Reduced-impact logging in Indonesian Borneo: some results confirming the need for new silvicultural prescriptions

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Abstract

Reduced-impact logging (RIL) and conventional techniques (CNV) were compared in a mixed dipterocarp hill forest in East Kalimantan in three blocks of about 100 ha each. Damage was evaluated using pre- and post-harvesting assessments in 24 one-hectare sample plots. RIL techniques nearly halved the number of trees destroyed (36 vs 60 trees/ha). RIL's main benefit was in the reduction of skidding damage (9.5% of the original tree population in RIL vs 25% in CNV). Before logging, mean canopy openness in CNV (three plots only) and RIL (9 plots) was similar (3.6 and 3.1%) and not significantly different (χ^2=2.73, P=0.254). After logging, the mean canopy openness was 19.2% in CNV (n=9 plots) and 13.3% in RIL (n=8 plots), and the distributions of the canopy class in RIL and CNV significantly different (χ^2=43.56, P<0.001). CNV plots showed a higher proportion of measurements in the most open class ≥30% than in RIL. At a larger scale, the area of skidtrail per unit timber volume extracted was halved in the RIL compartment (15 m^2 vs 27 m^2 m^{-3} for CNV). However, under high felling intensity (>8 trees/ha), both stand damage and canopy disturbance in RIL approached those recorded in CNV under low or moderate felling regime. Over this felling intensity threshold the effectiveness of RIL in reducing tree damage is limited. In mixed dipterocarp forest where harvestable timber density generally exceeds 10 trees/ha, a minimum diameter felling limit is clearly insufficient to keep extraction rates below 8 trees/ha. Based on these new results and previous studies in Borneo, we suggest three silvicultural rules: (1) to keep a minimum distance between stumps of ca. 40 m, (2) to ensure only single tree gaps using directional felling, (3) to harvest only stems with 60–100 cm dbh. Foresters, policy makers and certifiers should consider these as criteria for sustainable forest management. We emphasise the need to expand harvesting studies to look at impacts and trade-offs across larger forest landscapes, to expand RIL beyond silvicultural concepts and to include the maintenance of other forest goods and services.

Author Keywords: Hill mixed dipterocarp forest; East Kalimantan; Indonesia; RIL; Logging damage; Felling intensity; Sustainable; TPTI; Criteria and indicators

Article Outline

1. Introduction

In the Indonesian selective logging and planting system (TPTI), all dipterocarps (i.e. timber trees in the family Dipterocarpaceae) with a diameter at 1.3 m (height dbh) over 50 or 60 cm (depending on the type of forest) can be harvested with a polycyclic felling schedule of 35 years. One year prior to harvest, forest concessionaires must carry out an inventory to determine the annual allowable cutting granted by the Department of Forestry. However, in practice these inventories are generally too inaccurate to define a satisfactory harvesting plan. In the highly productive dipterocarp forests of Borneo, where harvesting intensities commonly exceed 100 m^3 ha^{-1} and more than 10 trees/ha, conventional logging generally damages more than 50% of the original stand (Nicholson, 1958; Kartawinata, 1978; Tinal and Palinewen, 1978; Abdulhadi et al., 1981; Cannon et al., 1994; Pinard and Putz, 1996; Bertault and Sist, 1997 and Sist et al., 1998a). Because over-harvesting and poor operational practices are now recognised as an important cause of deforestation, ITTO member countries, including Indonesia, are being encouraged to revise practices in order to achieve sustainable management of the estate forests. In this context, reduced-impact logging (RIL) techniques are regarded as vital to reduce damage to a level that will preserve forest regeneration and integrity (Dykstra and Heinrich, 1996 and Sist, 2000). Several experiments in mixed dipterocarp forests have demonstrated that RIL techniques can reduce damage by at least 30–50% compared with normal operation, also called 'conventional logging' (Pinard and Putz, 1996 and Bertault and Sist, 1997). Most of the studies comparing damage under RIL and conventional logging have neglected the variability in natural forest and the variation in damage that this implies. The current coverage of such studies is very limited. This is important as the proportion of stems damaged is generally correlated with extraction rates (Nicholson, 1958; Bertault and Sist, 1997 and Sist et al., 1998a) and possibly with other factors. Thus, it remains difficult to determine how general or local any conclusion might be. The main objective of this study is to assess how far RIL can reduce damage under varying felling intensity.

2. Study site and methods

2.1. Study site

The study area is located in the Indonesian Province of East Kalimantan (Borneo Island), in the district of Malinau (2°52′–3°14′N, 116°–116°40′E), within a 50,000 ha forest concession managed by Inhutani II, a state-owned timber company. The climate is equatorial with an annual rainfall measured at ca. 4000 mm. The monthly rainfall varies from ca. 200 to 400 mm (PT Inhutani II, 1996). The topography is deeply eroded with a dense network of steep ridges and drainage gullies. Elevations at the study area range from 100 to 300 m above sea level.

2.2. Logging operations, permanent sample plots and treatments

Three blocks (27, 28 and 29 in Inhutani II's 5-year plan of operations) of about 100 ha each were selected in the 1998–1999 annual coupe because of their similarity including the local presence of *Agathis borneensis*, a very valuable timber species, which occurred at similar density in these blocks (3–4 trees/ha, Inhutani II forest survey). Both blocks 28 and 29, totalising an area of 244 ha, included more than 50% of low-lying forest on periodically inundated ground unsuitable for heavily mechanised timber extraction. These blocks were merged to have a productive forest area similar to that of 27. Block 28/29 was logged with conventional logging in 1998 and block 27 with RIL in 1999 (Table 1). In the 'conventional' treatment referred to here as CNV, harvesting operations were not planned and loggers worked without any additional supervision (Table 2). In CNV, tree surveys required by the Indonesian legislation and completed before logging were not actually used by any field operators. In the RIL treatment, several training sessions were organised the year before the experimentation. These training courses included tree inventory and mapping, directional felling techniques, skidtrail planning and marking in the field (Table 2). The RIL techniques followed the harvesting guidelines published in Sist et al. (1998b). As part of RIL, pre-harvesting inventory led to the production of an operational map of block 27 at 1:2000 scale showing 5 m contour lines and position of harvestable timber trees. Skidtrails were then planned on the operational map and marked in the field with red plastic ribbons. Skidtrails were opened before felling mainly to help fellers to decide for the best directional felling. In CNV a bulldozer (D7G) was used for both log extraction and road construction. In RIL, we preferred two articulated skidders (CAT 527) for log extraction only instead of bulldozer because of their less damaging action to soil and their higher manageability in the forest involving consequently less damage to the stand. Although we recommended the use of skidder with narrow blade (<2 m) (Sist et al., 1998b), the two CAT 527 skidders that operated in the RIL block had 3 m wide blade. We accept that including multiple differences between the RIL and CNV treatment, such as different machinery, can make it harder to specifically link any one of them to the reduced impacts observed. It should be noted that the Inhutani II-CIFOR site also serves as a demonstration and training site to show the considerable reduction in damage and operational costs that are possible when the full range of RIL techniques, including lighter narrower skidders, are used.

Table 1. Permanent sample plots and treatment allocation in conventional and RIL blocks (conventional: blocks 28 and 29 gathering 12 plots, 1 ha each, set up during June–September 1998; RIL: block 27 gathering 12 plots, 1 ha each, set up in March–May 1999)

Treatments	Description	Plots	Blocks	Tree measurement	Logging
CNV 1	Conventional techniques with low felling intensity (≤5 trees/ha)	3	28/29	June–September 1998	November–December 1998
CNV 2[a]	Conventional techniques with moderate felling intensity (6–9 trees/ha)	3	28/29	June–September 1998 and August 1999	November–December 1998
CNV 3[a]	Conventional techniques with high felling intensity (>9 trees)	3	28/29	June–September 1998 and August 1999	November–December 1998
RIL 1	Reduced-impact logging techniques with low intensity (≤5 trees/ha)	3	27	March–May 1999	September 1999
RIL 2	RIL with moderate felling intensity (6–9 trees/ha)	3	27	March–May 1999	September 1999
RIL 3	RIL with high felling intensity (>9 trees)	3	27	March–May 1999	September 1999
CTCNV	Control plots with a 50 m buffer zone, no logging	3	28/29	June–September 1998	–
CTRIL	Control plots with a 50 m buffer zone, no logging	3	27	March–May 1999	–

Full-size table (<1K)

Table 2. Main activities (training, supervision, planning) of RIL and conventional techniques (from Sist et al., 1998b and Dwiprabowo et al., 2002)

Activities	Reduced-impact logging (RIL)	Conventional logging (CNV)
1. Forest survey	Pre-harvesting survey includes topography assessment and mapping of harvestable trees	Commercial trees with dbh ≥ 20 cm are mapped and dbh estimated. No topography assessment
2. Mapping	Topographic and tree location maps, 5 m contour lines, 1/2000 scale produced with software ROADENG®	Tree location maps only produced manually. No topographic contour lines
3. Vine cutting	All vines of at least 2 cm in diameter growing on each harvestable tree are removed during forest inventory 1 year prior to felling	No vine cutting
4. Skidtrails planning	Skidtrails are planned according to the topography and position of harvestable trees shown in the operational map. Skidtrails are then marked on the field with coloured ribbon flags	No skidtrail planning
5. Skidtrail opening	Skidtrails are opened before felling to help fellers for directional felling decision. Skidtrails width must not exceed 4 m, skidder operators are not permitted to leave the marked skidtrails, blading should be avoided as much as possible	Skidtrails are opened during extraction without any previous planning
7. Directional felling	Trees must be felled either toward or away from skidtrails at an oblique angle of about 30° to the skidding direction, unless the tree can be felled directly onto the skidtrail	None
8. Training	Training on topography assessment, forestry inventory, use of ROADENG software®, directional felling and skidding operations were provided in advance prior to logging. Training on directional felling 1 year before logging	None
9. Road construction	Because of the small scale of the experiment, road planning and construction were not included in this study. The road existed before the study was devised	Road planning is done two years before harvesting and the construction 1 year before. Road planning and location are based on rapid field survey and checking but not on systematic topographic assessment. No topographic maps are pro-

Seven different sub-treatments (3 RIL, 3 CNV and 1 control), each with three replicates, were defined to examine felling intensity (Table 1). Before logging, 24 one-hectare plots (12 in block 28/29 and 12 in block 27, Table 1) were selected randomly but stratified according to the respective timber density in each plot based on the pre-harvest map stock. A number of minor shifts in plot positions were necessary to remove road edge effects, and unworkable slopes. Each plot, 1 ha (100×100 m), was divided into 25 sub-squares (20 m×20 m) delimited by 36 PVC stakes driven into the ground. Before logging, the girth of all trees and lianas with dbh≥20 cm in the plots were measured and their position located in one of the four quarters of each sub-square. In the three control plots of the CNV blocks and the 9 plots of RIL 1, 2, 3, canopy openness was measured using a concave spherical densiometer at each of the 36 grid points at breadth height (i.e. 1.30 m above ground). Canopy openness was defined as the proportion of sky hemisphere not obscured by the vegetation when viewed from a single point (Jennings et al., 1999).

During the harvesting period of the CNV block 28/29, there was a commercial demand for *A. borneensis*. Consequently extraction focused on this species rather than dipterocarps. Among the nine plots in 28/29 slated for potential harvesting only the five that included harvestable *Agathis* were logged whereas four other plots, though on firm potentially accessible sites but with no *Agathis*, were left undisturbed. In order to restore the original treatment allocation, an issue we discuss more fully below, four new plots were set up randomly within the logged area but without overlapping existing plots (two in each CNV 2 and CNV 3 treatments) in the conventional blocks in August 1999 (Table 1). Taking into account both standing living trees, stumps and stems destroyed by logging (dbh=20 cm), it was possible to assess prior tree density and basal area. Our analyses show no structural difference between the original and the four additional plots (see results). In the RIL 1 treatment, one plot was subsequently excluded from analysis because only one tree, located at the border of the plot, was felled outside the plot limits, generating no damage inside it.

Our analysis focuses on harvest intensities in areas actually harvested, where felling and extraction operations actually took place. To obtain an adequate level of quantification, it was necessary to increase the original pre-logging sample to achieve a satisfactory replication in the harvested conventional areas. Few studies of timber harvesting in the tropics have examined these effects at the scale we have achieved. Examining real operations at this scale is never the neat and tidy controlled experiment that would be ideal. Almost all realistic studies will suffer from some lack of control and the subsequent issues of limited replication in time and space. It bears repeating therefore that in all the results and arguments that follow, our comparisons are based on the areas actually and not potentially harvested. Ideally future studies should be even larger and provide replication at the compartment level allowing us to also begin to generalise the degree to which intact forest remains in the post-harvest landscape with RIL and CNV approaches Cannon et al. (1994). Only when we have done that can we generalise these patterns.

2.3. Logging damage assessment

In both conventional and RIL, damage was assessed 8 months after logging (Table 1). In each plot, all trees (dbh≥20 cm) measured prior to harvesting were recorded as untouched, injured or dead. Snapped stems without any resprouting 8 months after logging were considered dead. Canopy openness was also reassessed in the 17 logged plots. In each block, all the skidtrails were mapped and classified as 'main' or 'secondary'. Main skidtrails were defined as those with at least three branch skidtrails. Secondary skidtrails usually had no branches (Chabbert and Priyadi, 2001). The total volume extracted from each block was estimated by measuring the log length and end diameters for every log removed. Skidtrail area per timber volume extracted could be therefore assessed and compared. Furthermore every 50 m, along each skidtrail, maximum width and maximum depth of the track were measured. At each point of measurement, the area of the skidtrail was also classed as one of three types: *low soil impact* (LSI) when the skidtrail was very superficial and topsoil still present, *moderate soil impact* (MSI) when topsoil was completely removed but the track damage still relatively superficial (20–50 cm depth), and *heavy soil impact* (HSI) when the trail was deeply excavated (>50 cm depth).

3. Results

The mean density and basal area of the four additional plots in the CNV blocks (243.6 trees/ha, SD=41; 30.4 m^2/ha, SD=4.9) were not distinct from those of the 12 plots (230 trees/ha, SD=35.8 and 32.85 m^2/ha, SD=4.7) set up before logging (t=0.57, df=14, P=0.58 for density, and t=0.87, df=14, P=0.40 for basal area). RIL (n=11) and CNV (n=12) plots showed similar tree densities and basal area (t=0.52, df=21, P=0.60 for density, and t=1.39, P=0.18, Table 3). The mean density and basal areas in each dbh class were similar in RIL and CNV (all t-tests not significant) except for the basal area in the largest dbh classes (dbh>60 cm, t=2.10, P=0.04, Table 3).

Table 3. Mean density and mean basal areas (±SD) in the RIL and CNV plots before logging (CNV=12 plots, RIL=11 plots)

	dbh (cm)			
	20–29	30–39	40–49	50–59
RIL plots density (n/ha)	124.3 ± 31.2	52.5 ± 12.9	26.3 ± 7.0	14.9 ± 5.6
CNV plots density (n/ha)	123.1 ± 27.0	55.0 ± 9.2	26.2 ± 5.6	15.7 ± 4.9
Mean density RIL + CNV (n/ha)	128.6 ± 24.7	54.3 ± 9.6	27.2 ± 5.8	15.3 ± 5.4
RIL plots basal area (m^2/ha)	6.3 ± 1.0	5.0 ± 0.9	4.4 ± 0.9	3.3 ± 1.4
CNV plots basal area (m^2/ha)	5.7 ± 1.2	5.2 ± 0.8	4.1 ± 0.9	3.6 ± 1.1
Mean basal area (m^2/ha)	5.9 ± 1.1	5.1 ± 0.9	4.3 ± 0.9	3.5 ± 1.2

Full-size table (<1K)

3.1. Logging damage to stand

Mean logging intensities in the CNV and RIL plots were similar in terms of density of trees harvested (7.6 and 7.5 ha^{-1}, respectively, t=0.04, P=0.48, df=15), harvested volume (83 and

60 m^3 ha^{-1}, t=1.03, P=0.16), and basal area removed (5.4 and 3.8 m^2 ha^{-1}, respectively, t=1.38, P=0.09). However, mean volume per harvested tree was higher in the CNV than in RIL compartment (10.5 m^3/tree vs 9 m^3/tree, t=3.76, df=708, P<0.01). This difference was likely due to the higher proportion of large *Agathis* harvested in the CNV areas.

In CNV plots, a mean of 24.7% (60 trees/ha) of the original tree population (dbh=20 cm) was destroyed by logging, whereas in RIL, 14.5% (36 trees/ha) of the stand was killed. RIL techniques succeeded therefore to reduce by 40% the proportion of trees killed by logging. In contrast, a similar proportion of trees was injured in CNV and RIL plots (26.1% or 63 trees/ha in CNV vs 23.4% or 59 trees/ha in RIL, Fig. 1). RIL's main benefit was in the reduction of skidding damage (9.5% of the original tree population in RIL vs 25% in CNV). In CNV plots, the proportion of trees killed by skidding was double than that killed by felling (38 trees/ha or 15.8% of the original tree population, and 17 trees/ha or 6.7%, respectively). In both RIL and CNV, the distribution of injured trees by diameter classes nearly matched the pre-logging tree population (χ^2=7.7, P=0.05 for CNV and χ^2=3.8, P=0.28, df=3 for RIL). In contrast, trees were killed in higher proportion in the smallest dbh class in both treatments (20–29 cm, χ^2=32.18 for CNV and χ^2=16.2 for RIL, df=3, P<0.01).

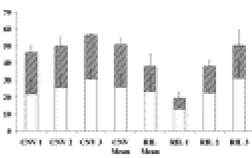 Full-size image (9K)

Fig. 1. Mean proportions of trees injured (empty bars±SD) and killed (hatched bars±SD) by conventional (CNV) and reduced-impact logging (RIL) under different intensities (CNV 1 mean intensity=5 trees/ha, CNV 2=6 trees/ha, CNV 3=11 trees/ha; RIL 1=3.5 trees/ha, RIL 2=7 trees/ha, RIL 3=10 trees/ha; empty bars: injured trees; hatched bars: dead trees).

There was a significant positive correlation between felling intensity (the density of trees harvested) and the proportion of trees damaged by RIL but not by CNV (Pearson's r=0.78, P=0.02 for RIL, r=0.53, P=0.14 for CNV, Fig. 2a). In RIL, the percentage of trees damaged (injured or killed) increased from 19.4% in RIL 1 to 50.3% in RIL 3, whereas in conventional, the proportion of trees damaged varied only from 46% in CNV 1 to 56% in CNV 3 (Fig. 1). Correlation between the density of harvested trees and felling damage, though implied to be positive by the data, did not quite achieve 5% significance levels in either treatment (Pearson's r=0.63, P=0.06 for CNV; r=0.69, P=0.056 for RIL, Fig. 2b). There was a significant positive correlation between skidding damage and felling intensity in RIL (r=0.72, P=0.04), whereas in CNV this relationship was far from significant (r=0.13, p=0.72, Fig. 2c).

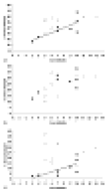 Full-size image (10K)

Fig. 2. Correlation between felling intensity and percentage of trees damaged in RIL and conventional: (a) between felling intensity and total trees damaged in RIL (filled black squares) and in CNV (empty lozenges), regression line equation for RIL=Y=4.54X+3.88; (b) between felling intensity and proportion of trees damaged by felling in RIL and CNV; (c) between felling intensity and proportion of trees damaged by skidding (regression line equation for RIL: Y=1.93X−5.03).

3.2. Impact of logging on canopy opening

Before logging, mean canopy openness in CNV (three plots only) and RIL (9 plots) was respectively 3.6 and 3.1%. The distributions of the values according to canopy openness classes in CNV and RIL plots were similar (χ^2=2.73, P=0.25, Fig. 3a). After logging, the mean canopy openness was 19.2% in CNV (n=9 plots) and 13.3% in RIL (n=8 plots). The distributions of the canopy class in RIL and CNV were significantly different (χ^2=43.56, P<0.001, Fig. 3b). There was a higher proportion of measurements in the 0–5% canopy openness class and a lower one in the last class (≥30%) in RIL than in CNV (Fig. 3b). Within treatments, canopy openness was significantly correlated with felling intensity in RIL but not in CNV (Pearson's r=0.84, P<0.01, df=7 for RIL, r=0.33, P=0.38, df=8 for CNV). Mean-per-plot canopy openness varied from 4% in RIL 1 to 18% in RIL 3, and from 17.5% in CNV 1 to 20.7% in CNV 3.

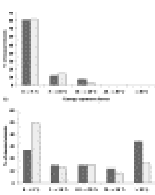 Full-size image (17K)

Fig. 3. Percentage of canopy openness measurements in each canopy class in CNV (hatched bars) and RIL (dotted bars): (a) before logging, (b) after logging.

3.3. Impact of skidtrails in CNV and RIL

In each block, we defined the harvested area as that within 30 m to the right and left of the skidtrails. In blocks 28 and 29, only 90 ha (37%) of the 244 ha total area were logged. In the RIL compartment, the harvested area covered 56 ha or 41% of the 138 ha total area of the block. The number of felled trees per hectare based on the harvested area was very similar in both compartments (6 trees/ha=53 m^3 ha^{-1} in CNV and 7 trees/ha, 61 m^3 ha^{-1} in RIL). The total length of skidtrails in CNV and RIL was 17,300 and 9090 m, respectively. Skidtrail area per unit timber volume extracted was twice larger in CNV than in the RIL compartment (27 m^2 vs 15 m^2 m^{-3}). In CNV, total length of main and secondary skidtrails was 10,120 m (59%) and 7180 m (41%), respectively. In contrast, the RIL compartment showed less primary skidtrails (3370 m or 37%) and more secondary ones (5720 m or 63%). Both main and secondary skidtrails in CNV blocks were wider than in RIL (mean 8.3 m vs 6.3 m, t=5.38, df=223, P<0.01 for main skidtrails; 7 m vs 5.4 m, t=9.54, df=482, P<0.01 for secondary skidtrails). Skidtrails belonging to the HSI type showed excavation in which depth varied from 50 to 140 cm, whereas in MSI skidtrail type, the track damage was still relatively superficial (<20 cm depth). In the conventional blocks, half of the main skidtrails belonged to the most damaging skidtrail type (HSI), whereas in the RIL compartment, this type represented only 6% (Fig. 4a). In the RIL compartment secondary skidtrails with HSI were rare (2%), whereas in conventional these still represented nearly a third (32%, Fig. 4b).

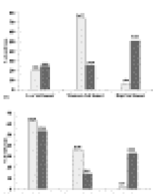 Full-size image (18K)

Fig. 4. Proportion of the three main types of impact in primary (a) and secondary skidtrails (b) in RIL (dotted bars) and conventional (hatched bars). LSI: low soil impact, MSI: moderate soil impact, HSI: high soil impact (see text for brief description). Numbers above bars indicates the length in meters of each category.

4. Discussion

Reduced-impact techniques reduced the number of trees destroyed by 40% in comparison with conventional harvesting practices. However, the proportions of trees injured were similar in both techniques, affecting about 25% of the original stand. The main benefit of RIL was to reduce skidding damage from 25% of the original stand in CNV to only 9.5%. Because skidding operations are the major causes of mortality (Bertault and Sist, 1997), the low proportion of trees killed in RIL appear to result from improved skidding. In contrast, despite careful application of directional felling techniques, RIL failed to significantly reduce felling damage, which depends mainly on the height of the tree, the size of its crown, and the topography (Cedergren, 1996). The noisy relation between felling intensity and felling damage in both conventional and RIL underlines the stochastic aspects of felling damage—here generating a high amount of unexplained residual variance. Although vine cutting prior to felling has long been regarded as promising techniques to reduce felling damage, the effectiveness has recently been questioned (Cedergren, 1996 and Parren and Bongers, 2001). Directional felling, commonly applied in RIL, aims essentially to lie the logs in position to facilitate ground-skidding extraction and limit skidding damage on the remaining stand. It is important to note that in a planned operation, skidding damage is correlated to felling intensity. In contrast, in CNV, the absence of skidtrail planning involves considerable damage independent of the harvest intensity.

Under high felling intensity (>8–9 trees/ha), the proportions of injured and dead trees in RIL were similar to those recorded in conventional harvesting (see Fig. 1 and Fig. 2). This result is consistent with previous studies in other tropical forests showing that RIL methods are only effective under low felling intensities (Sist et al., 1998a and Van der Hout, 1999). The felling intensity threshold of ca. 8–9 trees/ha in the present study corroborates that of ca. 8 trees/ha proposed by Sist et al. (1998a) based on a study in Berau, a different site in East Kalimantan. As already noted, virtually all logging studies, especially those that examine large scale commercial harvesting, suffer shortcomings of limited replication and imperfect sampling allocation. This problem allows anyone to question to what extent any given result is truly generalisable or may in fact be a local and specific result determined by an unknown number of specific local or temporary details. The conformity of the main results determined in this study and those found in Berau is therefore more important than may at first sight appear to be the case. Moreover, most of the previous studies related to logging damage assessment have been based on a total random sampling which generally failed to address the issue of the high variability of logging intensity in natural forests (Sist et al., 1998a and Putz et al., 2000). This study then has allowed us to reassess and lend support to the general proposition that RIL techniques must be implemented within a reasonable intensity threshold, and that this boundary lies at around 8 trees/ha in hill dipterocarp forests (Sist et al., 1998a). Foresters, managers and certifiers must now consider this threshold as an important criterion of sustainability.

In RIL the entire compartment was efficiently exploited while in CNV only the more accessible areas were accessed. Informal observation of CNV practices suggests that the choice of where to exploit was largely determined by the skidder drivers trying to get access to potential harvest sites from their seat in the skidder and without using any maps. These practices lead to many exploratory tracks with dead ends and wide turning zones, and are likely a major cause of skidder damage as well as reducing penetration into difficult terrain. Ultimately however, this difference, and the specific and transient demand for *Agathis* meant that in our study the conventional harvesting actually accessed a much lower area than could have been harvested by RIL. This implies that RIL provides much more efficient exploitation of the overall forest, whereas conventional methods leave substantial amounts of forest intact and probably therefore provide much lower volume outputs per unit area available for harvesting. If we are looking for some definition of 'best practice' it is relevant to stand back and to ask what is the appropriate measure of an optimal felling regime. For example in developing RIL techniques what is the best unit of 'reduced damage'? Are we, for example, looking to minimise trees destroyed per unit volume extracted or per stem cut or per annual coupe?

If we consider the wider forest landscape, we might be tempted to consider the possible trade-offs between more intensive extraction in more limited areas and lower extraction or even protection in others. Thus, our questions about what we should measure may continue with our observation that CNV actually makes incomplete use of the potential area available for harvest again raising concerns as to how to consider such non-damaged area. It is worth noting, for example, that relic patches of intact forest might be highly desirable for many ecological reasons, and are perhaps a desirable outcome of CNV. However, this could also be considered as a form of fragmentation with probably long term impact on regeneration processes, higher fragility to natural disturbances (strong winds) and exceptional climatic events (drought). Of course, it is also possible to leave *planned* areas of unlogged forest within the context of RIL whenever this is desirable. In this study, we have not yet developed an adequate database to examine these wider landscape questions, but have instead taken a more specific course in seeking to identify the limits of what might be called 'acceptable' as opposed to 'excessive' harvesting without considering trade-offs in the wider forest landscape. That is, we have sought a way to define limits for silvicultural practices in any area where harvesting is actually taking place which allows recovery without jeopardising immediate revenues.

Reduction of harvest damage is not the only criterion we should consider when assessing the technical sustainability of forest management. Even if we restrict our considerations to the stand level it is clear that high extraction levels also involve major impacts on dynamic processes and forest composition. There is scant evidence that any commercial dipterocarp species benefits canopy openings greater than those created by single-tree selection cutting practices (500–600 m^2) to establish and maintain good growth, especially those of commercial value (Kuusipalo et al., 1996; Tuomela et al., 1996 and Van Gardingen et al., 1998). However, it may be that *Agathis* requires larger gaps, although data confirming this are not yet available. High extraction rates, by creating big canopy openings, stimulate the growth of fast-growing pioneer species and create desiccating conditions (Nussbaum et al., 1995; Kuusipalo et al., 1996; Tuomela et al., 1996; Van Gardingen et al., 1998; Clearwater et al., 1999 and Sist and Nguyen-The, 2002), factors unfavourable to the establishment and growth of dipterocarps. Moreover, large openings are subject to invasion by lianas that can be an obstacle to tree regeneration. In heavily logged forests such openness also increases fire risks and propagation, particularly during long period of drought as this periodically occurs in southeast Asia during El Niño events. High extraction rates also result in a depleted residual stand which will not be able to recover an acceptable timber yield within a reasonable and economically profitable harvesting cycle period, usually evaluated to be less than 60 years (Favrichon and Young Cheol, 1998 and Huth and Ditzer, 2001). There is a need for simple and practical prescriptions which limit the local densities of trees harvested to 8 ha^{-1} or less (50–70 m^3 ha^{-1}) and keep the size of gap to less than 500–600 m^2. Three simple rules would appear to provide this: (1) a minimum spacing distance between harvested trees, (2) single tree gap formation from harvesting using directional felling, (3) a maximum (as well as a minimum) dbh limit for harvesting. We will now present in more detail the rules that we recommend for mixed diperocarp forests of southeast Asia.

In a homogeneous spatial distribution under maximum horizontal packing (triangular), the distance *D* between trees in meters is given by the formula:

$$D = \frac{200}{\sqrt{3x}}$$

where *x* is the density in stems per hectare. This is slightly longer than packing in a regular square lattice where

$$D = \frac{100}{\sqrt{x}}$$

Following these two equations, in a homogeneous distribution, the minimum spacing distance for a maximum felling intensity of 8 trees/ha for each of these is 40.8 and 35 m, respectively. These limits will be conservative when applied to the irregular distribution of real trees. We now need to develop simple operational ways for implementing such limits efficiently.

Because gap size is largely dependent on tree size, the most effective method to limit gap area is to favour single tree gap during felling and avoid harvesting of trees over a certain size. We suggest that this might be usefully set at dbh≥100 cm. These very large individuals are difficult to harvest, have structural defects that reduce their timber value, and create disproportionate damage on the surrounding stand. However, they have high ecological relevance as they are normally the most active individuals in terms of seed production and hence in long-term regeneration potential, serve as genetic stock well adapted to local site conditions, and provide valuable habitat for a myriad of organisms (Sheil and Van Heist, 2000). In the study area mean density of harvestable trees (Dipterocarps and *Agathis*) with dbh=60 cm was 15 trees/ha, whereas that of trees with dbh between 60 and 100 cm decreased to 12.5 trees/ha (i.e. 2.5 trees/ha with dbh>100 cm). Taking a stem rejection rate of 30% (estimate based on P. Sist pers. obs. in several localities of East Kalimantan), the density of harvested trees of 60–100 cm dbh is 8 trees/ha, which remains high in comparison with other tropical forests of Africa and South America. In other parts of Borneo, taking the same rejection rate, the mean density of commercial trees with 60–100 cm dbh is higher, around 10–11 trees/ha (Cedergren, 1996 and Sist and Saridan, 1999). Though limiting harvesting to commercial trees with 60–100 cm dbh in mixed dipterocarp forest would be certainly regarded as a major constraint by loggers, we must keep in mind that this limitation should also yield various long-term benefits both in terms of long-term timber potential and ecological values (Sheil and Van Heist, 2000).

Our three suggested felling rules for avoiding excessive stand damage are only a first step mainly focused on sustaining mixed dipterocarp forest for timber alone. It is now widely admitted that forestry practices need to consider not only timber production but also the numerous roles of forests in terms of goods and services to serve local communities requirements for diverse needs. Our work in Bulungan has begun to look at these factors, and we hope to develop these along with the larger scale trade-offs implied by any limits on felling intensities.

5. Conclusions

In mixed dipterocarp forests of East Kalimantan, where density of harvestable trees often exceed 10 trees/ha, the minimum diameter rule results in high felling intensities with excessive damage to the remaining forest. RIL techniques, though they would appear to be a vital part of the solution, are useful only under a moderate extraction regime in which 8 trees/ha is an upper limit.

Restricting felling intensity is essential in any case, both from the perspective of the growth and survival of the residual stand and the long-term ecological sustainability of the forest. RIL techniques do not guarantee silvicultural sustainability if based on a minimum diameter cutting limit alone. Therefore, new silvicultural prescriptions must be considered as a step forward to improve harvesting operations in mixed dipterocarp forests. Those we suggest are: (1) a minimum spacing distance between harvested trees (ca. 35–40 m); (2) single tree gap formation from harvesting using directional felling; (3) a maximum (as well as a minimum) dbh limit for harvesting (ca. 100 cm). In exploring the major issues that remain, we highlight an urgent need to expand logging studies to look at impacts and trade-offs across larger forest landscapes.

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