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Supervised logging and climber cutting improves stand development: 18 years of post-logging data in a tropical rain forest in Borneo

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We analyzed 18 years of post-logging data from Sabah, Borneo to evaluate the impact of two selective logging methods – Supervised logging (SL) including pre-aligned skid trails and directional felling, and conventional logging (CL), where trees were felled before the crawler tractor was called in for skidding and the fellers had no formal training in felling techniques – on net standing volume recovery, survivor growth, ingrowth and mortality of trees ($\geqslant$10 cm DBH). The logging treatments were either combined with- (CC) or without (NCC) pre-harvest climber cutting in a randomized 2×2 factorial design consisting 16 one-hectare treatment plots. We investigated the effect on the complete stand including all trees ($\geqslant$10 cm DBH) regardless of species, but also distinguished between the effects on the commercially interesting species of dipterocarps (*Dipterocarpaceae* family) and pioneer species (mainly *Macaranga* species). Supervised logging in combination with climber cutting was in many ways beneficial to stand development and these effects were mainly expressed at higher harvest intensities. For example, supervised logging reduced the ingrowth and survivor growth of pioneer *Macaranga* spp.; at high harvest intensities approximately 50% fewer pioneers grew in when SL was used in comparision to CL. In addition, climber cutting increased the ingrowth as well as decreased the mortality of highly valuable dipterocarp species with increasing harvest intensity. These effects appeared also to have stand level consequences as forests treated with the combination of supervised logging and climber cutting also exhibited faster recovery in standing volume of high value dipterocarps compared to any other combination of treatments. We conclude that, with improved ingrowth of dipterocarps, reduced overall mortality and generally better stand volume recovery; supervised logging (SL) in combination with climber cutting (CC) could be an attractive forest management system in mixed dipterocarp forests.

1. Introduction

Logging operations in tropical rain forests commonly cause severe damage to the residual stand, which is considered to be one of the main causes of poor forest recovery, degradation and subsequent conversion to other land uses (Bryan et al., 2013; Edwards and Laurance, 2013). The primary reason for the degradation is the poor selective logging systems (Smith et al., 2006; Holmes et al., 2002). The system commonly employed in South East Asia (SEA) is a selective logging system, targeting only commercially valuable tree species above a certain diameter at breast height (DBH) (Bertault and Sist, 1997). In this system, little action is taken to reduce forest damage during harvest. It has been shown that unsupervised logging, often referred to as conventional logging (CL), heavily degrades the forest, for example causing top soil damage and tree mortality, leaving a poor residual stand that cannot supply future demands (Matricardi et al., 2010; Bertault and Sist, 1997). Therefore it is important to improve forest management systems that not only deliver sustainable forest use, but also protect important forest ecosystem functions (Edwards and Laurance, 2013; Putz et al., 2000).

Reduced impact logging (RIL) has been promoted globally to reduce logging damage as well as improving the growth of seedlings and saplings (Edwards et al., 2012; Pena-Claros et al., 2008a). RIL is a modified form of selective logging that is increasingly suggested for timber production in the tropical forests of SEA (Pena-Claros et al., 2008b; Putz et al., 2008). It incorporates a series of pre- and post-logging guidelines, such as climber cutting, directional felling and planning of skid trails (Sist et al., 1998). Previous experiments show that RIL techniques can reduce the overall damage to a stand by 30–50% (Bertault and Sist, 1997; Pinard and Putz, 1996), and thereby should promote better stand development. Still, the underlying reasons for this positive effect

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are not well understood. For example we do not know which of the actions applied during RIL are effective in reducing negative impacts or how combined treatments may interact. There is also a lack of long-term studies of RIL, evaluating the effects on the stand development, including tree mortality as well as ingrowth and growth of trees. Although RIL is increasingly part of certification schemes in many countries, it is rarely practiced as intended (Sist and Ferreira, 2007; Sist et al., 2003a; Putz et al., 2000). The reasons underlying the inappropriate use of the system are its strict guidelines, resulting in lower felling intensities and higher costs than in unsupervised logging systems (Medjibe and Putz, 2012; de Blas and Perez, 2008; Pinard et al., 2000).

Consequently, incentives to provide more practical and easily applicable methods have been requested (Applegate, 2002). One such method is the supervised logging system (SL) (Forshed et al., 2006), which involves directional felling and planned skid-trails regularly spaced at 60 m intervals. With directional felling, trees are felled in a predetermined orientation, reducing the damage to potential crop trees. Directional felling has been successfully tested and it has been concluded that it could help to minimize damage to surrounding trees (Cedergren et al., 2002; Pinard et al., 1995). In addition, directional felling can improve forestry workers' safety, which is a major problem in tropical forestry (Dykstra and Heinrich, 1996). Several skidding systems have been tested as an approach to reduce erosion during harvest operations (Sist, 2000; Marsh et al., 1996).

Furthermore, SL can also be combined with pre-harvest climber cutting (CC). CC has been used throughout the tropics as a tool to reduce harvest damage (Schnitzer et al., 2004). Several logging experiments have included CC as a treatment, but often not separated the CC effect from other types of treatment effect, making it difficult to evaluate. However, some experiments that have separated the effects reported that CC reduces felling damage (Putz, 1985; Appanah and Putz, 1984), while others found no evidence of this (Cedergren et al., 2002; Parren and Bongers, 2001). Being able to address the effect of CC on stand development after felling could prove useful when evaluating long-term sustainability of different forest practices.

One requirement for sustainable forest management in the humid tropics is reliable information on growth and yield for different management regimes and silvicultural options. Here we report results from a long-term silvicultural experiment in a mixed dipterocarp forest (dominated by trees belonging to the *Dipterocarpaceae* family) established in Sabah, North Borneo, Malaysia, over 20 years ago. The experiment involved two logging methods; conventional logging (CL) and supervised logging (SL). In addition to the two logging methods, an additional treatment including climber cutting (CC) or no climber cutting (NCC) was applied. We evaluated the effects of climber cutting and the two logging treatments on forest recovery for 18 years of post-logging data. Specifically, we explored the possible interactions between these treatments on tree ingrowth and mortality, and the survivor growth of the stand. We also investigated the lag-time until standing volume started to recover. Further, we investigated the effect on the complete stand including all trees ($\geqslant$10 cm DBH) regardless of species, but also distinguished between the effects on the commercial dipterocarps (Whitmore, 1998) and pioneer species (mainly *Macaranga* spp.).

2. Materials and methods

The study area was located in the Malaysian state of Sabah (Borneo island) in the Gunung Rara forest reserve (approximately 4°33′N, 117°02′E). The forest is referred to as a virgin mixed dipterocarp forest, and the forest soil is Orthic Acrisoil, a clay-rich soil commonly associated with humid tropical climates and sedimentary bedrock (Cedergren, 1996). The climate is typical wet tropical with an average temperature of 27 °C and an average rainfall of 2700–3400 mm per year, distributed over two distinct wet seasons (WorldClim, 1950–2000). Altitude in the experimental area ranges from 300 to 600 m a.s.l.

The experiment was established as a randomized 2 × 2 factorial block design. The blocking factor was assigned according to the average slope within each plot and ranged from 4.1° to 24.7°. The logging methods in the experiment that were studied were conventional logging (CL, normal felling and extraction), and supervised logging (SL, including directional felling and pre-aligned skid trails). In CL no assistance or guidelines were given to the fellers and crawler tractor operators. Trees were felled before the crawler tractor was called in for skidding and fellers had no formal training in felling techniques. In SL, the contractors were instructed to implement special actions; skid trails were systematically aligned parallel to each other and at a fixed distance apart of about 60 m. This distance was based on a number of assumptions regarding log length, winching distance and allowable reversing distance for tractors into the stand (Cedergren, 1996). The assumptions derived from that crawler tractors had a winching distance of 25 m and were allowed to reverse into plot, maximum of 5 m if needed. Thus with a fixed distance of 60 m between skid trails, crawler tractors could winch out all logged trees of harvestable size within the plots (Cedergren, 1996). Both uphill and downhill skidding was allowed. Skid trails were opened up before felling and potential crop trees (PCT) in the range of 40–59 cm DBH along the skid trail were marked with paint to avoid damage. During felling, tree crowns were directed to fall into the skid trails to minimize damage to the remaining trees. Trees that could not be directed to skid trails were felled in a direction where they did least damage to surrounding trees. During the SL operation, tractors were not allowed to open up new tracks or leave the planned trails during the skidding of the logs.

The two logging treatments were also combined with either pre-harvest climber cutting (CC) or no climber cutting (NCC). Each combination of logging- and climber cutting method was repeated four times, once in every block. In addition, a control plot (virgin forest, no harvest) was established randomly within each block. Altogether the study area compromised 20 plots. Gross plot size was set to 5.76 ha (240 × 240 m). Within every gross plot, a net plot of 1 ha (100 × 100 m) was established, in which all tree measurements were taken. The net plots were divided into 100 10 × 10 m subplots and marked out on the ground for easy reference. Within every subplot, the maximum slope was recorded and used to calculate the average slope for the total 1 ha plot.

Plot establishment and the first DBH measurements of all trees $\geqslant$10 cm were carried out between March and June in 1992; these were followed by pre-harvest climber cutting where all woody climbers $\geqslant$2 cm were cut with machetes, except climbers belonging to the *Ficus* species. Within blocks, treatments were randomly assigned to plots. Harvesting commenced in June 1993 and was completed in August the same year, targeting only trees with a DBH $\geqslant$ 60 cm, excluding hollow trees, rare tree species (according to local registrations at time) and fruit trees. The first measurements of all trees $\geqslant$10 cm DBH after logging were carried out in November 1993. Recorded data for each tree were: tree number, distance and bearing from reference points giving the coordinates of individual trees, species and diameter (measured with a diameter tape) at breast height if possible, otherwise 0.3 m above the highest buttress. To relocate the unique id-tags for the trees, metal detectors were used. All trees were re-measured biannually from 1993 until 2011.

All tree data was recalculated from basal area ($m^2\,ha^{-1}$) to volume ($m^3\,ha^{-1}$), using specific volume equations obtained from