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Forest canopy damage and recovery in reduced-impact and conventional selective logging in eastern Para, Brazil

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Abstract

We investigated ground and canopy damage and recovery following conventional logging and reduced-impact logging (RIL) of moist tropical forest in the eastern Amazon of Brazil. Paired conventional and RIL blocks were selectively logged with a harvest intensity of approximately 23 m^3 ha^{-1} (geometric volume) in the dry seasons (July–December) of 1996 and 1998. Ground damage (roads + skid trails + log decks) in the conventional logging treatments occupied 8.9–11.2% of total operational area. In contrast, ground damage in RIL treatments ranged from 4.6 to 4.8% of the total area. Forest canopy damage was assessed using gap fraction measurements collected with an automated optical canopy analyzer (LAI-2000; Licor Inc.) in March 1999. Canopy opening varied by time since logging. The recently logged (1998) blocks had integrated canopy gap fractions of 21.6 and 10.9% of total area for conventional and RIL blocks, respectively. The blocks logged in 1996 had more closed canopies with 16.5 and 4.9% gap fraction for conventional and RIL blocks, respectively. For comparison, undisturbed forest had a canopy gap fraction of 3.1%. Measurements of ground disturbance and gap fraction using the Licor LAI-2000 generally agree with other field evaluations of RIL and conventional logging. Detailed understanding of canopy structural changes resulting from different logging intensities are critical to the prospect of logging damage estimation using current and future remote sensing products.

Keywords: Amazon; Brazil; Canopy; Gap fraction; Reduced-impact logging; Selective logging

1. Introduction

Selective harvest of timber is an important land use in forested areas throughout the humid tropics. Nepstad et al. (1999) estimated that approximately 10,000–15,000 km^2 per year were affected in the period 1996–1997 in the Brazilian Legal Amazon region. Selective logging leads to a variety of short-lived and long-lived effects including changes in the light regime and forest micro-climate, erosion, soil compaction, disruption of nutrient cycling and possibly long-term changes in tree species composition (Ter Steege et al., 1995; Jonkers, 1987; McNabb et al., 1997; Brouwer, 1996; Pinard et al., 1996). These changes can affect the recruitment of timber species and the diversity of forest fauna (Ter Steege et al., 1994; Pinard et al., 1996; Hill et al., 1995; Johns, 1991, 1992; Thiollay, 1992). Selective logging also

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increases the susceptibility of forest to fire through modification of the understory micro-climate and supply of fuel (Uhl and Buschbacher, 1985; Uhl and Kauffman, 1990; Holdsworth and Uhl, 1997; Nepstad et al., 1999; Cochrane et al., 1999).

Reduced-impact logging (RIL) practices significantly limit damage compared to conventional logging practices, particularly at intermediate harvest intensities (Hendrison, 1990; Pinard and Putz, 1996; Gerwing et al., 1996; Johns et al., 1996; Sist, 2000). The components of the RIL approach for Amazon basin forests have been summarized by Uhl et al. (1997) as: (1) inventory and mapping to reduce waste during logging; (2) planning of roads, log decks, and skid trails to minimize ground disturbance; (3) vine cutting 1 year prior to harvest to improve worker safety and to eliminate damage to neighbors of harvest trees; (4) planned directional felling and bucking to minimize damage to future harvests and reduce waste; and (5) planned extraction to minimize equipment time during skidding. These practices may be complemented by silvicultural treatments to improve the long-term prospects for forest stand productivity.

Quantifying the canopy effects of both RIL and conventional logging should be useful for understanding the effects of these practices on forest fauna, micro-climate, and regeneration. Understanding canopy damage and recovery is also needed for the interpretation and detection of logging using remote sensing. We investigated ground and canopy damage and recovery following logging at conventional and RIL sites in the eastern Amazon of Brazil. Relatively few studies have quantified the effects of selective logging on tropical forest canopies. Previous studies have used a variety of methods to quantify canopy damage including ground mapping and spherical densiometers (e.g. Verissimo et al., 1995; Whitman et al., 1997; Johns et al., 1996). In contrast to previous studies, we used automated optical instruments that allowed for fast, efficient collection of measurements over a large sampling area.

2. Site description

We conducted our studies at the Fazenda Cauaxi in the Paragominas Municipality of Para State, Brazil. The Tropical Forest Foundation maintains a camp and training center for demonstration of forest management and RIL techniques (3°43.878′S, 48°17.438′W). Training courses, demonstrations and research activities have been conducted there since 1995 with the collaboration of the property owners. Prior to current logging operations, there is no historical record of land use or collection of non-timber forest products, although there are indicators of indigenous activity. Ranchers and loggers first entered the area in 1976 through the Rio Capim and the Rio Surubiju. There were no roads in the area until the 1980 s.

The climate at Fazenda Cauaxi is humid tropical. Total annual precipitation averages about 2200 mm (Costa and Foley, 1998). A dry season extends from July through November (generally <50 mm per month) although June and December are also frequently dry enough for logging operations. Soils in the area are classified mainly as dystrophic yellow latosols according to the Brazilian system (RADAMBRASIL, 1983). The topography is flat to mildly undulating. The forest at Fazenda Cauaxi is classified as tropical dense moist forest (IBGE, 1988). The most common timber species that were harvested during 5 years of forest operations were *Manilkara huberi*, *Manilkara paraensis, Protium pernevatum, Dinizia excelsa*, and *Piptadenia suaveolens*. The most common tree species found are *Licania* sp., *Manilkara huberii, Astronium lecointei, Eschweilera odorata,* and *Parkia* spp. Stand basal area is approximately 57 m^2 ha^{-1} for trees >10 cm diameter at breast height (DBH).

We studied four logged blocks, including one conventional and one RIL block each logged in 1996 and 1998, and a natural forest area (50 ha) that had never been logged. Both 1996 model blocks were originally surveyed at 100 ha. Alongside these 100 ha blocks were buffer strips without harvest trees of about 25 m width on all sides. We included these buffers in our GIS analysis so that the studied blocks were about 10% larger than the original models. Exclusion of these buffers would increase damage estimates by approximately 10% for both RIL and conventional treatments. The RIL block for 1998 covered 57 ha, and the conventional block for 1998 covered only about 14 ha (Fig. 1A and B).

Forests in the region of the Fazenda Cauaxi are rich in species. A limited number of species (approximately 50 in 1995) were marketable in the region, therefore, loggers practiced single-tree selection.

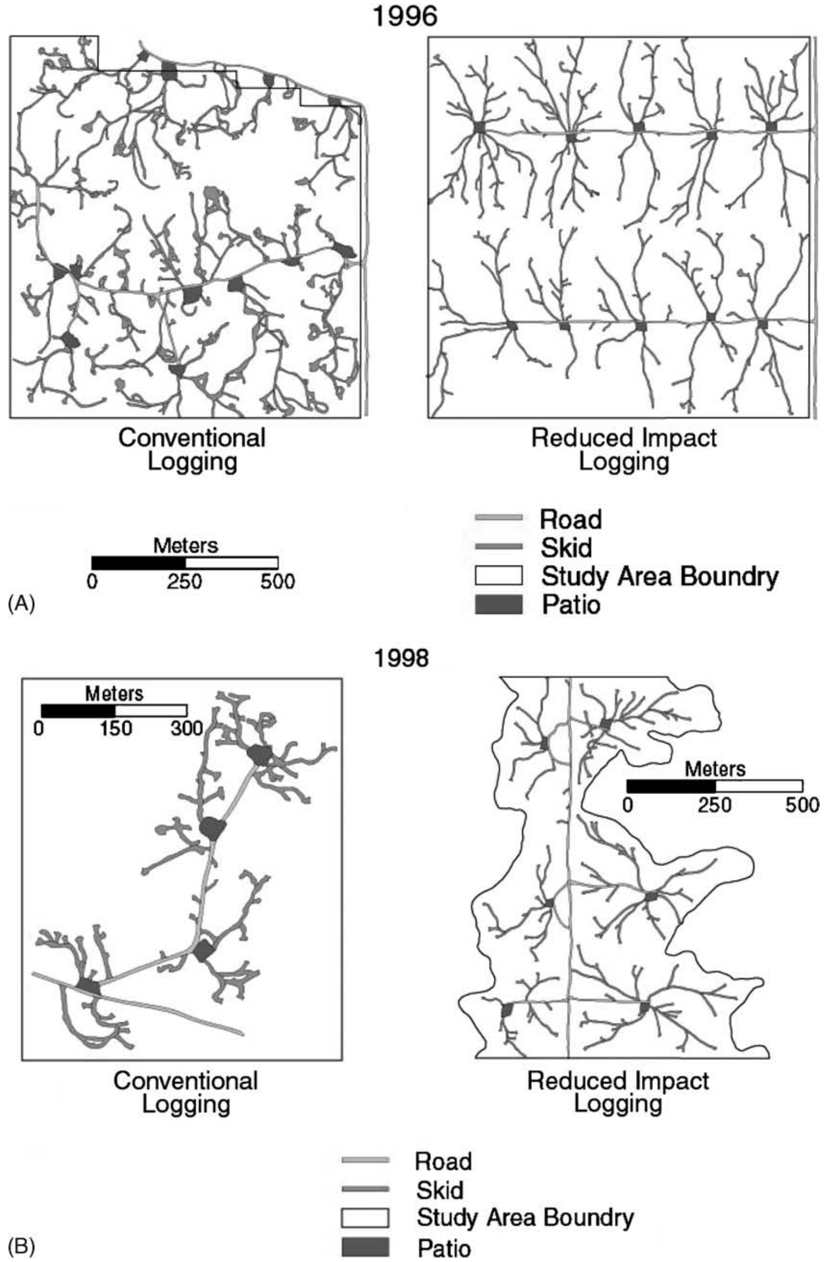

Fig. 1. (A) Geographic information system map showing area layout of log decks, roads, skids, and trees selected for harvest in the 1996 conventional and reduced-impact logging blocks; (B) same as part A, but for 1998 logging blocks.

Both conventional and RIL practices in this region have been described previously (Verissimo et al., 1992; Johns et al., 1996). Briefly, in conventional practice, woodsman marked harvest trees. They were followed by sawyers who felled and bucked trees. In many cases, the sawyer also selected trees for harvest. The sawyers were, in turn, followed by operators who prepared roads and decks (log landings), skidded logs, and loaded logs for transport. In conventional operations at Fazenda Cauaxi, a crawler tractor without a winch (Caterpillar D-6) was used for road and log deck construction as well as for skidding. Use of a single type of crawler for multiple tasks is very common in conventional logging operations in Amazonia (Johns et al., 1996).

In contrast to conventional logging, RIL practice employed a pre-harvest operation where blocks were surveyed and inventoried, roads were planned and built, and vines were cut from harvest trees about 1 year prior to harvest. Data from inventories were processed and tree location maps were prepared during the rainy season. Crews marked trees prior to harvest and maps were prepared to indicate preferred felling directions. Trained sawyers felled trees using directional techniques according to the plans whenever possible. After felling, skid trails were planned and marked considering the direction of the felled trees and the structure of the residual forest. Logs were extracted from the forest using a wheeled skidder with a grapple and winch (Caterpillar 525).

3. Methods

Both conventional and RIL areas were re-inventoried and mapped by foresters and technicians from the Fundação Floresta Tropical. The number of trees felled and the total geometric volume skidded from the forest were recorded. (All volumes referred to in this paper are geometric volume although Francon volume is widely used by commercial operators in the region.) Details of the costs and damages from both logging operations were collected by Holmes et al. (2001). Road, log deck, and skid lengths and areas were measured and mapped using fiberglass measuring tapes, Field Ranger®, and compasses. The Field Ranger® is a hands-free instrument that measures the passage of thread through a mechanical odometer as the operator walks. Road, skid, and log deck widths were also measured with a measuring tape at 50 m intervals. Tree locations, road, skid, and log deck data were transferred to paper maps at a scale of 1:1000. The maps were then digitized into a geographic information system (GIS Arc/Info®) and geo-rectified using 94 field GPS measurements. Thus, the GIS contained spatially explicit locations and areas of all roads, skids, log decks, and felled trees for each treatment.

We measured canopy gap fraction using an optical plant canopy analyzer (LAI-2000, Licor Inc.) at $\sim$1.5 m above the ground surface. Because the LAI-2000 instrument integrates over all azimuth angles, we used a 90° field-of-view optical block to prevent contamination of the measurement by the instrument operator (Welles and Norman, 1991). The instrument assumes a diffusely lit sky, and thus, we restricted our measurements to early mornings and late afternoons (low sun angle) or to times when there was a uniform cloud cover. Measurements below the canopy were referenced to measurements taken in large clearings immediately before and after the measurements along each transect. The LAI-2000 uses five concentric rings to measure light interception for gap fraction analysis (Welles and Norman, 1991). Data from the outermost ring, which views from 61–74°, was excluded from all analyses in order to avoid forest edges in the clearings during open sky calibration measurements.

Gap fraction (range 0–1) is defined as the proportion of the hemisphere above the instrument that has a clear view of the sky (no interfering plant canopy). While the LAI-2000 instrument is often used to report leaf area index (LAI), we choose to report gap fraction, the basic measurement of the instrument (Welles and Norman, 1991). The LAI is a quantity derived from the gap fraction measurement and a model of leaf distribution. Gap fraction is a more meaningful measurement than LAI under conditions of highly discontinuous, spatially structured canopy coverage as was the case in this study.

Gap fraction measurements were stratified according to landscape units. We divided the logged forests into five categories: (1) roads; (2) log decks; (3) skid trails; (4) tree falls and; (5) background relatively undisturbed areas. Log decks were considered completely open (gap fraction = 1). For roads, we made measurements on randomly selected transects. Each transect began at the edge of a log deck and ran for at least 100 m along a road. Gap fraction measurements were collected at 10 m intervals and averaged for each transect. These sub-samples were normalized to background clear sky measurements acquired immediately before and after the transect. For skid trails, we again selected random points and followed the same procedure as for roads, but the transect always began at least 20 m from a log deck. For tree falls, random trees were selected from the harvest maps.

The sampling transect began at the center point of the canopy gap, and ran for 100 m along a randomly selected radius. Gap fraction measurements for undisturbed forest were acquired in the 50 ha control plot along randomly selected 100 m transects. In total, we collected canopy gap fraction measurements on over 5000 m of transect in this study.

An estimate of total gap fraction for each of the four study blocks was made using the gap fraction measurements extrapolated using the GIS. Total gap fraction (F) was calculated as

$$F = \frac{\sum a_i f_i}{A} \quad (1)$$

where a_i and f_i are the area and gap fraction measured for particular sampling strata (decks, roads, skids, tree falls, and background area) and A the total block area. In the case of tree fall areas, f varied as a function of distance (x) from the center of the crown gap according to equations of the form

$$f = k \times 10^{bx} \quad (2)$$

where parameters k and b were estimated by least-squares regression for each harvest block. We integrated the gap fraction over a radius of 100 m. Where gaps overlapped with one another or with decks, roads, or skids, the greatest gap fraction was selected. We applied no additive effects.

4. Statistical analysis

Our design is admittedly pseudo-replicated (sensu Hurlbert, 1984). The commercial scale logging blocks are very large and expensive treatments, so true replication is difficult. For each sampling stratum (roads, skids, tree falls) in each year (1996, 1998), we tested the hypothesis that the gap fraction for the conventional treatment was greater than the corresponding gap fraction for the RIL treatment using a one-tailed t-test (Sokal and Rohlf, 1981). Independent, randomly selected transects were the units of replication. Variances were checked for homogeneity, and differences were considered significant for $P < 0.05$.

5. Results

The timber geometric volume removed was nearly identical ($\sim$23 m^3 ha^{-1}) for conventional and RIL blocks harvested in 1996. No measurements of timber volume were available for the 1998 blocks, but we assume that roughly similar volumes were extracted from the 1998 RIL site. This assumption is supported by the number of individual trees extracted per hectare from the RIL treatments. A total of 325 and 200 individuals were felled in the 1996 and 1998 RIL blocks, respectively (Table 1). On an area basis, the number of trees felled was 3.0 and 3.5 individuals per hectare for 1996 and 1998 RIL blocks, respectively. However, the intensity of logging was different between the two conventionally logged blocks. The total number of trees felled from 1996 to 1998, conventional treatments were 415 and 88, respectively. On an area basis, the number of trees felled were 3.7 and 6.4 individuals per hectare, respectively, for the two conventional blocks.

Both conventional and RIL logging practices affected substantial ground areas in the logging blocks (Table 1). The proportion of ground area affected was similar in 1996 and 1998 for RIL blocks. For the conventional blocks, the 1998 area suffered more ground damage than the 1996 area. The high density

Table 1
Ground disturbance expressed as a percentage of total area for four harvest blocks contrasting conventional and RIL logging in two different years[a]

Year	Treatment	Area (ha)	Trees felled (ha^{-1})	Volume (m^3)	Road area (%)	Deck area (%)	Skid area (%)	Disturbed (%)
1996	Conventional	112	3.7	2609	1.2	0.9	6.8	8.9
1996	RIL	108	3.0	2507	0.6	0.6	3.6	4.8
1998	Conventional	13.8	6.4	N.D.[b]	2.0	1.9	7.3	11.2
1998	RIL	57.1	3.5	N.D.	1.0	0.7	2.9	4.6

[a] The proportion of total ground disturbance ((road + skid + log deck)/total) is reported in the final column.
[b] N.D.: no data available.

Table 2
Mean (S.E.) canopy gap fraction for four sampling strata in RIL and conventional logging treatments in 1996 and 1998[a]

Year	Treatment	Road	*n*	Skid	*n*	Tree fall	*n*
1996	Conventional	0.43 (0.03)	6	0.44 (0.08)	4	0.20 (0.03)	3
1996	RIL	0.29 (0.05)	7	0.21 (0.06)	4	0.07 (0.02)	3
1998	Conventional	0.72 (0.12)	6	0.51 (0.13)	5	0.29 (0.10)	3
1998	RIL	0.36 (0.05)	6	0.27 (0.07)	4	0.13 (0.05)	3

[a] All sampling was completed in March 1999. Number of sample segments (*n*) per landscape stratum is also provided. Each segment included 9–47 gap fraction measurements.

of decks and the irregular path of the roads accounted for the higher proportion of damage in the 1998 conventional block. As a proportion of total area, conventional logging caused about twice as much ground damage. The distinction was particularly marked in the area of skid trails (Table 1).

Both RIL and conventional logging produced notable canopy damage. In undisturbed forest, we measured a mean (±standard deviation) canopy gap fraction of 0.031 (±0.002) for a total sample size of 80 points. Regardless of treatment and sampling stratum (road, skid, tree fall), all of the logging areas sampled had a greater canopy gap fraction than the intact forest (Table 2). The conventional treatment strata had significantly greater gap fractions than the RIL treatment measured ∼2.5 years after logging (1996 blocks), while only roads showed a significant difference ∼6 months after logging (1998 blocks).

Within each sampling stratum, the 1996 treatments had lower gap fractions than the 1998 treatments due to forest regrowth. On roads and skid trails, gap fraction values were greatest at points near to log decks. Otherwise, there were no clear spatial trends for the gap fraction along roads and skid trails. For the tree falls, the gap fraction dropped exponentially with the radial distance from the center of the downed tree crown (Fig. 2).

We modeled the landscape-scale canopy gap fraction in the four logged areas by combining our data from the randomly selected transects with the actual locations of all roads, skids, log decks and tree falls as mapped and digitized in the GIS (Fig. 3).

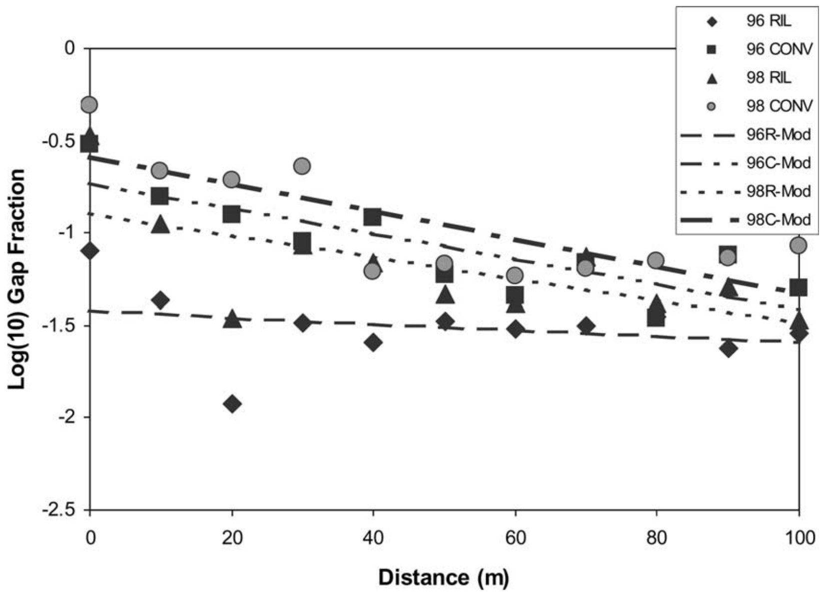

Fig. 2. Logarithm of canopy gap fraction measured in March 1999 vs. distance (m) from the center of tree fall gaps for RIL and conventionally logged areas in 1996 and 1998.

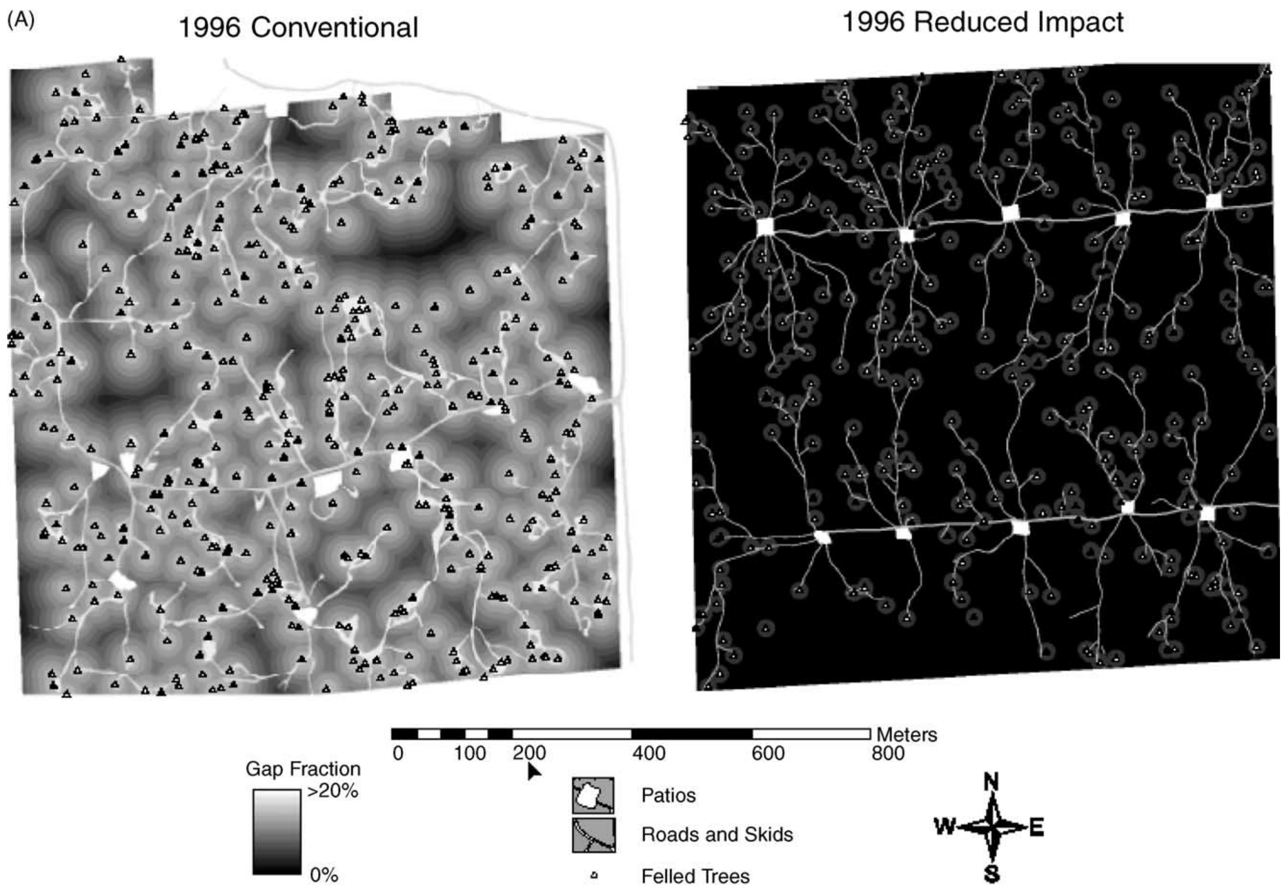

Fig. 3. A geographic information system (GIS) model of forest canopy gap fraction for (A) 1996 and (B) 1998 logging blocks.

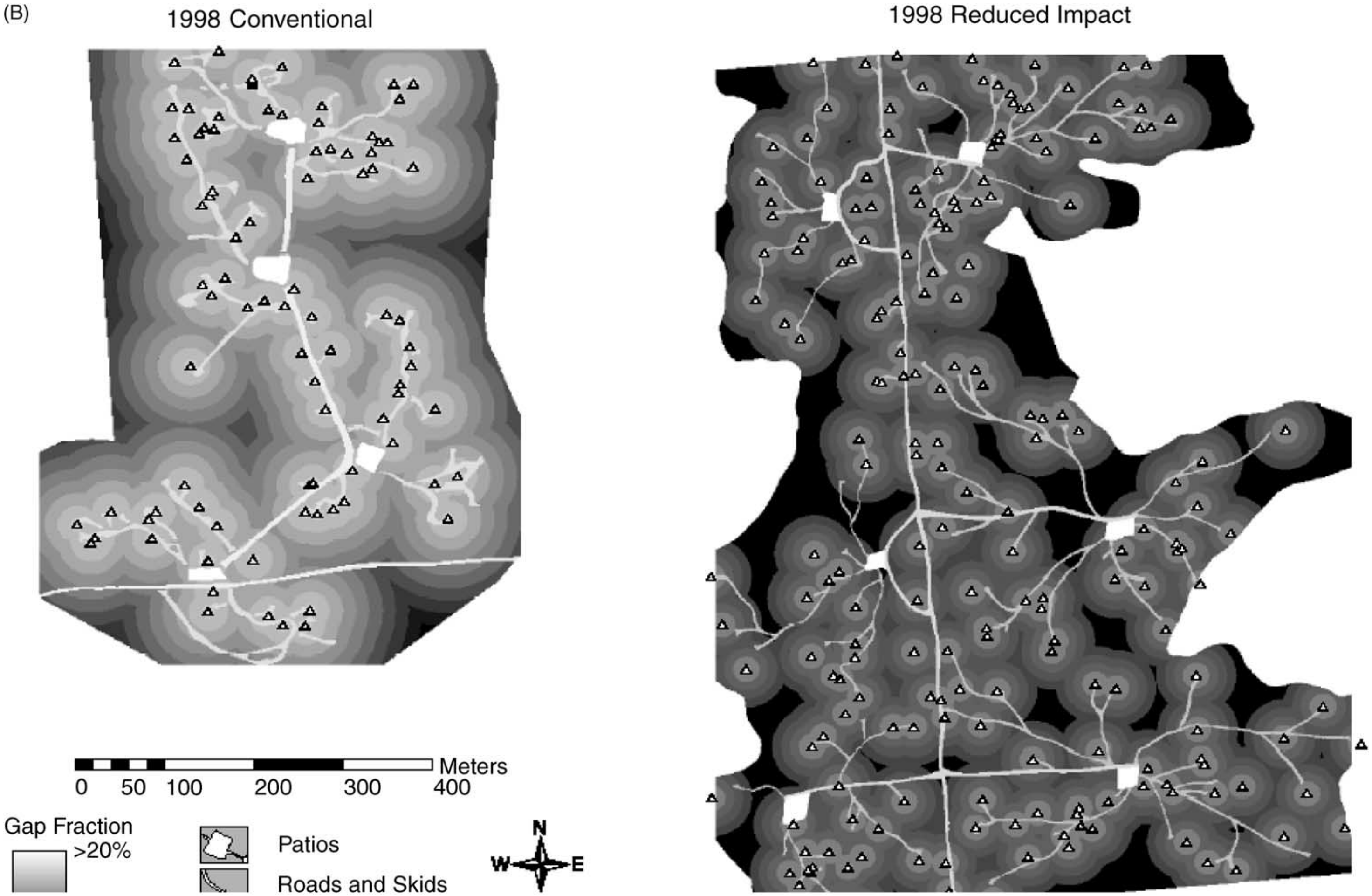

Fig. 3. (*Continued*).

Table 3
Percentage of canopy gap fraction from March 1999 for RIL and conventional logging treatments in 1996 and 1998[a]

Year	Treatment	Road (%)	Deck (%)	Skid (%)	Tree fall (%)	Total (%)
1996	Conventional	0.6	1.3	3.1	11.6	16.5
1996	RIL	0.3	0.7	0.7	3.1	4.9
1998	Conventional	1.5	1.9	3.8	15.0	21.6
1998	RIL	0.4	0.8	1.4	7.9	10.9

[a] Integrated total gap percentages were calculated using the GIS analysis.

Integrated (treatment level) gap fraction was greatest in the 1998 conventionally logged block (21.6%) and smallest in the 1996 RIL block (4.9%) (Table 3). Tree falls accounted for the largest portion of the total integrated gap fraction. Both the intensity of canopy disturbance (Table 2) and the extent of ground disturbance (Table 1) contributed to the integrated canopy gap fraction. Greater areas of ground disturbance from skids, decks and roads in the conventional treatments were reflected in the greater integrated gap fractions of these strata compared to the RIL treatments.

6. Discussion

At our study sites, both ground and canopy damage were greater at conventionally logged sites than at RIL sites. Disturbance in conventionally logged blocks was generally twice as severe on an area or gap fraction basis than in RIL blocks. This greater disturbance in the conventional blocks occurred both in the 1996 blocks where harvest volumes were nearly equal and in the 1998 blocks where harvest volume was substantially greater in the conventional block. The extent of the canopy damage was dependent, in part, upon the ground damage because roads, skids and log decks all resulted in more open canopies than the surrounding forest area. However, we found that canopy damage from tree falls was by far the greatest source of canopy opening (gap fraction) in our study plots. In both recently harvested blocks and in blocks harvested 2.5 years prior to canopy measurements, the proportion of canopy gap fraction derived from tree falls was always >65% of the total canopy disturbance.

The comparison of canopy disturbance suggests that vine cutting and planned directional felling are critical components of the RIL approach to minimize canopy damage. Previous studies in Malaysia (Appanah and Putz, 1984) and Brazil (Vidal et al., 1997) showed that cutting vines prior to felling helped to mitigate canopy disturbance. However, a recent study from forests in Cameroon (Parren and Bongers, 2001) showed no significant effect of vine cutting on canopy damage. These results and our experience suggest that the efficacy of vine cutting is site-dependent.

We compared our results of ground disturbance with 35 logged sites from eleven published studies of ground damage and four blocks from our study (Fig. 4). For this comparison, we considered only ground areas that were affected by machine operations (mainly decks, skid trails, and roads). For 22 conventional logging areas, we found a very highly significant relation ($r^2 = 0.65$, $P < 0.001$) between the ground damage and the log volume harvested. A similar highly significant linear relation was found for RIL areas ($r^2 = 0.48$, $P < 0.01$).

We reviewed data from 29 studies of canopy condition up to 1 year post-harvest, including the two blocks in our study that were harvested in 1998 (Fig. 5). Canopy loss expressed as a percentage of total cover was defined as the difference between canopy cover for logged and control sites or the difference in canopy cover measured before and after logging at the same site. The linear relations between canopy lost and harvest volume for conventionally logged and RIL blocks were highly significant ($r^2 = 0.89$, $P < 0.001$ and $r^2 = 0.81$, $P < 0.01$, respectively).

The association of canopy and ground damage with harvest intensity in selective logging of tropical forests has been recognized for many years (e.g. Redhead, 1960 as cited by Ewel and Conde, 1980). Our review of recent literature (represented in Figs. 4 and 5) clearly shows that RIL logging can reduce both canopy and ground damage compared to conventional logging. Canopy loss for RIL blocks was generally

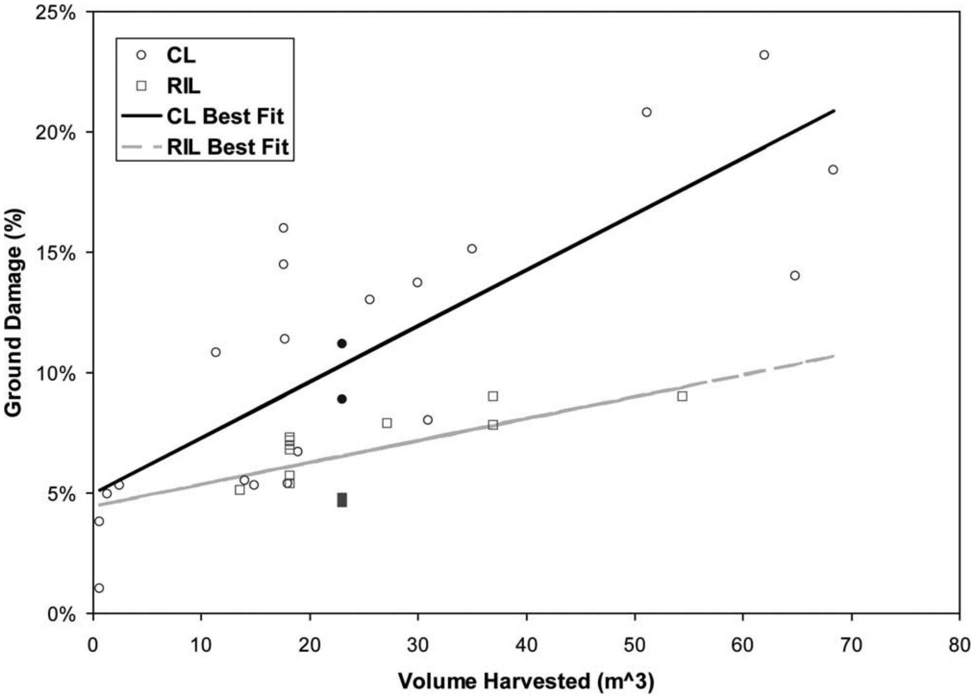

Fig. 4. Ground damage (roads + skid trails + log decks) vs. total volume harvested in 29 logging blocks shown for conventional logging (circles) and RIL (squares). Data derived from this study (filled symbols) and 11 previously published studies (open symbols) are shown (Van Der Hout, 2000; Whitman et al., 1997; Verissimo et al., 1995; Johns et al., 1996; Cannon et al., 1994; White, 1994; Gullison and Hardner, 1993; Verissimo et al., 1992; Uhl et al., 1991; Hendrison, 1989; Uhl and Viera, 1989). The best fit least-squares linear regression for ground damage in conventional logging areas (y; proportion of total area) vs. harvest geometric volume (x; m^3) was $y = 0.0023x + 0.050$ ($r^2 = 0.65$). For RIL, the regression equation is $y = 0.00091x + 0.045$ ($r^2 = 0.48$).

lower than for paired conventionally logged blocks. Of the logging blocks studied by Hendrison (1990) in Suriname, RIL logging resulted in canopy loss of 6.5–7.4%, while conventional logging opened 11.4–16.5% of the canopy. Johns et al. (1996) found that conventional logging led to canopy loss of 21.8% versus only 10% for RIL treatments in their study. In contrast, Van Der Hout (2000) found that at a harvest intensity of eight trees per hectare, RIL and conventional logging led to nearly equivalent canopy loss (15.4 and 15.8%, respectively). When 16 trees per hectare were harvested, RIL logging caused greater canopy loss (29.4%) than conventional logging (24.5%). In this particular case, the harvest consisted almost entirely of *Chlorocardium rodiei* (greenheart) which grows in dense stands. The conventional practice focused on dense clumps of this species. The RIL approach attempted to limit the size of an individual gaps to <300 m^2. At high harvest intensities, this practice led to dispersion of the harvest trees and greater canopy damage overall than in conventional practice.

The strong relationship between canopy opening and harvest volume for conventionally logged blocks (Fig. 5) is surprising given the large differences in forest type, logging practices, and measurement techniques. Different measurement approaches may lead to compensating errors. Mapping of canopy gaps from the ground will tend to overestimate the gap fraction within the gap, while neglecting damage far from the gap.

Non-automated approaches for gap fraction estimation, such as the spherical densiometer, appear to give results similar to our automated measurements. However, manual methods are prone to operator bias, and they are relatively slow which ultimately limits the total ground area that can be covered. Fast, automated methods such as the LAI-2000 allow for internally

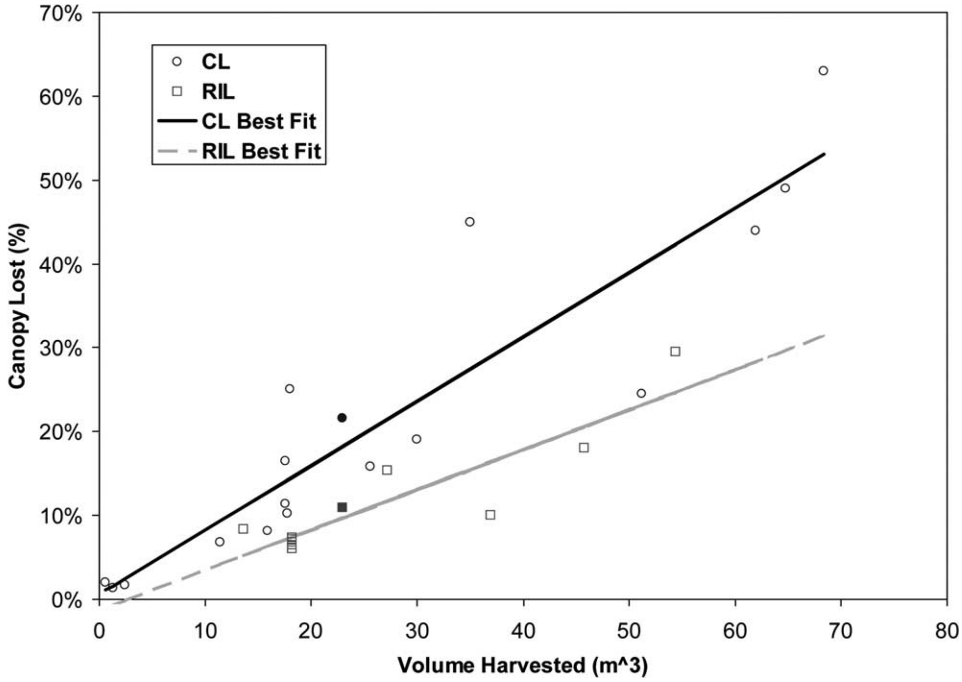

Fig. 5. Canopy damage vs. total volume harvested in 24 logging blocks shown for conventional logging (circles) and RIL (squares). Data shown were derived from this study (filled symbols) and 10 previously published studies (open symbols) (Van Der Hout, 2000; Whitman et al., 1997; Webb, 1997; Johns et al., 1996; Verissimo et al., 1995; White, 1994; Cannon et al., 1994; Verissimo et al., 1992; Uhl et al., 1991; Hendrison, 1989). The best fit least-squares linear regression for canopy loss (y; proportion of total area) vs. harvest geometric volume (x; m^3) was $y = 0.0077x + 0.0058$ ($r^2 = 0.84$). For RIL, the regression equation is $y = 0.0048x - 0.013$ ($r^2 = 0.81$).

consistent (high precision) measurements, and the speed with which the measurements are collected facilities large sample sizes and areas covered.

Few studies have attempted to quantify the recovery of canopy cover following logging disturbance. Cannon et al. (1994) studied blocks in West Kalimantan, Indonesia that had been logged 0.5, 1, and 8 years prior to survey with estimated harvest intensities of 68, 65, and 49 $m^3\,ha^{-1}$, respectively. They found that total canopy opening was approximately 63, 49, and 21% for the 0.5, 1, and 8 years following harvest, respectively. Like Cannon et al. (1994), we found that canopy gap fraction decreased quickly following logging disturbance. We believe that our RIL treatments may recover more quickly than conventional treatments, although we do not yet have sufficient data to confirm this observation. Repeated visits to paired RIL and conventional blocks will be necessary to confirm this possibility.

Detailed understanding of canopy structural changes resulting from different logging intensities is critical to the prospect of logging damage estimation using current and future remote sensing observations. To date, only a few studies have attempted to quantify logging damage from satellite multispectral or radar data (Stone and Lefebvre, 1998; Kuplich et al., 2000). These studies have highlighted the significant difficulty in detecting the presence of logging, and no studies have successfully estimated variations in logging intensity. Due to the fast rate of vegetation regrowth following selective logging, it is a major challenge to detect the spatial extent of logged forests just a year or so following disturbance. Forest canopy gap fraction is the structural variable having the best chance of detection using the newer remote sensing technologies now available (Asner, 2000). However, any test of a remote sensing technology or technique must be squarely based upon the range of gap fractions that result from different logging methods as well as the rate of canopy closure that occurs following abandonment of the site. This study, and the studies summarized here, provide gap fraction and ground damage information needed to further improve remote sensing approaches for improving forest management and quantifying the spatial extent and intensity of selective logging in tropical forests of the Amazon basin.

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