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Soil disturbance and post-logging forest recovery on bulldozer paths in Sabah, Malaysia

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Abstract

We examined the extent of soil disturbance associated with bulldozer yarding and the regrowth of woody vegetation on bulldozer paths (skid trails) in selectively logged dipterocarp forest. In an area logged in 1993, using conventional, i.e., uncontrolled, harvesting methods, about 17% of the area was covered by roads and skid trails. In contrast, in a 450-ha experimental area where reduced-impact logging guidelines were implemented, 6% of the area was similarly disturbed. Skid trails in the reduced-impact logging areas were less severely disturbed than those in conventional logging areas; the proportion of skid trails with subsoil disturbance was less than half that in conventional logging areas. Four years after logging, woody plant recovery on skid trails was greater in areas logged by reduced-impact than by conventional methods. Skid trails where topsoil had been bladed off had less woody vegetation than skid trails with intact topsoil. In a chronosequence of logging areas (3, 6, and 18 years after logging), species richness and stem densities of woody plants (>1 m tall, <5 cm dbh) were lower on skid trail tracks than on skid trail edges or in adjacent forest. Both richness and density increased with time since logging, but even 18 years after logging, abandoned skid trails were impoverished in small woody stems compared with adjacent forest. Minimizing soil and stand disturbance during logging appears to allow a more rapid recovery of vegetation on bulldozed soils, but the long-term fate of trees growing on compacted soils remains uncertain.

Keywords: Dipterocarp forest; Malaysia; Harvesting guidelines; Reduced-impact logging; Soil disturbance; Skidding; Tree regeneration; Tropical forest

1. Introduction

In East Malaysia, though only 8–15 trees are extracted per hectare, typically 15–40% of the area is traversed by bulldozer paths (Chai, 1975; Jusoff, 1991). Alternative harvesting systems, for example, skyline (Miller and Sirois, 1986) or helicopter (Blakeney, 1992) yarding, cause less soil disturbance, but these techniques are generally more expensive than ground skidding on all but the most difficult terrain (Aulerich et al., 1974). Furthermore, forest contractors are hesitant to make redundant their fleets of bulldozers and cadres of skilled operators to reinvest in alternative skidding systems. Thus, ground-based

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extraction systems are likely to continue to be important in spite of their negative impacts on soils.

The extent and degree of soil disturbance associated with bulldozer yarding are variable and appear to be related to slope (Dyrness, 1965; Stuart and Carr, 1991), soil texture (Daddow and Warrington, 1983; Clayton, 1990; Jusoff, 1992), and soil moisture content at the time of logging (Burger et al., 1989; Rachal and Karr, 1989; Jusoff, 1992). Certain logging practices also influence soil disturbance, for example, size of logs extracted (Dickerson, 1968) and extent of bulldozer blade use (Miller and Sirois, 1986). Preharvest planning increases the efficiency of log extraction and reduces the area disturbed (Froehlich et al., 1981). Prohibiting wet-weather skidding, skidding on steep slopes, and use of the bulldozer's blade further reduces soil disturbance. Installation of proper drainage structures on bulldozer paths (hereafter, skid trails), roads, and landings lessens erosion substantially (Stuart and Carr, 1991).

One of the goals of the Reduced-Impact Logging (RIL) Project in Sabah was to reduce the area affected by soil disturbance while using existing equipment and personnel. Bulldozer and chain-saw operators were trained in damage-control techniques, and harvesting guidelines were implemented in 1400 ha of dipterocarp forest (Pinard et al., 1995). The objective of the first part of this study was to compare areas logged using conventional (hereafter, CL is used for conventional logging) and RIL techniques in terms of extent and degree of soil disturbance to describe the reduction achieved in the RIL project area. In the second part of the study, we explored the importance of skidding disturbance for plant regeneration by studying vegetation on abandoned skid trails.

The extraction of logs with bulldozers disturbs soil in a number of ways that affect plant regeneration; soil compaction and topsoil displacement may be particularly important. As soils are compacted from loads applied by bulldozers and logs skidded across the forest floor, soil porosity decreases (Nyland et al., 1976), often causing decreased water infiltration, soil moisture availability, aeration and rooting space (Greacen and Sands, 1980). During heavy rains, seeds and seedlings may be washed away (Borhan et al., 1987; Pinard et al., 1996). When the bulldozer blade is used during skid trail construction, topsoils, and the organic matter and buried seed they contain, are displaced. Although total soil organic matter content may not change across the entire logged area, its distribution does (Johnson et al., 1991), with bulldozed areas losing, and sidecast mounds accumulating, soil organic matter (Gillman et al., 1985; Rab, 1994). These localized losses in organic matter can have substantial effects on soil fertility (Gillman et al., 1985; Zabowski et al., 1994) and tree seedling growth and survival (Nussbaum et al., 1995; Woodward, 1995). While unfavorable conditions may limit plant establishment on skid trail tracks and (Pinard et al., 1996) along the edges of skids, the accumulation of organic matter and buried seed may create potentially good habitat for the establishment of pioneer vegetation (Guariguata and Dupuy, 1997).

Where skidding restrictions are enforced and soil disturbance from skidding is minimized, one might expect a more rapid recovery of woody vegetation on skid trails. To explore the implications of implementation of RIL guidelines for plant regeneration, we compared woody stem densities and species richness on skid trails in RIL and CL areas four years after logging. We sampled three habitats (skid trail tracks, skid trail edges, and adjacent forest) to allow for a comparison of the contrasting substrate conditions. We also sampled abandoned skid trails in a chronosequence of logged forest (areas logged 3, 6, and 18 years prior to our study) to look for evidence of recovery of structural and floristic conditions.

2. Methods

2.1. Study site

The study was based in the Yayasan Sabah concession in Ulu Segama Forest Reserve (5°0′N, 117°30′E, 150–750 m a.s.l.). The conventional timber harvesting system used in Sabah since the mid-1960s is based on a minimum harvesting diameter of 60 cm dbh, and bulldozers are used to extract logs (Chai and Udarbe, 1977; Sabah Forestry Department, 1989; Kleine and Heuveldop, 1993). Between 1970 and 1998, the degree of disturbance associated with logging has varied with extraction rates (a function of stocking, but also merchantability), terrain, size of bulldozer used, skill and attitude of the operator, and other factors. For this study, we sampled four different logging areas (1976, 1988, 1991 and 1993). In the

Table 1
Estimated timber volume extracted within each of the four logging areas sampled, along with mean (SD noted parenthetically) width of skid trail track surface for skid trails sampled[a]

Annual logging area	Volume extracted (m^3 ha^{-1})	Skid trail width (m)
1976 Conventional logging	93–118	3.9 (0.2)
1988 Conventional logging	94	4.1 (0.2)
1991 Conventional logging	90–95	5.4 (0.7)
1993 Conventional logging	134–173	7.1 (1.8)
1993 Reduced-impact logging	87–175	5.4 (2.3)

[a] Sample sizes given in text.

1993 area, we worked on sites logged by CL and RIL methods. The other three areas had been logged conventionally.

All of the areas had been logged only once and were old-growth forest at the time of logging. Prior to logging, the tall, diverse forest was dominated by dipterocarps, particularly *Parashorea tomentella* (Sym.) W. Meijer, *Parashorea malaanonon* (Blanco) Merr., and *Shorea johorensis* Foxw. (Fox, 1978; Newbery et al., 1992; Pinard and Putz, 1996). The terrain in the areas varied from fairly flat in the 1976 area to steeply dissected ridges in the 1993 area. Mean levels of timber extraction were relatively high in all four areas, and mean width of skid trails sampled followed a trend of increasing width with more recent harvesting (Table 1). Soils in Ulu Segama are varied, but primarily are Acrisols, Luvisols, and Cambisols (Nussbaum, 1995).

2.2. Soil disturbance in RIL and CL areas

In 1992, the RIL project was established between Innoprise Corporation and New England Electric Systems; the project aimed to train staff and implement harvesting guidelines (see Pinard et al., 1995) in 1400 ha. One of the project sites, a 450-ha tract in the 1993 area in Ulu Segama, was used in this study.

The harvesting guidelines followed in RIL areas are described in detail in Pinard and Putz (1996). The key differences between the RIL and CL system are as follows:

1. RIL follows a pre-harvest plan, with locations of all skid trails identified on a stock map of trees to be harvested, whereas CL involves little or no pre-harvesting skid trail planning;
2. RIL restricts bulldozers to slopes <35°, whereas CL has no slope restriction within the logging unit; and
3. RIL restricts bulldozer blade use and encourages the use of the winch cable, whereas CL does neither.

To determine the extent and severity of soil disturbance associated with CL and RIL logging, we mapped, measured, and classified all soil disturbance associated with bulldozer activity in eight logging units (approximately 50 ha each) in the 1993 area within a month after logging. Four units were selected randomly from the experimental area logged according to the RIL guidelines by trained crews and closely supervised by forest rangers; four units were selected randomly from an adjacent area logged by unsupervised and untrained crews using conventional methods. Prior to logging, forest structure and composition were similar in the CL and RIL areas, with mean basal area ranging from 25–33 m^2 ha^{-1} (Pinard and Putz, 1996).

We used three broad disturbance categories: (i) roads and log storage landings; (ii) bulldozer paths (skid trails); and (iii) areas covered by sidecast soils, i.e., soil displaced by bulldozer blade, either dispersed over slopes or in linear mounds along the edges of skid trails. Roads and log landings generally are leveled and graveled surfaces on subsoils. Skid trail surfaces are variable and were further classified by degree of soil disturbance as follows: (i) subsoil exposed, either by blading or heavy bulldozer churning; (ii) churned, but topsoil mixed with upper layers of subsoil; and (iii) compacted by bulldozer passing over the area, but with relatively little mixing of topsoil with subsoil. In the eight logging units, 100% of the area was surveyed for soil disturbance caused by logging. We measured lengths and slopes of roads and skid trails by sections; a section was a length of road or skid trail that was relatively uniform in slope, width, and direction. Widths were measured every 10–15 m or, for more rapidly changing sections, at the midpoint of each section. Contiguous areas of sidecast soils, e.g., linear soil mounds or tips, were also measured. For large areas with sidecast soils adjacent to roads and skid trails, we measured the average slope and distance to the end of each soil mound, or slide. No effort was made to measure areas crushed or scraped during the winching of logs to the skid trails. The area of disturbed soil was calculated based on net logged area per unit (defined in Pinard and Putz, 1996). *t*-tests performed on arcsine-transformed data were used to compare treatments.

2.3. Plant regeneration on abandoned skid trails in RIL and CL areas

To determine if early woody plant establishment on skid trails differed between RIL and CL areas, we sampled vegetation in logging units four years after logging (November 1997) in RIL and CL units in the 1993 area. Using skid trail maps made immediately post-logging, we stratified the skid trails by degree of disturbance (bladed, churned, compacted), and located points in a stratified random manner within the two treatment areas. In each treatment area, 11 sampling points were located with a minimum distance of 100 m between points (in CL, 10 bladed, 1 churned; in RIL, 4 bladed, 6 churned, 1 compacted).

At each sampling point, three 2 m $\times$ 2 m plots were established, one in the center of skid trail, another at the edge of the skid trail, and the third 10 m into adjacent forest, following a line perpendicular to the skid trail. The width of the skid trail was measured edge to edge. Random numbers were used to determine whether the edge and forest plots would be placed to the left or the right of the skid trail; edge plots did not include skid trail surfaces, though side-cast soil was included often. Within each plot, we recorded the following: canopy cover (>1 m) using a spherical densiometer (Lemon, 1957), number of woody stems (>1 m tall, <5 cm dbh), and number of species. Trees >5 cm dbh were not included in the samples because the plot size was too small to adequately sample their densities at this level of replication. All dipterocarps, i.e., commercial species, and colonizing tree species, e.g., *Macaranga* spp., were noted as such.

Because the degree, as well as the extent, of soil disturbance was less in RIL than in CL areas, we compared plant regeneration on bladed and churned skid trails within the RIL area to determine if the degree of soil disturbance affected woody plant densities four years after logging. Using the map of skid trails, ten sites were located within the RIL area where bladed and churned skid trail surfaces occurred within 50 m of each other. Plots were established randomly within these sites, one each on the bladed and the churned skid trail tracks. Horizontal distance between paired plots was at least 10 m and less than 50 m. Paired *t*-tests were used to compared woody stem densities, species richness, and canopy cover on the bladed and churned tracks. We also compared plant regeneration on only bladed skid trail tracks in CL and RIL areas to examine whether differences between the two treatments could be attributed to stand conditions. Stands in CL areas were more heavily disturbed during logging than were those in RIL areas, with 59 and 27%, respectively, of the residual trees <60 cm dbh damaged (Pinard and Putz, 1996).

2.4. Plant regeneration on abandoned skid trails in a chronosequence of CL areas

To describe woody plant establishment in older logging areas, we sampled old skid trails in three logging areas (1976, 1988, and 1991) in 1994. Within each logging area, skid trails were located in four logging units (30–50 ha each) that were separated by at least 1 km. Main skid trails originating at log landings or roads were selected in all cases. Skid trails were easily located in all three logging areas. Often, the edge of the skid trail was marked by an uneven soil surface, probably the result of side-cutting with the bulldozer blade.

In each logging unit, we established 10 sampling points at 20-m intervals along a skid trail, with the first point located at a random distance (0–20 m) from the landing or road. For plots on the surface of the skid trail, 1 subplot (1 m^2) was randomly selected for determination of above- and below-ground biomass. All vegetation was clipped at ground level, weighed, and subsampled for dry weight determination. Coarse roots (>5 mm diameter) were collected from a 50 cm $\times$ 50 cm $\times$50 cm pit located in the center of subplot; roots were washed, and live and dead roots were separated, weighed and subsampled for dry weight determination.

For analyses of the data from the chronosequence, logging units were considered replicates, and the plots within each unit were considered samples. Analysis of variance, followed by Tukey multiple comparisons, were used to compare stem densities, species richness, and canopy cover among the three logging areas and the three habitats within each area. To compare skid trail width and biomass in skid trails in the three logging areas, Kruskal-Wallis tests were used, followed by Tukey-type nonparametric multiple comparisons (Zar, 1984). In all cases, the significance level used to reject the null hypothesis was 0.05.

3. Results

3.1. Soil disturbance in RIL and CL areas

A greater area of soil was disturbed in CL units than in RIL units ($t = 5.6$, df $= 6$, $p = 0.001$; Fig. 1; Table 2). Road area was similar in the two treatments ($t = 1.04$, df $= 6$, $p = 0.34$), but skid trail area was three times less in the RIL units than in CL units ($t = 4.95$, df $= 6$, $p = 0.003$). Including only logged areas, mean skid trail density was three times greater in CL units (mean $= 199$ m ha^{-1}, SD $= 35.8$) than in RIL units (mean $= 66.5$ m ha^{-1}, SD $= 25.7$; $t = 6.0$, df $= 6$, $p < 0.001$).

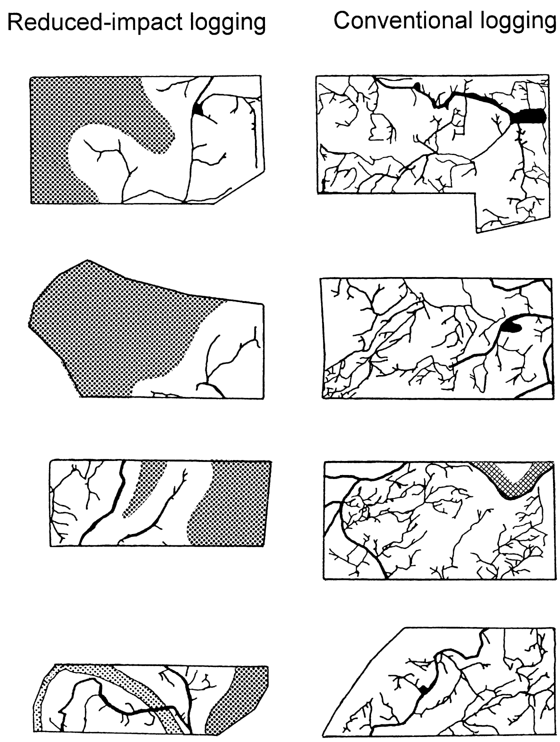

Fig. 1. Diagrams of the eight logging units in which soil disturbance was measured. The thick black lines represent roads; the thin black lines, skid trails; the blackened areas, log landings; the stippled areas, riparian and unlogged zones; and the hatched area represents a landslide below a road.

Table 2
Soil disturbance in conventional and reduced-impact logging units (100% area)[a]

	Conventional logging units	Reduced-impact logging units
Total area disturbed[b]	16.6 (2.3)	6.8 (2.6)
Roads and landings	4.7 (0.8)	3.3 (2.5)
Skid trails[b,c]	11.9 (2.7)	3.5 (2.1)

[a] Values are mean percentages (SD noted parenthetically) of logged areas ($N = 4$ per treatment).
[b] Denotes significant differences between logging treatments; $p < 0.01$.
[c] Area includes area covered with sidecast soil.

Total volume of timber extracted per logging unit was not statistically different between the two methods ($t = 1.88$, df $= 6$, $p = 0.11$; Fig. 2); however, high variability and low replication limit the power of this

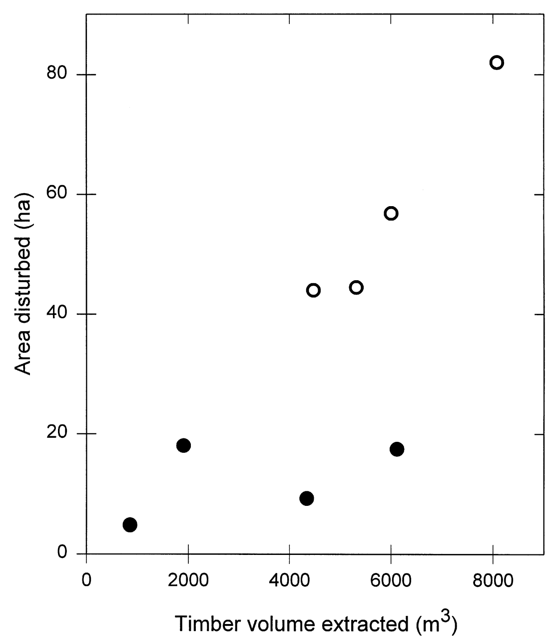

Fig. 2. Total skid trail area (hectare per logging unit) related to timber volume extracted (cubic meter per logging unit) for reduced-impact logging areas (solid circles) and conventional logging areas (open circles).

Table 3
Types of soil disturbance recorded in conventional and reduced-impact logging units[a]

	Conventional logging units	Reduced-impact logging units
Area with sidecast soil[b]	2.1 (0.2)	0.4 (0.5)
Skid trail surface area[b]	9.9 (2.7)	3.2 (1.6)
Bladed[b]	87.2 (5.6)	37.7 (9.9)
Churned[b]	11.1 (4.9)	50.2 (7.3)
Compacted[c]	1.6 (1.1)	12.1 (9.5)

[a] Values are mean percentage (SD noted parenthetically) of total area logged ($N = 4$ per treatment).
[b] Denotes significant differences between logging treatments; $p < 0.01$.
[c] Denotes significant differences between logging treatments; $0.1 < p < 0.05$.

analysis. Excluding unlogged sections within units, mean volume extracted was 136 m^3 ha^{-1} (SD = 29) in conventional units and 92 m^3 ha^{-1} (SD = 40) in RIL units (Pacific Hardwoods Sdn Bhd, unpubl. data). Skid trail area, including sidecast mounds, per timber volume extracted was greater in conventional units (mean = 8.8 m^2 m^{-3}, SD = 0.56) than in RIL units (mean = 4.6 m^2 m^{-3}, SD = 3.04; $U = 15$, df = 1, $p = 0.04$). Including road area, soil disturbance per harvested tree was 140 m^2 per tree (SD = 16) in conventional and 94 m^2 per tree (SD = 28) in reduced-impact logging areas. Skid trail disturbance was positively correlated with volume extracted for conventional units (Pearson Correlation Coefficient = 0.97, $p = 0.03$) but not for RIL units (Pearson Correlation Coefficient = 0.53, $p = 0.54$).

Within the area disturbed by skid trails, the severity of disturbance to the soil was greater in conventional than in RIL logging units (Table 3). Skid trails with a bladed surface (or sidecut) were predominant in the conventional units (mean = 87.2%, SD = 5.6%), whereas only 38% (SD = 9.9%) of the skid trails in the RIL units had a bladed surface. The most common surface condition for skid trails in the RIL units was churned, i.e., the topsoil remaining in place, but being mixed with the upper layer of subsoil (Table 3). Skid trails with intact topsoil and litter layer (hereafter, compacted) were uncommon in conventional logging units, but covered about 12% of the skid trail surfaces in RIL units. In these compacted areas, saplings and vines resprouted soon after logging.

3.2. Plant regeneration on abandoned skid trails in RIL and CL areas

Four years after logging, mean canopy cover on skid trail tracks was less in CL areas than in RIL areas (Table 4). In both treatment areas, canopy cover on skid trail tracks was less than on skid trail edges and adjacent forest; edges of skids and forest adjacent to skids had relatively closed canopies (at 1 m), though the height of the canopy was greater in the forest than at the edge of the skid.

Species richness of woody stems was greater on skid tracks in RIL than in CL areas (Table 4) and species composition differed. The most frequently observed species on skid trails in the RIL areas were *Callicarpa* sp. and *Melastoma* sp., relatively short-lived, pioneer treelets. A few dipterocarp saplings were found on RIL skids, whereas none was found on CL skids. The giant herb *Eupatorium* sp. was the most frequently observed species on skid trails in CL areas.

The density of woody stems was greater on skids in RIL than in CL areas (Table 5); five of the eleven plots

Table 4
Characteristics of forest habitats four years after logging by conventional and reduced-impact logging methods[a]

Variable	Logging method	Skid trail track[b]	Skid trail edge[b]	Adjacent forest[b]
Canopy cover	Conventional logging	47 (19) a[1]	81 (9) b	96 (3) b
	Reduced-impact logging	81 (18) a[2]	93 (6) b	95 (3) b
Species richness	Conventional logging	0.9 (0.9) a[1]	4.3 (2.5) b	5.6 (3.9) b
	Reduced-impact logging	2.5 (1.0) a[2]	6.3 (3.6) b	7.7 (3.3) b

[a] Different letters within a row indicate significant differences between habitats; different superscripted numbers within a column, within a variable, indicate significant differences between logging methods.Two-way analysis of variance followed by Fisher LSD pairwise comparisons was used to compare treatments and habitats.
[b] Values are mean percentage (SD noted parenthetically) for $N = 11$ plots per treatment.

Table 5
Stem densities (>1 m tall, <5 cm dbh) four years after logging (in 1997) on skid trail tracks, skid trail edges, and adjacent forest in forest logged conventionally or by reduced-impact logging guidelines in 1993[a]

	Logging method	Skid trail track[b]	Skid trail edge[b]	Forest[b]
Saplings and vines (ha^{-1})	Conventional logging	3750 (5250) a^1	19 000 (11 250) b	18 750 (12 000) b
	Reduced-impact logging	9000 (5000) a^2	21 500 (13 250) a,b	24 500 (11 750) b
Pioneer saplings (ha^{-1})	Conventional logging	750 (1250) a^1	5000 (7250) b	500 (1000) a
	Reduced-impact logging	4750 (3500) a^2	1750 (3500) a,b	0 (0) b
Dipterocarp saplings (ha^{-1})[c]	Conventional logging	0 (0) a	1500 (3000) a	4000 (4750) b
	Reduced-impact logging	250 (750)	1,750 (5,250)	2,000 (2,250)

[a] Different letters within a row indicate significant differences between habitats; different superscripted numbers within a column, within a variable, indicate significant differences between logging methods.Two-way analysis of variance followed by Fisher LSD pairwise comparisons was used to compare treatments and habitats.
[b] All values are means (SD noted parenthetically) per ha; densities were calculated from 4 m^2 plots, 11 plots per logging method.
[c] Data contained too many zeroes to allow treatment comparison of densities on skid trail tracks.

established in CL areas had no woody stems. As in the other CL areas sampled (1976, 1988, 1991 areas), more woody stems were found on edges of skid trails and adjacent forest than on skid trail tracks. For the RIL areas, the edges of skid trails had woody stem densities that were intermediate to tracks and adjacent forest. The variability in densities was relatively high for both treatment areas and all three habitats.

Comparing only bladed skid trail tracks in RIL and CL areas to eliminate variability related to degree of soil disturbance, CL tracks were more open (percent canopy cover, $mean_{CL} = 46\%$, $SD = 20$, $N = 10$; $mean_{RIL} = 81\%$, $SD = 18$, N = 11), had lower densities of woody stems ($mean_{CL} = 4{,}000$, $SD = 5{,}500$; $mean_{RIL} = 9{,}000$, $SD = 5{,}000$), and lower species richness ($mean_{CL} = 1.0$, $SD = 0.9$; mean $_{RIL} = 2.5$, $SD = 1$; per 4 m^2 plot) than tracks in RIL areas.

Pioneer tree species tended to be more abundant in skid trail edges than forest or tracks. *Callicarpa* and *Melastoma* species were the most frequent pioneer tree species recorded in both treatment areas. *Macaranga* species, although common in other parts of Ulu Segama Forest Reserve, were recorded in only four plots (3 skid trail edges, 1 forest). The frequency of climbing bamboo (*Dinochloa* spp.) in the plots was low in both treatment areas (5 of 96 plots in total); climbing bamboo was found in edge and forest habitat, but not on skid trail tracks.

Within the RIL area, bladed skid trails were wider than churned skid trails, but had similarly closed canopies (Table 6). Furthermore, bladed skid trails had lower densities of woody stems and were less species rich than churned skid trails. Species composition was similar for the two types of skid trail, although liana stems were possibly more abundant on the churned than on the bladed skid trails ($t = 1.94$, $df = 9$, $p = 0.08$).

3.3. *Plant regeneration on abandoned skid trails in a chronosequence of CL areas*

The canopies of both skid trail and forest habitats in the two older logging areas were nearly closed at the time of sampling (Table 7). The canopies of skid trail tracks in the 1991 area were more open than those of edges or adjacent forest plots. For all three logging areas, species richness (woody plants >1 m tall, <5 cm dbh) was less on skid trail tracks than in edge or adjacent forest habitat (Table 7).

Table 6
Characteristics and stem densities for bladed and churned skid trail tracks in reduced-impact logging areas

Variable	Bladed skid trail tracks	Churned skid trail tracks
Skid width (m)[a]	6.2 (2.3)	4.4 (0.4)
Canopy cover (%)[b]	80 (19)	88 (10)
Species richness per plot[a]	2.5 (1.1)	3.9 (1.2)
Saplings and vines (ha^{-1})[a]	9,500 (5,000)	15,000 (5,250)
Liana stems (ha^{-1})[b]	3,000 (2,500)	5,750 (5,500)

[a] Denotes significant differences between logging treatments; $0.05 < p < 0.01$.
[b] Denotes significant differences between logging treatments; $0.1 < p < 0.05$.

Table 7
Characteristics of vegetation in 1994 on skid trail tracks, skid trail edges, and adjacent forest in three logging areas[a]

	Area	Skid trail track[b]	Skid trail edge[b]	Forest[b]
Canopy cover (%)	1991	66 (14) a	83 (3) b	89 (2) b
	1988	90 (3) a	92 (4) a	94 (2) a
	1976	93 (2) b	90 (2) a	93 (2) b
Species richness[c]	1991	1.8 (1.1) a	5.5 (2.2) b	7.0 (0.7) b
	1988	1.1 (0.1) a	3.8 (1.1) b	5.1 (1.0) b
	1976	2.7 (0.9) a	5.2 (1.0) b	6.5 (1.0) b

[a] Different letters within a row denote a significant difference ($p < 0.05$) between habitats within an area using Tukey multiple comparisons following ANOVA.

[b] All values are means (SD noted parenthetically) per plot for four logging units, each unit with 10 sampling plots (2 × 2 m).

[c] Refers to all woody stems >1 m tall and <5 cm dbh.

Fewer saplings were found on skid trail tracks than on skid trail edges or adjacent forest in all three logging areas (Table 8). Mean sapling densities in the 1976 and 1991 logging areas were identical on skid trail tracks although variance was greater in the 1991 area than in the 1976 area. Relatively few pioneer tree saplings were found in forest habitats in the three areas. Pioneer tree saplings were relatively abundant on skid trails and edges in the 1991 area. Edges in the 1988 area had more pioneer saplings than either the skid trails or adjacent forest. In the 1976 area, pioneer tree sapling density was similar in the three habitats.

Dipterocarp sapling density was less on skid trails than adjacent forest in the 1976 and 1991 areas (Table 8). In the 1988 area, similar densities of dipterocarp saplings were found in the three habitats. The observed densities of dipterocarp saplings on skid trail edges and in adjacent forest habitats were similar to densities recorded for unlogged forest (mean = 430 saplings per hectare, SD = 158; 1993 area).

Above-ground biomass on skid trail tracks was low (1.1–2.2 Mg biomass per hectare) relative to the other habitats sampled and was similar for the three logging areas (KW = 1.5, df = 2, $p = 0.47$; Table 9). Coarse root biomass was generally greatest under older skid trails. Coarse root biomass under skid trails in the 1976 area was greater than it was under skid trails in the 1991 area ($q = 4.16$, $p < 0.05$). Coarse root biomass under skid trails in the 1988 area was intermediate and not statistically different from either the 1991 or 1976 year-old skid trails ($q_{1991 \text{ vs } 1988} = 2.08$, $p > 0.05$; $q_{1976 \text{ vs } 1988} = 2.08$, $p > 0.05$). Dead root mass under skid trails was higher in the 1991 area ($\text{median}_{1991} = 6.6$ Mg necromass per hectare, $N = 4$) than in either the 1988 or 1976 areas ($\text{median}_{1988} = 1$; $\text{median}_{1976} = 0.6$). Total coarse root mass was not different among the three logging areas (KW = 3.04, df = 2, $p = 0.22$). Woody roots >15 mm diameter made up about 43, 50, and 69% of total living coarse roots under skid trails in the 1991, 1988, and 1976 logging areas, respectively.

Table 8
Stem densities (>1 m tall, <5 cm dbh) in 1994 on skid trail tracks, skid trail edges, and adjacent forest in three logging areas[a]

	Area	Skid trail track[b]	Skid trail edge[b]	Forest[b]
Saplings and vines	1991	8130 (4880) a	22 060 (8670) b	22 500 (2280) b
	1988	3500 (710) a	12 630 (3350) b	15 880 (2950) b
	1976	8130 (2070) a	18 380 (1830) b	22 750 (4410) b
Pioneer tree saplings	1991	2630 (2630) a,b	4690 (2100) a	560 (800) b
	1988	1000 (890) b	3560 (970) a	880 (720) b
	1976	310 (320) a	440 (720) a	60 (130) a
Dipterocarp saplings	1991	60 (130) a	560 (560) a,b	810 (130) b
	1988	130 (250) a	250 (500) a	310 (470) a
	1976	0 (0) a	440 (330) b	1560 (1390) b

[a] Different letters within a row denote a significant difference ($p < 0.05$) between habitats within an area using Tukey multiple comparisons following ANOVA. Similar results were obtained when habitats were compared using frequency data in contingency table analyses.

[b] All values are means (SD noted parenthetically) per ha; densities were calculated from 4 m^2 plots, 10 sample plots per unit, four units per area.

Table 9
Above- and below-ground biomass and necromass for three ages of skid trails[a]

	3 years old[b]	6 years old[b]	18 years old[b]
Aboveground biomass	2.2 (0.8–7.9) a	1.1 (0.5–1.7) a	1.4 (0.8–1.6) a
Living coarse roots	0.3 (0.0–1.0) a	1.7 (0.7–4.2) a,b	4.6 (2.2–7.6) b
Dead coarse roots	6.6 (0.4–12.0) a	1.0 (0.2–2.1) a	0.6 (0.2–3.4) b

[a] Different superscripted letters within rows denote a significant difference ($p < 0.05$) between ages in nonparametric pairwise comparisons.
[b] Values are medians (Mg organic dry mass per hectare, with range noted parenthetically) for $N = 4$ logging units ($n = 10$ samples per unit).

4. Discussion

4.1. Soil disturbance in RIL and CL areas

In sites logged according to the RIL harvesting guidelines, proportionally less area of soil was disturbed than in sites logged by conventional methods (Fig. 1, Table 2). An inefficient layout of skid trails, typical of unplanned, unsupervised operations, was apparent in conventional logging areas. Skid trails in conventional logging units were often cross-linked and located within 10 m of each other, whereas, in general, skid trails in RIL units were widely spaced and evenly dispersed across the logged area. A time-motion study of skidding practices in the two treatment areas documented the greater efficiency of yarding in RIL as compared with CL operations, US$ 1.98 m^{-3} and US$ 4.51 m^{-3}, respectively (Tay, 1999). Other studies involving comparisons of planned and unplanned harvesting in tropical forests have found similar patterns of reductions in ground area affected by skidding (Chua, 1986; Hendrison, 1990; Johns et al., 1996), and increased efficiency (Chua, 1986; Hendrison, 1990; Barreto et al., 1998) with planned extraction.

The harvesting guidelines adopted by the RIL project include specifications about road location and construction, but the road in the RIL pilot project area was constructed before adoption of the RIL guidelines by the concessionaire, compromising flexibility in locating skid trails. The road was positioned low on slopes; this location was suboptimal and often forced downhill skidding. There was no difference in road density for the two methods (Table 2), but the area covered by sidecast soils, associated with the road, was less in RIL areas than in conventional logging areas, even though the roads in RIL units were used for processing logs.

The extent of soil disturbance associated with conventional logging in this study (mean = 17%, range = 14–20%) was at the low end of the range of published values for unsupervised logging in Malaysia (e.g., 43%, Fox, 1968; 17%, Borhan et al., 1987; 16%, Jusoff and Nik, 1992; 30%, Nussbaum et al., 1995) and was similar to values for operations in Suriname (14.5 and 16.0%, Hendrison, 1990) and Indonesia (16%, Cannon et al., 1994). Skid trail area in RIL units was similar to values obtained with planned operations in Suriname (5–7%, Hendrison, 1990) and Australia (5%, Crome et al., 1992). The large variation in values reported for dipterocarp forests in Sabah may be due to differences in sampling methods, biases towards roadside locations, or differences in local topographical conditions. We expect the results from this study to be relatively free from sampling biases because soil disturbance associated with logging was measured in 100% of the area of the eight logging units.

In general, damage to the residual stand is positively correlated with timber volume extracted (Nicholson, 1979). In this study, soil disturbance was positively associated with harvested volumes in conventional logging areas, but not in reduced-impact logging areas (Fig. 2). If main skid trails are located to optimize efficiency of log extraction, bulldozers are restricted to main skid trails, and logs are winched from the forest to the skid trail, one might expect that, after the whole area was rendered accessible by the main skid trails, the proportion of the area disturbed by logging would remain fairly constant, regardless of the number of trees removed.

Unfortunately few studies of soil disturbance associated with logging in tropical forests include information on the volume of timber extracted or express disturbance in terms of volume extracted. Failure to include information about logging intensity makes it difficult to compare sites. One exception is a study conducted in the Brazilian Amazon; Verissimo et al. (1992) found that 218 m^2 of ground surface was scraped by bulldozers (roads and skid trails) for each harvested tree. Comparable figures for this study are much less ($mean_{CL} = 140\ m^2$ per tree and mean RIL = 94 m^2 per tree), perhaps reflecting differences in the size of harvested trees and number extracted per hectare.

Skid trails in RIL units were, in general, less severely disturbed than those in CL logging units, the proportion of skid trails with subsoil disturbance was less than half that in the CL areas (Table 3). In part, this difference may be due to the fact that bulldozers did not traverse slopes >35° in RIL areas, so may have been less likely to require the use of the blade. Blading is often considered essential on slopes >24° to increase stability and control (Stuart and Carr, 1991). But blading and side-cutting were not restricted to steep areas in the conventional logging units; ≈87% of the skid trails had exposed and disturbed subsoils. The skid trails where subsoil was disturbed in RIL units (≈38%) were typically main skid trails that received heavy traffic. In conventional logging units, branch and main trails were not distinguishable in terms of soil disturbance class. The restriction on wet-weather skidding in RIL areas also probably contributed to the observed differences; in RIL units, all skid trails showing subsoil disturbance had been logged during the wetter season.

4.2. Plant regeneration on abandoned skid trails in RIL and CL areas

Four years after logging, woody plant regeneration on abandoned skid trails was better (more stems, greater species richness) in RIL than in CL areas. The lesser degree of soil disturbance recorded for skid trails in RIL, as compared with CL, areas explains some of the observed difference, as churned skid trails had more woody stems than did the more heavily disturbed bladed skid trails. However, the lesser amount of residual stand damage in RIL areas, as compared to CL areas, appears also to have had an effect on woody plant establishment on skid trails. When we compared only bladed skid trails in the two areas, the same pattern, more stems and more species in RIL than in CL areas, was found. It is possible that our classification of soil disturbance was too coarse to identify differences in the degree of damage to soil structure and other characteristics, or that bladed skid trails in RIL areas were less severely disturbed than bladed skid trails in CL areas. Further characterization of soils is needed to evaluate the pattern recorded in our study.

In CL areas, pioneer tree establishment was greater on skid trail edges than on skid trail tracks or adjacent forest, as predicted. The pattern in RIL areas differed, with relatively high numbers on both skid trail tracks and edges. One explanation for the relatively high densities on tracks in RIL areas is that the soil seed bank was retained on churned skid trails. Because a larger proportion of the skid trails area in RIL areas were churned, not bladed, one might expect more pioneer trees (originating from buried seed) on tracks in RIL than in CL areas. This hypothesis, however, is not supported by our data comparing pioneer tree stem densities on bladed and churned skid trails in RIL areas. Densities of pioneer tree species were similar on both types of skid trail tracks ($mean_{BL} = 4750$, $SD = 3750$, $N = 10$; $mean_{CH} = 4250$, $SD = 3750$, $N = 10$).

Densities of dipterocarp saplings were similar in the two treatment areas and followed a trend of increasing densities across the skid trail track, skid trail edge, and adjacent forest habitats. Prior to logging, CL areas had higher dipterocarp sapling densities than RIL areas (Pinard, unpubl. data), explaining the suggestion of higher post-logging densities in adjacent forest in our results.

4.3. Plant regeneration on abandoned skid trails in a chronosequence of CL areas

Fewer sapling and pole-sized trees were found on abandoned skid trail tracks than in adjacent, residual forest in 1976, 1988 and 1991 logging areas. This result suggests that, even 18 years after logging, tree regeneration on skid trails is less than that in residual forest. Tree regeneration on the edges of skid trails was similar to that in adjacent forest in terms of sapling densities and species richness. However, species composition is different in the two habitats, with pioneer tree species being more common on skid trail edges than in residual forest.

Sapling densities in the 1991 and 1976 areas were very similar, suggesting that conditions for tree regeneration on older skid trails are no better than those on younger skid trails. The similarity in biomass on skid trails from the three logging areas also suggests little change. Immediately after logging, 98% of the skid trail area in conventional logging units was bare of vegetation. Above-ground biomass on the 3-, 6-, and 18-year-old skid trails was only slightly greater than that recorded on one-year-old skid trails (0.3 Mg biomass per hectare; SD = 0.38; Pinard, 1995). Living coarse root biomass increased with time since logging, as one might expect, but at 18 years after logging, coarse root biomass was 12% of the pre-logging value observed elsewhere in the forest reserve (Pinard and Putz, 1996).

We interpret the results from this study with caution and recognize that pre-logging conditions in the three logging areas studied may have differed. Nevertheless, we are confident that all three areas were heavily logged (Pacific Hardwoods, unpubl. data) and that the areas have not been re-entered by heavy equipment after the initial selective cut. We chose three different-aged logging areas in order to assess the potential for recovery on skid trails over time, but comparisons among habitats within an area involve fewer assumptions than do comparisons across the three areas.

We expected that if soil disturbance favors pioneer trees over more persistent species, then the density of pioneers on skid trails would be greater than in adjacent forest. This was supported by the data from the younger areas, where pioneer sapling densities on skid trail edges were greater than densities in adjacent forest. Densities on skid trail surfaces were not different from densities in forest plots. Perhaps pioneer tree densities in forest plots were high relative to undisturbed forest because of the inclusion of felling gaps, which may provide opportunities for pioneer tree establishment, in some of the plots. Also, few pioneer saplings would be expected to survive under the closed canopy observed in the 1976 and 1988 areas.

Several studies in neotropical rain forest recorded vigorous tree seedling establishment along the edges of skid trails and roads (e.g., Jonkers, 1987; Verissimo et al., 1992; Guariguata and Dupuy, 1997) 2–3 years after logging. It does not necessarily follow, however, that high densities of saplings on skid trails will eventually develop into a stand of trees; unfavorable soil properties, e.g., compaction and low-nutrient status, may continue to limit tree growth on skid trails for many years. In some forests, changes in soil physical properties due to logging are apparent decades after logging (Congdon and Herbohn, 1993; Van der Plas and Bruijnzeel, 1993).

We attribute lower densities of saplings on skid trails, as compared with adjacent forest, to unfavorable establishment conditions in those habitats. An alternative explanation for lower sapling densities on skid trails is that crowns and root systems of residual trees occupy these areas and the competition for resources on skid trails is greater than that in adjacent forest. Sapling densities in these sites may have been lower than in adjacent forest prior to skid trail construction. A manipulative study of tree establishment in these habitats that controlled for competition with neighboring trees would help to elucidate the mechanisms driving differences in sapling densities. Saplings on skid trails also appear to suffer from high levels of browsing by elephants, macaques, sambar deer, and pigs (M. Pinard, pers. obs.). Through browsing and trampling, vertebrates may play a role in keeping open skid trail tracks (Hawthorne, 1993) and canopy gaps (Struhsaker et al., 1996) in logged forest.

5. Conclusions

Implementation of harvesting guidelines in a ground-based yarding system substantially reduced the extent and degree of soil disturbance associated with logging. About 84% of the skid trail area in conventional logging areas had subsoil disturbance. Distribution patterns in biomass, species richness and sapling density across habitats in logged forest suggest that even 18 years after conventional logging, areas with soil disturbance are less productive than areas without. In reduced-impact logging areas, about 62% of skid trail area retained topsoil. Retention of organic matter in these compacted areas may partially explain the observed improved plant regeneration in RIL areas, but for many soils, most compaction associated with skidding happens with the first few passes of the bulldozer (Dias and Nortcliff, 1985; Koger et al., 1985). If disturbance to soil structure is to be minimized, reducing the area traversed by bulldozers will be more important than reducing the traffic on any particular skid trail.

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