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Tree-based approach to evaluate size dependence of residual tree damage caused by selective logging: Case study in tropical semi-evergreen forests of Cambodia

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ABSTRACT

Logging damage to residual trees is one of the fundamental components in evaluating the sustainability of tropical selective logging in terms of timber production, carbon retention and biodiversity conservation. Although many studies have taken an area-based approach to tropical rain forests, we adopted a tree-based approach to quantify the dependence of residual tree damage on the size of residual and felled trees. We used data from 179 plots, each 25 m × 40 m, covering the stump and crown of one felled tree in Cambodian tropical semi-evergreen forests. We used the mixed-effects multinomial logistic regression model to predict the probability of a residual tree sustaining severe, slight or no damage. Increasing size of residual trees decreased the probability of severe damage and increased that of slight damage. The probability of total damage (severe plus slight) was nearly constant, regardless of the size of residual trees. Increasing size of the felled tree caused greater probability of severe damage, but did not influence the probability of slight damage. Interestingly, our prediction of total damage rate from the tree-based modeling approach of the Cambodian semi-evergreen forests is very consistent with the findings of previous studies using the area-based approach in Indonesia. The departure of our study results from those of other studies may be explained by differences in felled tree size and terrain slope. The inclusion of tree-size dependence in logging damage estimation would increase its accuracy and comparability across different types of tropical forests.

1. Introduction

Tropical forests have been widely recognized as an important ecosystem locally and globally to maintain carbon stock and biodiversity, while playing an important role in wood production. Selective logging has been commonly used over long periods for timber production in tropical natural forests, and there have been many studies addressing the sustainability of tropical selective logging in terms of timber production (Kammesheidt et al., 2001b; van Gardingen et al., 2006; Sist and Ferreira, 2007), carbon retention (Zimmerman and Kormos, 2012; Sasaki et al., 2012; Medjibe et al., 2013; Sist et al., 2014; Griscom et al., 2014; Pearson et al., 2014), and biodiversity conservation (Edwards et al., 2012, 2014; Putz et al., 2012; Burivalova et al., 2014).

Logging damage to residual trees is one of the most fundamental elements in evaluating the sustainability of selective logging (Sist and Ferreira, 2007; Picard et al., 2012). Numerous studies have investigated residual tree damage in conventional logging and/or reduced-impact logging (e.g. Veríssimo et al., 1992; Johns et al., 1996; Pinard and Putz, 1996). The latter is a practice with carefully planned, controlled felling and skidding by trained logging crews (Putz and Pinard, 1993; Putz et al., 2008). One of the important findings of the previous studies is that damage rate (%), which is the proportion of damaged trees or areas, increases linearly or curvilinearly with logging intensity in terms of the number or volume of felled trees ha^{-1}. These findings have been well documented in individual case studies (Sist et al., 1998, 2003; Sist and Ferreira, 2007) and meta-analyses covering various sites in different countries (Webb, 1997; Pereira et al., 2002; Picard et al., 2012). In addition, it is recognized that the size of felled trees and residual trees affects the amount and types of residual tree damage. That is, larger felled trees cause more damage to residual

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trees (Jackson et al., 2002; Medjibe et al., 2011), and smaller residual trees are more likely to be killed or severely damaged whereas larger residual trees are less affected (Bertault and Sist, 1997; Webb, 1997; Alder and Silva, 2000; Parren and Bongers, 2001). This suggests that the dependence on size of residual and felled trees should be considered to predict logging damage more accurately (Bertault and Sist, 1997; Picard et al., 2012). Nevertheless, no study has predicted different degrees of logging damage with consideration of the size of both residual and felled trees simultaneously for tropical forests. For temperate forests, logistic regression models were applied to predict the probability of a residual tree sustaining logging damage, using the size of felled tree or harvested amount, the size of residual tree, and the distance to the felled tree and/or skid trails as explanatory variables (Granhus and Fjeld, 2001; Surakka et al., 2011; Tatsumi et al., 2014). Such modeling can be used for tropical forests, but the distance-dependent model would not be preferred since the measurements of individual-tree position have not been common and would be too time-consuming for logging damage studies in tropical forests.

There are two approaches to estimate logging damage, area-based and tree-based (Picard et al., 2012). Many studies have used the area-based method, which investigates relatively large forest areas covering several felled trees to describe the damage percentage of residual trees. The tree-based method focuses only on small areas near a felled tree to quantify the number of damaged trees or area of damage per a single felled tree, providing more mechanistic details on how the tree fall impacts the understory (Johns et al., 1996; Parren and Bongers, 2001; Jackson et al., 2002; Picard et al., 2012; Griscom et al., 2014). However, some studies suggest that this method can only be used for low logging intensity, because logging damage could be a concave increasing function of logging intensity rather than linearly increasing, owing to overlapping damages from different felled trees (Parren and Bongers 2001; Picard et al. 2012). This argument is reasonably understood, but other studies have shown linear relationships between logging intensity and damage rate (%), rather than concave curvilinear ones (Webb, 1997; Sist et al., 1998, 2003). Picard et al (2012) developed a pantropical equation of concave form between those two variables. Nevertheless linearity is likely found for logging intensity less than ~5 trees ha^{-1}. Logging intensity is generally high in the Southeast Asia archipelago, where as much as ~10 trees ha^{-1} are harvested, whereas 0.7–4 trees ha^{-1} are harvested in Central Africa and middle intensity in Neotropics (Picard et al., 2012). Studies have suggested that logging intensity be reduced to a maximum of 8 trees ha^{-1} in Indonesia to effectively reduce logging damage (Sist et al., 1998, 2003), to 3–4 trees ha^{-1} in Eastern Amazonia to ensure sustained yield (Sist and Ferreira, 2007), and to <10 m^3 ha^{-1} to maintain tropical forest biodiversity for most taxonomic groups (Burivalova et al., 2014). Considering the above practices of low logging intensity in Africa and recommendations of reduced logging intensity in other regions, it is believed that tree-based study of logging damage is still useful for improving estimations of damage caused by selective logging in the tropics.

The objective of this study was to quantify residual tree damage caused by selective logging in relation to the size of felled and residual trees using the tree-based approach. We used multinomial logistic regression to predict probabilities of a residual tree sustaining severe, slight or no damage during selective logging. The data used were collected in tropical seasonal forests of Cambodia in mainland Southeast Asia, where reduced-impact logging (RIL) was experimented. Logging damage from RIL is expected to be lower than from conventional logging (CL), but there has been no study evaluating logging damage from RIL and CL in Cambodia. Most of other studies of logging damage in the tropics were based on the area-based approach in tropical rain forests of the Neotropics, central Africa and the Southeast Asia archipelago. The present study also compared its results with the others from tropical rain forests where RIL was applied.

2. Methods

2.1. Study site

The study was conducted in three annual coupes in former concession forests of Cambodia, where Cambodia's Forestry Administration (FA) conducted logging experiments using reduced impact logging (RIL) techniques in 2007 and 2008. The experimental sites are in Kratie, Ratanakiri and Stung Treng provinces of northeastern Cambodia, with areas 1490 ha (13°13′53″–13°16′51′′N, 106°11′22″–106°13′29″E), 4650 ha (13°42′57″–13°48′24″N, 106°41′35″–106°44′52″E) and 1520 ha (13°23′90″–13°21′30″N, 106°11′27″–106°14′41″E), respectively. The coupes are on nearly flat slopes with an elevation range 80–220 m above sea level. The study sites have a typical monsoon Asian climate. There is a distinct dry season in the 6 months between November and April, and a rainy season during which nearly 90% of annual precipitation falls (Miyazawa et al., 2014). Based on records from 1995 to 2005 at the Stung Treng Provincial Meteorological Station, annual precipitation is 1526 mm, and annual maximum, average and minimum temperatures are 33.4, 26.7 and 22.6 °C. The main soil type in the region is an acid lithosol and the main forest type is semi-evergreen forest, containing both evergreen and deciduous trees.

The logging experiment was carefully designed and followed a series of forest planning handbooks and field guides for RIL. The main procedures were pre-harvest planning with forest inventories of systematic sampling and estimation of sustainable yield, harvest planning containing tree marking and mapping of all harvestable trees, skid-trail and road planning, and controlled felling and skidding. Forest inventories at the study sites were conducted from April 2007 to September 2008. The systematic sampling for assessment of potential yield of commercial timber was conducted with sampling intensity of about 1–3% on area. The line transects were laid out, being composed of subsequent plots with each size 250 m length and 30 m width. In each plot, trees with DBH of 10–29 cm, 30–59 cm and ⩾60 cm were measured in the sub-plots 10 m × 50 m, 10 m × 250 m and 30 m × 250 m, respectively. For the tree marking, all trees with DBH greater than the DBH limits for harvesting, which are listed in the logging regulation, were measured and marked on the maps, together with trees retained for future harvest or as mother trees. As there were few large lianas that intertwined stems and crowns of the marked trees, lianas cutting prior to logging was not carried out.

Felling and skidding were carried out from 2008 to 2009 by trained operators. Directional felling was applied in order to minimize damage to residual trees. The rubber-tired forwarder with the winch and log bunk was used for skidding, and the log was pulled out with the winch cable to the forwarder being at ~20 m apart from the stump. Then, the log was loaded onto the bunk and transported to the log-yard.

2.2. Assessment of damage on residual trees

In a few weeks after felling and skidding, sample plots were established to evaluate damage to residual trees caused by a single felled tree. A rectangular plot of 0.1 ha of 25 m width and 40 m length was laid out along the direction of each felled tree to encompass its stump and crown. A total of 179 felled trees that did not have the overlap with other felled trees were randomly