}]_{T}$ denotes the residual stand after harvest. Matrix $G_{x}$ is the $nm \times nm$ forest growth matrix, where $x$ indicates the scenario at hand. It consists of an upgrowth matrix and an ingrowth matrix:

$$G_{x} = A_{x} + R_{x}$$

(2)

Matrix $A_{x}$ 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 ($b_{x,ij}$), or move to a larger diameter class ($b_{x,ij} = 1 - a_{ij} - o_{xij}$). Among other things, we analyze the effect of a higher mortality rate for injured varieties while keeping the probability of an injured tree to stay in the same diameter class constant. Hence, the mortality rate $o_{xij}$ and the probability to move to a larger diameter class $b_{xij}$ depend on the scenario at hand, $x$:

$$A_{x} = \begin{bmatrix} a_{i1} & 0 & \ldots & 0 \\ 0 & a_{i2} & \ldots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \ldots & a_{im} \end{bmatrix} ; \quad A_{xl} = \begin{bmatrix} b_{x12} & a_{ij} & \ldots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \ldots & b_{xm\in} & a_{jn} \end{bmatrix}$$

(3)

Matrix $R_{x}$ 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 & Michie, 1980; Buongiorno, Peyron, Houllier, & Bruciamacchie, 1995; Lu & Buongiorno, 1993). In Section 3, we develop scenarios with different assumptions about the impact of injured trees on ingrowth into the healthy variety of the own species group. We assume that there is no ingrowth in injured species varieties: Trees enter these varieties only when being injured after harvest. That is,

$$R_{x} = \begin{bmatrix} R_{x,11} & R_{x,12} & \ldots & R_{x,1m} \\ R_{x,21} & R_{x,22} & \ldots & R_{x,2m} \\ \vdots & \vdots & \ddots & \vdots \\ R_{x,m1} & R_{x,m2} & \ldots & R_{x,mm} \end{bmatrix} ; \quad R_{xik} = \begin{bmatrix} e_{x,ik1} & e_{x,ik2} & \ldots & e_{x,ikn} \\ 0 & 0 & \ldots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \ldots & 0 \end{bmatrix}$$

for $i \leq l$;

$$R_{x,ik} = 0 \quad \text{for } i > l.$$ 

(4)

Furthermore, ingrowth is positively affected by trees from the own species group because of the presence of seedlings ($e_{x,ikj} > 0$ for $i = k$) but negatively affected by trees from other species groups because of competition for light and nutrients ($e_{x,ikj} < 0$ for $i \neq k$), and $e_{x,ikj} = e_{x,ijk}$ for $i \neq k$.

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:

$$c = \begin{bmatrix} c_{1} \\ c_{2} \\ \vdots \\ c_{m} \end{bmatrix} ; \quad c_{i} = \begin{bmatrix} \rho_{i0} \\ 0 \\ \vdots \\ 0 \end{bmatrix} \quad \text{for } i \leq l; \quad c_{i} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \quad \text{for } i > l.$$

(5)
Harvest at the end of the cutting cycle is represented by vector $h_T = [h_{ij}]$, where $h_{ij}$ is the number of trees harvested of variety $i$ and diameter at breast height (DBH) class $j$. The damage to the residual stand $d_{xsT}$ 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 in Section 2.2. Equation (6) represents the stand immediately after harvest:

$$z_T = y_T - h_T - \Gamma_{xsT}d_{xsT}.$$  (6)

A novelty in our model is the introduction of matrix $\Gamma_{xs}$. 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 are assumed to decay sufficiently fast such that they no longer affect the ingrowth of new trees. The exact design of this matrix depends on the scenario at hand and will be explained in Section 2.2. 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 assume that RIL leads to a smaller fraction of injured trees after harvest than CL.

### 2.1.2 | Economic model

Optimal management of a multiage multispecies tropical forest concerns the choice of three variables: (a) type of logging practice (CL or RIL), (b) length of the cutting cycle $T$, and (c) harvest intensity $h_T$ (i.e., number of trees harvested for each variety and diameter class per hectare). 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 and logging practice looks as follows:

$$\max_{y_T, h_T} \text{LEV} = \frac{v_s^i h_T - F_s}{(1 + r)^T} - v_s^i z_T,$$  (7)

subject to Equations (1), (6), and

$$y_T \geq h_T + d_{xsT}$$  (8)

$$h_T, \quad y_T, \quad z_T \geq 0$$  (9)

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

$$y_t = y_{t+T} \quad \text{for all } t = 1, \ldots, \infty.$$  (11)

Vector $v_s$ denotes the net revenue per tree (i.e., price minus variable costs and taxes) under logging practice $s$, $F_s$ represents the fixed costs per hectare of harvesting using logging practice $s$, and $r$ represents the discount rate. Equations (8) and (9) are the harvest and nonnegativity constraints. Equation (10) represents the minimum diameter harvested, where $\eta$ is the minimum diameter harvested as restricted by government regulation. Equation (11) shows the
equilibrium steady-state constraint. Harvesting cycle in years $T$ is the product of the growth period of the forest growth model, $\theta$, and the number of growth periods within one harvesting cycle, $\gamma$. We solve the model for different values of $\gamma$ and then find the value of $\gamma$ that maximizes the LEV.

### 2.2 Scenarios

Our focus in this paper is on the effects of introducing a more realistic representation of the role of injured trees in a model for optimal tropical forest management as compared to existing literature. We are especially interested in the effects on stand density and composition, the amount of carbon stored in above-ground biomass and optimal management decisions (harvest intensity and cutting cycle). We proceed to describe our scenarios. For each scenario, we make assumptions on the following model characteristics:

1. The effect of harvesting on the stand through damages: $d_{xT}$;
2. The effect of damages on stand composition, that is whether some damaged trees move from healthy species varieties to injured species varieties: $\Gamma_{x}$;
3. The effect of injured trees on the ingrowth of healthy trees: $R_{xik}$;
4. The growth parameter and mortality rate for injured trees for $i > l$: $b_{xij}$ and $o_{xij}$.

#### 2.2.1 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, Holvorsen, Bollandsas, Gobakken, & Hofstad, 2012; Ingram & 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 and establish a baseline quantity of carbon stored in above-ground biomass. In subsequent scenarios, we will introduce more realistic assumptions about damaged trees.

We denote this scenario Scenario $A$, that is, $x = A$ in which we assume

$$d_{xA} = 0$$  \hspace{1cm} (12)

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

$$\Gamma_{A} = I_{nm \times nm}.$$  \hspace{1cm} (13)

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

$$o_{Aij} = o_{ij}.$$  \hspace{1cm} (14)

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

For Scenario $B$, we follow Macpherson, Schulze, Carter, and Vidal (2010) and Indrajaya et al. (2016) and assume that harvest intensity and stand composition affect damages in the following way:
\[
\mathbf{d}_{BT} = \left( \sum_i \sum_j h_{ijT} \right) \mathbf{D}_s \mathbf{Y}_T,
\]

where \( \mathbf{D}_s \) is an \( mn \times mn \) damage matrix, the diagonal of which contains the logging damage coefficients under logging practice \( s \) (damage coefficients are lower for RIL than for CL). The damage coefficients represent the proportion of trees damaged, per tree harvested, within each species group \( i \) and diameter class \( j \). Matrix \( \mathbf{D}_s \) consists of damage coefficient matrices \( \mathbf{E}_s \) and null matrices:

\[
\mathbf{D}_s = \begin{bmatrix}
\mathbf{E}_s & 0 & \cdots & 0 \\
0 & \mathbf{E}_s & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & \mathbf{E}_s
\end{bmatrix}.
\]

In this scenario, we assume that all damaged trees decay sufficiently fast such that they do not affect growth of the remaining stand, irrespective of their physical condition: injured but still alive (e.g., because of a bark or crown injury) or dead (e.g., because of a broken trunk). This is a common assumption in the literature on the optimal management of multiage forests (e.g., Boscolo & Vincent, 2000, 2003; Boscolo et al., 1997; Indrajaya et al., 2016; Tahvonen, 2009). As a result, as in Scenario A, no trees need to be moved from healthy to injured species varieties so,

\[
\mathbf{\Gamma}_{BS} = \mathbf{I}_{nm \times nm}
\]

and

\[
\mathbf{o}_{Bi} = \mathbf{o}_{ij}.
\]

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.

### 2.2.3 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:

\[
\mathbf{d}_{CS} = \left( \sum_i \sum_j h_{ijT} \right) \mathbf{D}_s \mathbf{Y}_T.
\]

However, in the current scenario, we divide damaged trees into two groups: injured trees and dead trees. We follow the existing literature in assuming that dead trees decay sufficiently fast not to affect the growth rate of the other trees or the carbon pool (Boscolo & Buongiorno, 1997; Boscolo & Vincent, 2000; Boscolo et al., 1997; Indrajaya et al., 2016; Ingram & Buongiorno, 1996). This assumption can be justified using insights from the literature on the decomposition of woody debris in the tropical forest of South-East Asia. Yoneda, Tamin, and
Ogino (1990) and Yoneda, Yoda, and Kira (1977) found that the half-time of litter in these forests ranges from less than 1 to 2.5 years. Mori et al. (2014) found that half times of litter ranging from less than 1 year to almost 28 years, with most species having a half time of less than 5 years and a third of the species having a half-time of less than 2 years. None of these studies explicitly looks at the effects of litter on other trees. Given that the decay rates of most species appear to be rather high, and given that our growth model has 2-year growth steps, we assume that dead trees do not affect the growth of other trees. Note that this is not the same as assuming that dead trees fully decay in 2 years.

Crucially, we differ from the literature by assuming that 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. This proportion depends on $s$, and the logging technique used. In Scenario C, we assume

$$
\Gamma_{Cs} = \begin{bmatrix}
\Gamma_{1,1,s} & \ldots & \Gamma_{1,m,s} \\
\vdots & \ddots & \vdots \\
\Gamma_{m,1,s} & \ldots & \Gamma_{m,m,s}
\end{bmatrix},
$$

(20)

where $\Gamma_{i,k,s} = I_{nlxn}$ for $i, k \leq l$ so all previously healthy trees that got damaged during harvest move out of the “healthy” species variety; $\Gamma_{i,k,s} = 0$ for $i \leq l$ and $k > l$ as after harvest, previously injured trees do not suddenly become healthy; $\Gamma_{i,k,s} = -I_{nlxn}\omega_i$ for $i > l$ and $k \leq l$, where $\omega_i = [\omega_{i,1,s} \cdots \omega_{i,l,s}]$’ and $\omega_{i,s} = [\omega_{i,1,s} \cdots \omega_{i,n,s}]$’—that is, a fraction $\omega_{i,j,s}$ of previously healthy trees in diameter class $j$ that got damaged during harvest moves to the injured variety while the remainder dies; and $\Gamma_{i,k,s} = I_{nlxn} - \omega_i I_{nlxn}$ for $i, k > l$ (i.e., some trees that were previously injured, and therefore have zero commercial value, get damaged again).

In our growth model, the ingrowth of new trees is positively affected by the basal area of the own species group and negatively affected by the basal area of other species groups. Injured trees negatively affect the ingrowth of trees from other species. Regarding the effect of injured trees on ingrowth of the own species, however, we compare two different assumptions regarding ingrowth matrix $R$. First, we assume that injured trees still carry seedlings and thereby positively contribute to ingrowth of healthy trees of the own species, just like healthy trees: $e_{ij} > 0$. We denote this case as “Subscenario Positive.” We subsequently analyze the effects of assuming that injured trees do not carry seedlings but do require nutrients and light and thereby 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: $e_{ij} < 0$. We denote this case as “Subscenario Negative.”

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

$$
o_{Cij} = o_{ij} \quad \text{for all } i.
$$

(21)

Comparing the results for this scenario with those for Scenario B allows us to analyze the effect of the presence of injured trees that have zero commercial value but negatively affect the ingrowth of new trees from other species groups (and possibly of the own species group) because of competition for light and nutrients.
Scenario D: Damage occurs and injured trees have a higher mortality rate

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

\[ d_{DT} = \left( \sum_i \sum_j h_{ij} \right) D_i Y_T \] (22)

and

\[ \Gamma_{D_i} = \begin{bmatrix} \Gamma_{1,1,s} & \cdots & \Gamma_{1,m,s} \\ \vdots & \ddots & \vdots \\ \Gamma_{m,1,s} & \cdots & \Gamma_{m,m,s} \end{bmatrix} \] (23)

As in Scenario C, we also compare two different assumptions regarding the effect of injured trees on ingrowth of the own species (Subscenarios Positive and Negative).

In Scenario D, we assume that injured trees have a higher mortality rate than trees that are undamaged:

\[ o_{Dij} = o_{ij} + \xi \quad \text{for } i > l. \] (24)

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

2.3 Parameterization of the model

2.3.1 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, Suhendang, and Parthama (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 \( \theta \) of 2 years. There are three (healthy) species groups \( i \) in the growth matrix with \( i = 1 \) for commercial dipterocarp, \( i = 2 \) for commercial nondipterocarp, and \( i = 3 \) for noncommercial species. Correspondingly, \( i \in \{4, 5, 6\} \) indicates the respective injured variety of each species group. Each species group consists of thirteen 5-cm diameter classes (\( j = 1 \) for 10–14 cm DBH, and \( j = 13 \) for >70 cm DBH). Since the growth matrix is empirically calibrated, trees entering the smallest diameter class are not seedlings but rather the number of trees that have reached a diameter of at least 10 cm DBH. Note that, in our model, trees are classified according to diameter class, not age in years. Furthermore, it is important to note that a cutting cycle of \( T \) years does not mean that harvested trees are \( T \) years old. Hence, ignoring trees with <10 cm DBH does not affect the cutting cycle as long as the ingrowth into the 10–14 cm class is empirically calibrated, as it is in our model.
Following current Indonesian policy, we apply a diameter cutting limit of 40 cm (i.e., $\eta = 40$). Which diameter classes above this DBH limit are being harvested is endogenously determined in the model through harvest intensity $h$ (i.e., number of trees harvested for each variety and diameter class per hectare)—see Equation (7): 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 $D_s$ in Scenarios B – D are as in Indrajaya et al. (2016) and are based on Priyadi et al. (2007). Parameter values are such that the lower the DBH class, the larger the number of damaged trees. Furthermore, CL causes more damages to the remaining stand than RIL: The latter reduces damages per tree harvested by 17% on average over all diameter classes and by 25% on average for trees of 50 cm diameter and larger relative to CL.

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 CL techniques with those after harvests based on RIL 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 die 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. Our growth model has 5-cm DBH classes with the largest class being 60–70 cm. Pinard and Putz (1996) only report numbers for the fraction of damaged trees that dies or gets injured for the DBH classes 10–20, 20–40, and 40–60 cm; hence, 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. This can be justified based on the findings by Bertault and Sist (1997), who report combined data for CL and RIL. We scale the numbers for the 10–20, 20–40, and 40–60 cm DBH classes as reported in Pinard and Putz (1996) down using the average fractions presented above and the fractions reported in Pinard and Putz (1996), which results in ratios 53/61 and 43/46 for CL and RIL, respectively. These steps result in the parameters $\omega_{ijs}$ of the transition matrix $\Gamma_{xs}$, that is, 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 values are presented in Table 1. Note that the remaining fraction $1 - \omega_{ijs}$ dies after harvest.

In Scenario D, we use an increased mortality rate for injured trees as compared to healthy trees. To our knowledge, only one article has analyzed the mortality of injured trees. We increase the annualized mortality rate of injured trees by 3.1% 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, found by Sist and Nguyen-Thé (2002). Because our model is based on two-year growth periods, we use $\xi = 0.059923$, which roughly implies a doubling of the mortality rate as compared to healthy trees.\(^1\)

\[\xi = \frac{(1 - (1 - 0.049)^2) - (1 - (1 - 0.018)^2)}{2} = 0.059923.\]

\(^1\)Sist and Nguyen-Thé (2002) report that 4 years after harvest they do not find statistically significant differences between mortality rates of the two groups, but the authors admit that “this 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). As it is rather expensive, removal of badly
damaged stems is usually not applied in managed tropical forests. In Scenario D, we assume that the increase in mortality rate for injured trees is permanent. While this is a rather extreme assumption, it can be compared against the other extreme of no increase in mortality rate for injured trees, which is assumed in Scenario C.

We estimate the weight of above-ground biomass (AGB) in metric tonnes per tree with the allometric equation developed by Chave et al. (2005):

\[ AGB_j = \rho \times \exp \left( -1.499 + 2.148 \ln \text{DBH}_j + 0.207 \ln \text{DBH}_j^2 - 0.0281 \ln \text{DBH}_j^3 \right)/1,000, \]

where \( \text{DBH}_j \) represents the middle point of the diameter values in diameter class \( j \), and \( \rho \) represents the wood density (i.e., 0.68 based on Rahayu, Lusiana, & van Noordwijk, 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 \( \chi_t = AGB'_t \chi_f \). The average amount of carbon stored in AGB in one cutting cycle is therefore: \( \bar{\chi} = \sum_{t=0}^{T} \chi_t / \gamma \), where \( \gamma \) is the number of growth periods within a cutting cycle.

### Economic parameters

The production cost parameters for CL and RIL used in our study are those reported by Dwiprabowo, Grulois, Sist, and Kartawinata (2002) for a forest concession on East-Kalimantan and used in Indrajaya et al. (2016).\(^2\) We use the investment and administration costs data from a technical proposal of a company in Kalimantan (Sumalindo Lestari Jaya, 2008). The standard prices determined by the Indonesian government are used for gross prices of timber per m³, in which commercial species are sorted into two groups: dipterocarp and non-dipterocarp.\(^3\) The net price \( v_i \) 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. The latter assumption is based on the

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\(^2\) We express monetary values in USD of 2012 throughout the article.

\(^3\) Ministry of Trade Decree No 22/M-DAG/PER/4/2012. The dipterocarp species price used is 1.270.000 IDR/m³ and the price for commercial non-dipterocarp is 953.000 IDR/m³.
observation that, in Indonesia, commercial trees from tropical forests are only used for construction, which requires high-quality timber, and not for pulp. Total variable costs are slightly lower for RIL than for CL (46.4 USD/m³ vs. 44.8 USD/m³), 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 preharvesting 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, Carter, Holmes, and Pereira (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/m³ for dipterocarp and 32 USD/m³ for non-dipterocarp in CL and 61 USD/m³ for dipterocarp and 34 USD/m³ for non-dipterocarp in RIL.

Because 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 sensitivity analysis, we use a discount rate of 4% based on the average real interest rate for Indonesia for the past 20 years.4 In addition, we analyze the case of a fixed 30-year cutting cycle, which is prescribed by Indonesian policy.

3 | RESULTS

3.1 | Results for optimal management with CL techniques

The results for all scenarios for the case of CL are presented in Table 2, where “Positive” and “Negative” indicate the positive and negative effect of damaged trees on the ingrowth of trees from the own species group, respectively.

In Scenario A, we assume that logging activities do not cause damage to the residual stand. As a result, the basal area and LEV are the largest and the cutting cycle is the shortest over all scenarios. The optimal cutting cycle is 10 years, which is twice as long as in Ingram and Buongiorno (1996), in which damages are ignored as well, probably because the diameter cutting limit in that study is lower than in ours (30 vs. 40 cm). Basal area is 11.2 m²/ha before harvest and 9.3 m²/ha after harvest, and the average amount of carbon in AGB is 54.9 tonnes/ha. It should be noted that these basal areas are the equilibrium (i.e., steady state) basal areas with repeated harvests by a commercial company. Therefore, these numbers need not be comparable with the results found on experimental plots as these typically have not been harvested repeatedly and harvested volumes need not result from commercial decisions. Basal areas found on Kalimantan after logging of experimental plots range from 10 to 28.3 m²/ha (e.g., Johns, 1988, Sist & Nguyen-Thé, 2002). The climax forest that results from our growth model, that is, the forest that would result from our growth model, if it was never harvested, has a basal area of 26.4 m²/ha, which is somewhat thinner than the 31.3–35 m²/ha found in primary forests on Kalimantan (Brearley, Prajadinata, Kidd, Proctor & Suriyantata, 2004; Cannon, Peart, Leighton, & Kartawinata, 1994; Johns, 1988).

4Source: World Bank World Development Indicators.
In Scenario B, damages to the remaining stand impose an additional implicit harvesting cost relative to Scenario A, which increases the cutting cycle from 10 to 18 years and reduces basal area. Basal area after harvest decreases by more than 50% and carbon in AGB (average over the cutting cycle) by almost 50% (from 54.9 to 29.3 tC/ha) as compared to the case of no damages. Lower harvest revenue combined with a longer cutting cycle (and hence more discounting) implies that LEV in Scenario B is much lower than in Scenario A.

In both scenarios, Scenario C Positive (“Positive” in Table 2) and Scenario C Negative (“Negative” in Table 2), the total basal area before harvest increases by more than 50% relative to Scenario B (62% with C Positive and 53% with C Negative) while basal area after harvest roughly doubles. Indeed, in Scenario C Positive, the basal area before and after harvest is comparable to the case, in which damages are completely ignored (Scenario A). Furthermore, the average amount of carbon stored in AGB over the cutting cycle roughly doubles relative to Scenario B (to 61.2 tC/ha in Scenario C Positive and 57.2 tC/ha in C Negative) and is for both subscenarios even higher than in Scenario A. Injured trees make 50% of the basal area after harvest, which reduces to 36–37% just before harvest due to ingrowth of new healthy trees.

These results show the importance of including injured trees with zero commercial value in economic models for the optimal management of tropical forests: Ignoring them leads to strong underestimates of the potential of such forests to store carbon in the context of Reducing Emissions from Deforestation and forest Degradation (REDD+) and payment for ecosystem services programs.

There is a little difference in the basal area of healthy trees between Scenarios B and C, for which there are two reasons. First, in our model injured trees negatively affect the ingrowth of new trees but do not affect the upgrowth of existing trees. Second, the stand composition is different between the two scenarios with a larger share of trees belonging to the fast-growing commercial dipterocarp species in Scenario C. The latter also explains why extracted volume does not differ much between the scenarios. Indeed, volume harvested and cutting cycles are the same for Scenarios B and C.

### Table 2  Results for optimal management with conventional logging

| Scenarios Subscenario | A     | B     | C Positive | C Negative | D Positive | D Negative |
|-----------------------|-------|-------|------------|------------|------------|------------|
| Land expectation value (USD/ha) | 305   | 32    | 35         | 31         | 35         | 32         |
| Cutting cycle (years) | 10    | 18    | 16         | 18         | 18         | 18         |
| BA healthy trees before harvest (m²/ha) | 11.2  | 7.0   | 7.1        | 6.9        | 7.4        | 7.0        |
| BA healthy trees after harvest (m²/ha) | 9.3   | 4.3   | 4.6        | 4.2        | 4.5        | 4.3        |
| BA injured trees before harvest (m²/ha) | 0.0   | 0.0   | 4.2        | 3.8        | 0.9        | 0.8        |
| BA injured trees after harvest (m²/ha) | 0.0   | 0.0   | 4.6        | 4.3        | 1.8        | 1.6        |
| Total BA before harvest (m²/ha) | 11.2  | 7.0   | 11.3       | 10.7       | 8.3        | 7.8        |
| Total BA after harvest (m²/ha) | 9.3   | 4.3   | 9.2        | 8.5        | 6.3        | 5.9        |
| Extracted volume (m³/ha) | 23.2  | 11.8  | 11.0       | 11.8       | 12.2       | 11.8       |
| Volume damaged (m³/ha) | 0.0   | 17.1  | 28.8       | 28.5       | 21.5       | 19.5       |
| Net harvest revenue (USD/ha) | 938   | 512   | 477        | 505        | 528        | 511        |
| Average amount of C stored in AGB (t/ha) | 54.9  | 29.3  | 61.2       | 57.2       | 38.6       | 36.1       |

Note. AGB: above-ground biomass.
Negative. The cutting cycle in the subscenario, in which injured trees still carry seedlings, is shorter than that of the one, in which they do not, because harvest damages in the former scenario have a smaller impact on future growth. As opportunity costs of harvesting in Subscenario Positive are lower, the average growth rate is higher (because of injured trees producing seedlings) and the cutting cycle is shorter than in C Negative, which results in less discounting and a higher LEV.

In Scenario D, the higher mortality rate for injured trees causes basal area and carbon stored in AGB to be lower than in Scenario C but still higher than in Scenario B. As expected, the higher mortality rate for injured trees leads to a smaller share of injured trees in the basal area as well as a smaller total basal area as compared to Scenario C. Basal area before harvest is still 11–19% larger and average amount of carbon stored is still 23–32% higher than in Scenario B. These results show that even in the extreme case that the mortality rate of injured trees is permanently higher than that of healthy trees, ignoring the presence of injured trees on the plot in economic models of optimal tropical forest management leads to underestimates of the amounts of carbon stored in such forests.

3.2 Results for optimal management with RIL techniques

RIL not only leads to less damages after harvest as compared to CL, but within the group of damaged trees also to a smaller fraction of dead trees. In Scenario A, we assume that logging activities do not cause damage to the residual stand. 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. Comparing the results for Scenario A in Table 3 with those in Table 2 shows that the stand state of the forest and volumes harvested are the same for CL and RIL. With a lower variable cost per m³ timber harvested, RIL gives higher net harvest revenue and LEV than CL does. However, the lower variable cost cannot offset the

| Scenario | Subscenario | A   | B   | C Positive | C Negative | D Positive | D Negative |
|----------|-------------|-----|-----|------------|------------|------------|------------|
|          |             | 274 | 29  | 32         | 27         | 31         | 28         |
|          | Land expectation value (USD/ha) |     |     |            |            |            |            |
| Cutting cycle (years) | 10  | 20  | 18  | 20         | 20         | 20         |
|          |          |     |     |            |            |            |            |
|          |          | 11.2| 7.5 | 7.7        | 7.3        | 8.0        | 7.4        |
|          | BA healthy trees before harvest (m²/ha) |     |     |            |            |            |            |
|          |          | 9.3 | 4.5 | 4.8        | 4.4        | 4.7        | 4.5        |
|          | BA healthy trees after harvest (m²/ha) |     |     |            |            |            |            |
|          |          | 0.0 | 0.0 | 6.6        | 5.7        | 1.3        | 1.1        |
|          |          | 0.0 | 0.0 | 7.6        | 6.7        | 2.6        | 2.3        |
|          |          | 11.2| 7.5 | 14.3       | 13.0       | 9.2        | 8.6        |
|          | Total BA before harvest (m²/ha) |     |     |            |            |            |            |
|          |          | 9.3 | 4.5 | 12.3       | 11.1       | 7.4        | 6.8        |
|          |          | 23.2| 14.2| 13.6       | 14.2       | 14.8       | 14.2       |
|          | Extracted volume (m³/ha) |     |     |            |            |            |            |
|          |          | 967 | 638 | 605        | 625        | 662        | 634        |
|          | Net harvest revenue (USD/ha) |     |     |            |            |            |            |
|          |          | 0.0 | 18.5| 37.0       | 34.4       | 24.2       | 21.6       |
|          | Volume damaged (m³/ha) |     |     |            |            |            |            |
|          |          | 54.9| 31.4| 83.2       | 74.8       | 44.5       | 41.1       |
|          | Average amount of C stored in AGB (t/ha) |     |     |            |            |            |            |

Note. AGB: above-ground biomass.
much higher fixed costs in RIL, so LEV is higher in CL than in RIL. Therefore, 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.5

Comparing the LEV of each scenario for RIL with that for CL shows that a commercial forest manager (i.e., with a 12% discount rate) prefers to apply CL as it gives a higher LEV irrespective of the role of damaged trees. However, the environmental services provided with RIL may be much larger than with CL as basal areas and volumes of carbon stored in AGB are higher with the use of more sustainable logging techniques.

With RIL, the effects of the various assumptions regarding injured trees are qualitatively the same as with CL, but the effects on basal area and carbon stored are even stronger.6 Indeed, basal area before harvest is larger for both Scenarios C Positive and C Negative as compared to Scenario A, whereas it increases by 91% and 74%, respectively, as compared to Scenario B. Relative to this scenario, the average amount of carbon stored in AGB increases by 165% and 139% in Scenarios C Positive and C Negative, respectively. Therefore, the role of injured trees in calculating the amount of carbon stored in AGB is even stronger in case of RIL.

4 | SENSITIVITY ANALYSIS

In Table 4 we present results for a sensitivity analysis, in which we use discount rates of 4% (e.g., for a government forest manager rather than a commercial one). In Scenario A, in which only costs differ between CL and RIL, CL is still the preferred logging practice, as with a 12% discount rate. However, the cutting cycle is now longer with RIL than with CL as the difference in fixed costs is sufficiently large to induce a longer cutting cycle for RIL. For all other scenarios, the LEV is higher for RIL than for CL, contrary to the case of a 12% discount rate: In the presence of harvest damages a noncommercial forest manager may prefer RIL over CL.

Cutting cycles are much longer than with a 12% discount rate. As this allows for more harvestable volume, the costs of having large damages are higher and RIL becomes more attractive as compared to the case with a high discount rate.

Conclusions regarding the effect of different assumptions about the role of damaged trees are qualitatively the same as in the previous section: Accounting for damaged trees on the stand implies considerably larger basal areas and volumes of carbon stored. Again, these effects are even stronger for RIL.

Table 5 presents the results for the case of an exogenous cutting cycle of 30 years, which is in line with Indonesian forestry policies. We use a 12% discount rate. Again, the effects on basal area and carbon stored are qualitatively similar to the findings in Section 3. As with the 4% discount rate, the long cutting cycle goes with more harvestable volume and higher costs of having large damages, and for all scenarios with damages, RIL is more attractive than CL.

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5Note that our model uses a growth period of 2 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 increased from 389 to 425 USD/ha, the cutting cycle for RIL increases from 10 to 12 years.

6The difference in cutting cycle between Scenarios A and B is 10 years for RIL and 8 years for CL. This is the result of rounding with the 2-year growth period in our model (see the previous footnote). If we increase fixed costs for RIL to 425 USD/ha, the cutting cycle for RIL is 12 years under Scenario A and 22 years under Scenario B, that is, a difference of 10 years as with CL. Therefore, the increase in the difference in cutting cycle between CL and RIL appears to be an artifact of the two-year instead of the one-year growth period.
| Scenario | CL  | RIL | CL  | RIL | CL  | RIL | CL  | RIL | CL  | RIL | CL  | RIL |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| **Scenario A** |     |     |     |     |     |     |     |     |     |     |     |     |
| Land expectation value (USD/ha) | 1,429 | 1,380 | 239 | 248 | 254 | 270 | 236 | 243 | 251 | 264 | 238 | 247 |
| Cutting cycle (years) | 16 | 18 | 26 | 30 | 26 | 28 | 26 | 30 | 24 | 28 | 24 | 30 |
| BA healthy trees before harvest (m²/ha) | 12.4 | 12.7 | 8.2 | 9.0 | 8.7 | 9.3 | 8.1 | 8.8 | 8.3 | 9.2 | 7.8 | 8.9 |
| BA healthy trees after harvest (m²/ha) | 9.4 | 9.4 | 4.3 | 4.4 | 4.4 | 4.7 | 4.2 | 4.4 | 4.5 | 4.7 | 4.3 | 4.4 |
| BA injured trees before harvest (m²/ha) | 0.0 | 0.0 | 0.0 | 0.0 | 4.5 | 6.7 | 4.0 | 5.7 | 0.9 | 1.1 | 0.8 | 1.0 |
| BA injured trees after harvest (m²/ha) | 0.0 | 0.0 | 0.0 | 0.0 | 5.4 | 8.4 | 4.8 | 7.4 | 2.1 | 3.2 | 1.9 | 3.0 |
| Total BA before harvest (m²/ha) | 12.4 | 12.7 | 8.2 | 9.0 | 13.1 | 16.0 | 12.0 | 14.5 | 9.2 | 10.4 | 8.6 | 9.9 |
| Total BA after harvest (m²/ha) | 9.4 | 9.4 | 4.3 | 4.4 | 9.8 | 13.1 | 9.0 | 11.7 | 6.6 | 7.8 | 6.2 | 7.4 |
| Extracted volume (m³/ha) | 37.6 | 42.5 | 16.4 | 20.8 | 17.0 | 20.4 | 16.3 | 20.6 | 15.8 | 20.2 | 15.3 | 20.7 |
| Net harvest revenue (USD/ha) | 1,544 | 1,804 | 721 | 945 | 748 | 928 | 716 | 935 | 690 | 916 | 668 | 943 |
| Volume damaged (m³/ha) | 0.0 | 0.0 | 26.7 | 30.2 | 48.0 | 56.6 | 42.0 | 50.8 | 29.7 | 34.9 | 27.0 | 33.7 |
| Average amount of C stored in AGB (t/ha) | 58.9 | 60.3 | 32.6 | 35.7 | 69.5 | 91.6 | 63.4 | 82.3 | 42.0 | 49.2 | 39.3 | 46.7 |

**Note.** AGB: above-ground biomass; CL: conventional logging; RIL: reduced-impact logging.
### TABLE 5 Results for CL and RIL with exogenous cutting cycle of 30 years

| Scenario | CL | RIL | CL | RIL | CL | RIL | CL | RIL | CL | RIL | CL | RIL | CL | RIL | CL | RIL |
|----------|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|----|-----|
| **Scenario A** |    |     |    |     |    |     |    |     |    |     |    |     |    |     |    |     |
| Land Expectation Value (USD/ha) | 95 | 95 | 18 | 19 | 19 | 19 | 17 | 18 | 18 | 19 | 17 | 19 | 18 | 19 | 17 | 19 |
| Cutting cycle (years) | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| BA healthy trees before harvest (m²/ha) | 14.9 | 14.9 | 8.8 | 9.0 | 9.3 | 9.4 | 8.6 | 8.8 | 9.2 | 9.5 | 8.6 | 8.9 | 9.2 | 9.5 | 8.6 | 8.9 |
| BA healthy trees after harvest (m²/ha) | 9.4 | 9.4 | 4.2 | 4.4 | 4.4 | 4.5 | 4.1 | 4.3 | 4.4 | 4.6 | 4.1 | 4.4 | 4.4 | 4.6 | 4.1 | 4.4 |
| BA injured trees before harvest (m²/ha) | 0.0 | 0.0 | 0.0 | 0.0 | 4.5 | 6.7 | 4.0 | 5.7 | 0.8 | 1.1 | 0.7 | 1.0 | 0.8 | 1.1 | 0.7 | 1.0 |
| BA injured trees after harvest (m²/ha) | 0.0 | 0.0 | 0.0 | 0.0 | 5.6 | 8.6 | 5.0 | 7.4 | 2.4 | 3.3 | 2.2 | 3.0 | 2.4 | 3.3 | 2.2 | 3.0 |
| Total BA before harvest (m²/ha) | 14.9 | 14.9 | 8.8 | 9.0 | 13.8 | 16.2 | 12.6 | 14.5 | 10.1 | 10.6 | 9.4 | 9.9 | 10.1 | 10.6 | 9.4 | 9.9 |
| Total BA after harvest (m²/ha) | 9.4 | 9.4 | 4.2 | 4.4 | 10.0 | 13.0 | 9.1 | 11.7 | 6.8 | 7.9 | 6.3 | 7.4 | 6.8 | 7.9 | 6.3 | 7.4 |
| Extracted volume (m³/ha) | 71.8 | 71.8 | 18.7 | 20.8 | 19.3 | 21.6 | 18.6 | 20.6 | 19.2 | 21.6 | 18.7 | 20.7 | 19.2 | 21.6 | 18.7 | 20.7 |
| Net harvest revenue (USD/ha) | 3,040 | 3,040 | 819 | 945 | 849 | 936 | 799 | 933 | 843 | 968 | 798 | 942 | 843 | 968 | 798 | 942 |
| Volume damaged (m³/ha) | 0.0 | 0.0 | 31.9 | 30.2 | 55.6 | 62.4 | 49.2 | 50.8 | 38.3 | 37.8 | 35.1 | 33.8 | 38.3 | 37.8 | 35.1 | 33.8 |
| Average amount of C stored in AGB (t/ha) | 68.3 | 68.3 | 34.3 | 35.7 | 72.6 | 92.5 | 65.8 | 82.3 | 45.3 | 50.1 | 41.8 | 46.7 | 45.3 | 50.1 | 41.8 | 46.7 |

*Note.* AGB: above-ground biomass; CL: conventional logging; RIL: reduced-impact logging.
5 | CONCLUSIONS

In this study, we analyzed four scenarios to identify the effects of various assumptions regarding injured trees on LEV, cutting cycle, basal areas, and carbon stored in AGB. We find that allowing injured trees to stay on the plot leads to much larger basal areas and much more carbon stored in AGB. This effect is stronger for RIL than for CL: With RIL, the average amount of carbon stored can increase by up to 165% as compared to the case where injured trees are assumed to decay so fast that they do not affect ingrowth or the composition of the stand, just like dead trees. In managed tropical forests, biodiversity and ecosystem services are positively correlated with the basal area. The potential of managed tropical forests to store carbon and provide ecosystem services in response to programs, such as payments for ecosystem services and REDD and the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks in developing countries (REDD+), may hence be grossly underestimated when ignoring injured trees in the analysis.

An important area of future research would be to assess the role of damages when injured trees do not only affect the ingrowth of new trees but also the upgrowth of (small) existing trees. A lower growth rate would, ceteris paribus, imply smaller effects of the presence of injured trees on basal area and carbon stored, although this would be partly offset by a longer cutting cycle. The effect on the choice between CL and RIL (in terms of LEV) is a priori unclear. Such an analysis would require a more advanced forest growth model. Second, the modeling of the decomposition of dead trees can be improved by allowing for almost full decomposition to take more than two years, although it should be noted that the literature on the decomposition of woody debris in the tropical forests of South-East Asia presents a wide range of estimates of half time rates. Furthermore, the economic model can be improved by allowing for nonrepetitive cutting cycles. Notwithstanding these drawbacks of the model used in this article, we have shown that including damaged trees can have large effects on the potential of managed tropical forests to store carbon.

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