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Spatial and temporal dynamics of forest canopy gaps following selective logging in the eastern Amazon

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Abstract

Selective logging is a dominant form of land use in the Amazon basin and throughout the humid tropics, yet little is known about the spatial variability of forest canopy gap formation and closure following timber harvests. We established chronosequences of large-area (14–158 ha) selective logging sites spanning a 3.5-year period of forest regeneration and two distinct harvest methods: conventional logging (CL) and reduced-impact logging (RIL). Our goals were to: (1) determine the spatial characteristics of canopy gap fraction immediately following selective logging in the eastern Amazon; (2) determine the degree and rate of canopy closure in early years following harvest among the major landscape features associated with logging – tree falls, roads, skid trails and log decks; and (3) quantify spatial and temporal differences in canopy opening and closure in high- and low-damage harvests (CL vs. RIL).

Across a wide range of harvest intensities (2.6–6.4 felled trees ha^{-1}), the majority of ground damage occurred as skid trails (4–12%), whereas log decks and roads were only a small contributor to the total ground damage (<2%). Despite similar timber harvest intensities, CL resulted in more ground damage than RIL. Neither the number of log decks nor their individual or total area was correlated with the number of trees removed or intensity of tree harvesting (trees ha^{-1}). The area of skids was well correlated with the ground area damaged (m^2) per tree felled.

In recently logged forest (0.5 years postharvest), gap fractions were highest in log decks (mean RIL = 0.83, CL = 0.99) and lowest in tree-fall areas (RIL: 0.26, CL: 0.41). However, the small surface area of log decks made their contribution to the total area-integrated forest gap fraction minor. In contrast, tree falls accounted for more than two-thirds of the area disturbed, but the canopy gaps associated with felled trees were much smaller than for log decks, roads and skids. Canopy openings decreased in size with distance from each felled tree crown. At 0.5 years postharvest, the area initially affected by the felling of each tree was approximately 100 m in radius for CL and 50 m for RIL. Initial decreases in gap fraction during the first 1.5 years of regrowth diminished in subsequent years. Throughout the 3.5-year period of forest recovery, tree-fall gap fractions remained higher in CL than in RIL treatments, but canopy gap closure rates were higher in CL than in RIL areas. During the observed recovery period, the canopy gap area affected by harvesting decreased in radius around each felled tree from 100 to 40 m in CL, and from 50 to 10 m in RIL. The results suggest that the full spatial and temporal dynamics of canopy gap fraction must be understood and monitored to predict the effects of selective logging on regional energy balance and climate regimes, biogeochemical processes including carbon cycling, and plant and faunal population dynamics. This paper also shows that remote sensing of log decks alone will not provide an accurate assessment of total forest area impacted by selective logging, nor will it be closely correlated to damage levels and canopy gap closure rates.

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Introduction

Selective logging is a dominant form of land use in the Brazilian Amazon. Nepstad *et al.* (1999) estimated that the total logged area of this region was 9000–15 000 km^2 in 1996–1997, or nearly equal to the area of forest converted to pasture or agriculture. Selective logging results in less forest damage than clear-cutting, yet the ground and canopy damage caused by timber harvests affect a wide range of ecological, biogeochemical and micrometeorological processes (Uhl & Buschbacher, 1985; Jonkers, 1987; Uhl & Kauffman, 1990; Johns, 1991; Thiollay, 1992; Hill *et al.*, 1995; Ter Steege *et al.*, 1995; Brouwer, 1996; Pinard *et al.*, 1996; Pinard and Putz, 1996; Holdsworth & Uhl, 1997; McNabb *et al.*, 1997; Cochrane *et al.*, 1999; Nepstad *et al.*, 1999, this issue).

The most important constraint over plant growth and regeneration in tropical forests is the low light intensity at the canopy understory (Johns *et al.*, 1996). In closed-canopy moist tropical forests, only about 2–3% of photosynthetically active radiation (PAR; 400–700 nm) reaches the understory (Lee, 1987; Gastellu-Etchegorry *et al.*, 1999), and upper canopy opening or gap fraction typically ranges from only 2% to 8% (e.g., Chazdon & Fetcher, 1984, Asner *et al.*, 2002). Plant productivity or carbon uptake by vegetation is tightly linked to PAR availability (Monteith, 1972).

Canopy gaps created by selective timber harvests have immediate impacts on PAR interception, latent and sensible heat fluxes, water stress and plant productivity in tropical forests (Healey *et al.*, 2000; Pinard & Cropper, 2000). Rates of forest regeneration can thus be linked to the size, number and spatial arrangement of canopy gaps following harvest (Pinard *et al.*, 2000, 2002). Other aspects of the carbon cycle are also affected by selective logging. Carbon is lost from the forest in logs transported to sawmills (and beyond). Selective logging can increase the fallen coarse woody debris on the forest floor by 47–135% over background levels, where much of the measured variation is caused by logging method, intensity and location (Keller *et al.*, this issue). Root mortality resulting from timber cutting and extraction further increases the pool of respiring carbon from land to atmosphere. Logged forests are also more vulnerable to fire than unlogged forests (Uhl & Kauffman, 1990; Holdsworth & Uhl, 1997; Cochrane *et al.*, 1999; Nepstad *et al.*, 1999, this issue), and fires can result in significant carbon releases and efflux of particles and greenhouse gases (Holdsworth & Uhl, 1997; Keller *et al.*, 1997).

Beyond its direct effects on forest structure and the carbon cycle, selective logging can alter nutrient cycles and other key biogeochemical processes regulating forest productivity and neighboring aquatic systems. For example, nitrate losses from logged areas in Guyana vary in proportion to the area of soil disturbance surrounding harvested trees (Brouwer, 1996). Increases in nitrate availability in tropical forest soils stimulate denitrification and nitrogen oxide emissions (Keller & Reiners, 1994). Logging often has its most obvious effect on soils via increased erosion and runoff, with concomitant losses of nutrients and organic matter (Brouwer, 1996; Johns *et al.*, 1996; McNabb *et al.*, 1997). Moreover, selective logging has many documented effects on tropical forest wildlife, at times resulting in biotic impoverishment of species and communities or alternatively in stimulating population growth of some species (Johns, 1992; Thiollay, 1992; Hill *et al.*, 1995). Both the magnitude and direction of ecological change following harvest depends heavily upon the initial logging intensity and the subsequent spatial and temporal dynamics of forest gap fraction.

Logging results in a spatially complex array of canopy gaps caused by tree falls, roads, skid trails and areas used to stage logs for transport called log decks. Canopy gaps vary substantially in size and shape, and in spatial density and arrangement, depending upon the type of logging operations employed and pre-existing forest structural attributes (e.g., species, stand age, tree architecture). This broad variation in gap characteristics imparts an equally wide range of responses in the aforementioned ecological, physiological and biogeochemical processes, both immediately following harvest and during subsequent years of forest regeneration. Despite the central importance that gap dynamics play in regulating ecosystem processes following selective logging, we have a poor understanding of the spatial and temporal characteristics of canopy gaps at landscape to regional levels.

Some studies have quantified canopy gaps soon after harvest or after a specific amount of time or regrowth stage (e.g., Cannon *et al.*, 1994; Johns *et al.*, 1996; Whitman *et al.*, 1997). Few studies have provided multi-temporal gap information during forest regeneration, especially in a spatially explicit context over time. We recently reported the first multi-temporal, spatial analysis of canopy gap dynamics following selective logging in the eastern Amazon (Pereira *et al.*, 2002). We quantified differences in initial gap fraction among tree fall, road, skid and log deck areas based on a few replicates of high- and low-damage logging operations. While there was some evidence for differential rates of canopy closure following harvest based on initial logging intensity and canopy damage, the multi-temporal nature of the data set was very limited. To our knowledge, there are no other published studies relating canopy gap dynamics to selective logging practices in a spatially and temporally explicit context. This lack of information impedes our ability to understand, model and predict ecological and biogeochemical processes following logging in the Amazon. Moreover, it limits our ability to develop, improve and assess remote sensing approaches to logging detection and canopy damage monitoring (Stone & Lefebvre, 1998; Asner *et al*., 2002).

We present the results of a spatially explicit study of canopy gap dynamics following selective logging in an eastern Amazon forest. The study spans a 4-year period of forest regeneration among two distinct types of selective harvest methods: conventional logging (CL) and reduced-impact logging (RIL) (Verissimo *et al*., 1992; Uhl *et al*., 1997; Sist, 2000; Pereira *et al*., 2002). While RIL methods are rarely employed in the Brazilian Amazon, inclusion of RIL in this study provided both a greater range of initial canopy damage levels to observe, as well as a biophysical assessment of this important management approach, which may be critical to the future sustainability of timber extraction in the humid tropics. The specific goals of this study were to: (1) determine the spatial characteristics of canopy gap fraction immediately following selective logging of *terra firme* forest in the eastern Amazon; (2) determine the degree and rate of canopy closure in years following harvest, with explicit representation of the major landscape features inherent to logging operations – tree falls, roads, skid trails and log decks; and (3) quantify spatial differences in canopy opening and closure in relatively high- and low-damage harvests (CL vs. RIL). The results presented here bear on field, modeling and remote sensing studies of forest ecology, biogeochemistry and micrometeorology in the Amazon basin.

Methods

Study region

Our study was conducted at the Fazenda Cauaxi, on lands owned by the CIKEL-Brasil Verde S.A. and other surrounding areas in the Paragominas Municipality of Pará State, Brazil, in the eastern Amazon (Fig. 1). The climate of the region is humid tropical with annual precipitation averaging 2200 mm (Costa & Foley, 1998).

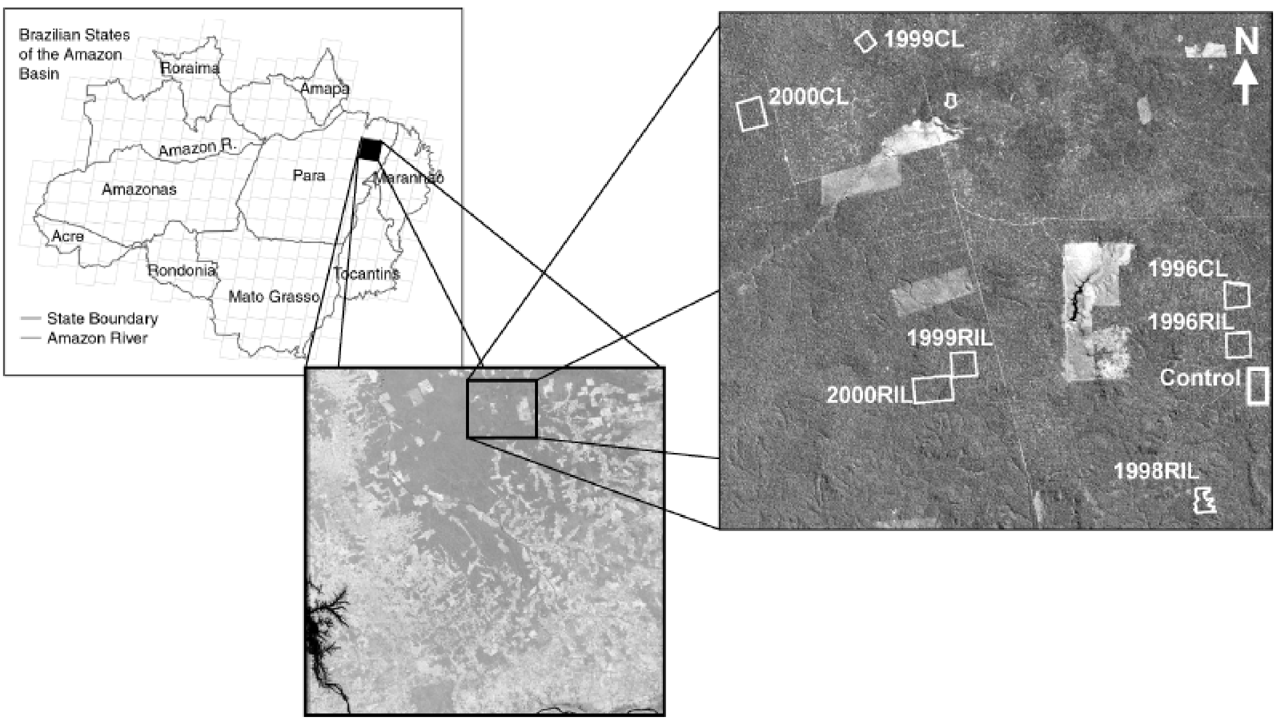

Fig. 1 Map and Landsat image showing the location of the study region in the State of Pará, Eastern Brazilian Amazon. The region contains conventional logging (CL) and reduced-impact logging (RIL) treatments, with harvest year indicated. The forest control (unlogged) area is also shown.

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, and the vegetation is classified as tropical dense moist forest (IBGE, 1988).

Selective logging is practiced throughout the region by a few large companies and many small landholders, resulting in a wide range of logging intensities and methodologies. Logging operations occur mainly during the dry season, which extends from July to November (generally <50 mm/months), although June and December are also frequently dry enough for harvests (Pereira *et al.*, 2002). The Tropical Forest Foundation (Fundaçao Floresta Tropical) has maintained a training center for demonstration of forest management and RIL techniques (S 3°43.878′, W 48°17.438′; Fig. 1). There is no historical record of human disturbance prior to logging operations, although there is evidence of indigenous habitation in the region.

We studied forest gap dynamics in both CL (high collateral damage) and RIL (low collateral damage) to observe a range of canopy damage intensity. CL and RIL practices in this region have been described previously (Verissimo *et al.*, 1992; Johns *et al.*, 1996; Pereira *et al.*, 2002). Briefly, in CL practices, woodsman mark harvest trees that are later felled by sawyers. The sawyers are, in turn, followed by operators who prepare roads and log decks, and who skid and load logs onto trucks for transport. A crawler tractor without a winch is typically 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 CL operations in the Brazilian Amazon (Johns *et al.*, 1996), and it plays a central role in determining ground damages resulting from selective logging (Pereira *et al.*, 2002).

In contrast to CL practices, RIL operations employ a preharvest methodology where blocks are surveyed and fully inventoried, roads are planned and built and vines are cut from harvest trees about 1 year prior to cutting to reduce collateral damage during tree felling (Sist, 2000). Prior to harvest, crews mark trees and determine preferred felling directions, then sawyers fell the trees using directional techniques. Skid trails are then planned and marked considering the direction of the felled trees and the structure of the remaining forest. Logs are extracted using a wheeled skidder with a grapple and a winch (Caterpillar 525).

We studied nine logging areas and a natural forest area (50 ha) that has never been logged. One CL and one RIL area each were harvested in 1996, 1998, 1999 and 2000. An additional 2000 CL harvest block employed a wheeled skidder, allowing for a comparison of damage levels relative to the 2000 CL block skidded with a crawler tractor. The treatment areas ranged in size from 14 to 158 ha, with tree extraction intensities of 2.6–6.4 harvested trees ha^{-1} (Table 1). These values are within the common ranges reported for both CL and RIL operations throughout the region (Uhl *et al.*, 1991; Verissimo *et al.*, 1995; Johns *et al.*, 1996).

Field studies

Four CL and four RIL blocks were inventoried and mapped prior to and following harvest operations using the techniques detailed by Asner *et al.* (2002) and Pereira *et al.* (2002): 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; ArcGIS®; ESRI, Redlands, CA, USA) and geo-rectified using field global positioning system (GPS)

Table 1 Conventional logging (CL) and reduced-impact logging (RIL) blocks, year of harvest (1996–2000), area surveyed, number of trees harvested in survey area and matrix Canopy gap fraction data collections at various stages of forest regeneration (0.5–3.5 years postharvest)

				Time since harvest (years)			
Treatment type	Harvest (year)	Area (ha)	Trees felled	0.5	1.5	2.5	3.5
CL	1996	112	415			X	X
RIL	1996	108	325			X	X
CL	1998	14	88	X	X	X	
RIL	1998	57	200	X	X	X	
CL	1999	72	185	X	X		
RIL	1999	99	379	X	X		
CL	2000	39	120	X			
CL-b*	2000	~75	n/a	X			
RIL	2000	158	453	X			

*CL-b was harvested using a skidder, whereas all other CL treatments employed a crawler-tractor. CL-b was only surveyed for gap fraction in log decks, roads and skids.

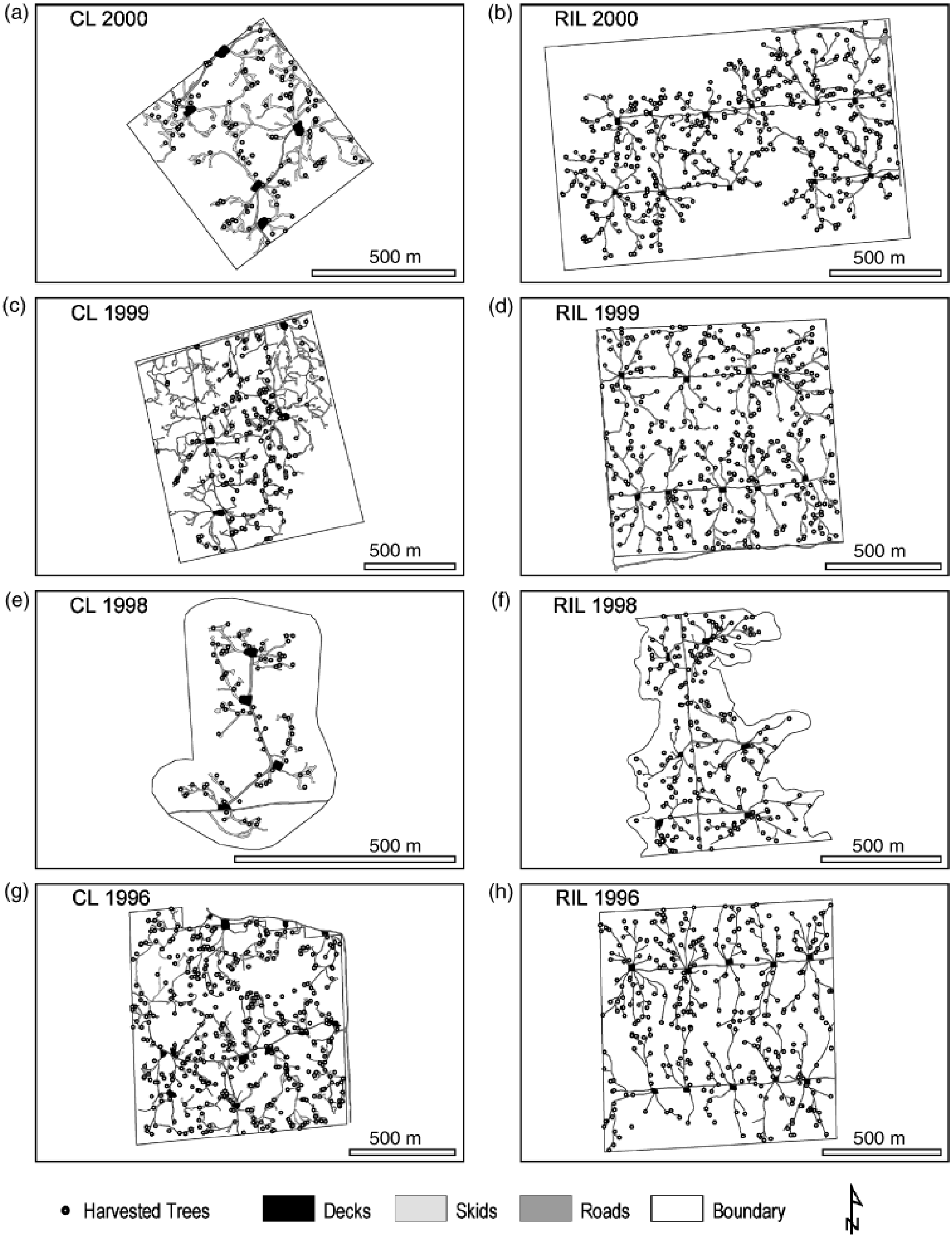

Fig. 2 Geographic information system coverages showing location of treatment boundaries, log decks, roads, skids and each felled tree crown in conventional logging (CL) and reduced-impact logging (RIL) treatments.

measurements (Fig. 2). The root mean square error of the geo-located maps ranged from 5 to 15 m, depending upon the logging area. The GIS thus contained spatially explicit locations and areas of all roads, skids, log decks and felled trees.

Field surveys of canopy damage were conducted in March 1999, July 2000 and July 2001. These campaigns occurred approximately 0.5 years postharvest for the 1998, 1999 and 2000 CL and RIL areas, 1.5 years post-harvest for 1998 and 1999 CL and RIL, 2.5 years post-harvest for 1996 and 1998 CL and RIL and 3.5 years following harvest in the 1996 CL and RIL areas (Table 1). These surveys provided a means to construct chronosequences of forest canopy gap fraction in both CL and RIL timber operations.

Gap fraction (range 0–1) is defined as the proportion of the skyward hemisphere with no interfering plant canopy. We measured canopy gap fraction using optical plant canopy analyzers (LAI-2000, Licor Inc., Lincoln, NE, USA) at 1.5 m above the ground surface. Although these canopy analyzers are often used to estimate leaf area index (LAI), we focused on gap fraction, the measurement directly collected by the instrument (Welles & Norman, 1991). LAI is a quantity derived from the gap fraction measurement and a model of leaf angle distribution and light attenuation. Gap fraction is a more meaningful result from the canopy analyzers than is LAI under conditions of discontinuous, spatially structured canopy coverage in this study.

The gap fraction algorithm used in the instrument assumes a diffusely illuminated sky (Welles & Norman, 1991), so we restricted our measurements to 1 h after dawn or prior to dusk (low sun angle) or to times when there was uniform cloud cover. Measurements below the canopy were referenced to open sky measurements collected in large clearings. The LAI-2000 uses five concentric rings to measure light interception for gap fraction analysis. Data from the outermost ring, which views from 61–74°, were excluded from all analyses to avoid forest edges in the clearings during open sky calibration measurements.

Gap fraction measurements were stratified according to landscape units. We divided the logged forests into five strata: (1) roads, (2) log decks, (3) skid trails, (4) tree falls and (5) undisturbed areas. For roads, we made measurements on randomly selected segments. Each segment began at the edge of a log deck and ran along the road for 100 m or more. Gap fraction measurements were collected at 10 m intervals and averaged for each segment. For skid trails, we again selected random points and followed the same procedure as for roads, but transects always began at least 20 m from a log deck. For tree falls, random trees were selected from the harvest maps. A sampling transect began at the center point of the canopy gap, and ran for 100 m along a randomly selected radius in one of eight cardinal directions. Directions that crossed back over a skid trail, log deck, or road were excluded. Gap fraction measurements for undisturbed forest were acquired in the 50 ha control plot along nonoverlapping randomly selected 500 m transects (Pereira et al., 2002). In total, we collected canopy gap fraction measurements over 29 000 m of transect in this study.

An estimate of total gap fraction for each study block was made using the gap fraction measurements extrapolated in a GIS. Total gap fraction (F) was calculated by

$$F = \sum (a_i f_i)/A, \tag{1}$$

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

$$f_i = k^* 10^{bx}, \tag{2}$$

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 tree falls overlapped with one another or with decks, roads, or skids, the greatest gap fraction was selected. We applied no additive effects, resulting in a conservative damage estimate.

Except where noted, we used Student's t-tests for statistical comparisons between treatments and time-steps in the chronosequences. Subsequent reporting of statistical significance is provided by P-values throughout this paper.

Results

Ground damage

Selective logging caused wide variation in ground damage, as expressed in areas of log decks, roads and skids (Fig. 2). Different harvest methods resulted in significantly different levels of ground damage, with CL (11.5 ± 2.7%) nearly double that of RIL (5.8 ± 1.9%) ($P < 0.01$; Table 2). There was no difference in road area between CL (1.5 ± 0.4%) and RIL (1.0 ± 0.5%) treatments. However, the percentage area damaged by log decks in CL (1.3 ± 0.5%) was twice that of RIL (0.5 ± 0.2%), as was the damage from skid trails in CL (8.8 ± 2.4%) vs. RIL (4.2 ± 1.6%) treatments ($P < 0.05$).

Much higher levels of ground damage from CL were observed despite statistically indistinguishable tree harvest intensities between the two harvest methods (CL: 4.0 ± 1.7 and RIL: 3.3 ± 0.5 felled trees ha^{-1}; $P = 0.13$;

Table 2 Ground disturbance expressed as a percentage of total area for eight harvest blocks contrasting conventional logging (CL) and reduced-impact logging (RIL) treatments

Treatment	Year	Felled trees ha−1	Road area (%)	Deck area (%)	Skid area (%)	Total ground disturbed (%)	Ground damage per tree felled (m2)	# log decks	Total log deck area (m2)	Mean log deck area (m2)
CL	1996	3.7	1.2	0.9	6.8	8.9	240	10	11451	1145
RIL	1996	3.0	0.6	0.6	3.6	4.8	160	10	5879	587
CL	1998	6.4	2.0	1.9	7.3	11.2	180	4	1702	425
RIL	1998	3.5	1.0	0.7	2.9	4.6	130	6	3584	597
CL	1999	2.6	1.1	0.6	8.8	10.5	400	5	7293	1458
RIL	1999	3.8	1.7	0.4	6.5	8.6	230	9	4746	527
CL	2000	3.1	1.5	1.6	12.2	15.3	492	5	5999	999
RIL	2000	2.9	1.1	0.4	3.7	5.2	181	11	5801	527

Values are derived from geographic information system (GIS) analysis presented in Fig. 2. The proportion of total ground disturbance [= (log deck + skid + road)/total] and area ground disturbed per tree harvested are provided. Additional statistics on log deck areas are also shown.

Table 2). Therefore, the total area of ground damage per tree felled was significantly greater in CL ($328 \pm 143\,m^2$) than in RIL ($175 \pm 42\,m^2$; $P = 0.02$). The number of log decks employed was significantly lower in CL (6.0 ± 2.7 decks block^{-1}) than in RIL treatments (9.0 ± 2.2 decks block^{-1}; $P = 0.05$), although log deck areas were higher in CL ($1000 \pm 432\,m^2$) than in RIL ($560 \pm 38\,m^2$; $P = 0.04$).

Gaps by landscape stratum

Canopy gap fractions of individual landscape strata – log decks, roads, skids and tree crowns – are summarized in Table 3. The highest canopy gap fractions were found in the 1998 CL treatment at 0.5 years postharvest, with mean ($\pm$ SD) values of 0.99 ($\pm$ 0.01), 0.51 ($\pm$ 0.26), 0.72 ($\pm$ 0.22) and 0.49 ($\pm$ 0.14) for decks, roads, skids and tree crowns, respectively. Canopy gaps were lowest in the 1996 and 1998 RIL treatments at 3.5 and 2.5 years postharvest, respectively.

For each CL–RIL treatment pair, canopy gap fractions were almost always higher in the CL block (Table 3). Some of the most obvious differences between treatment pairs were observed in tree crown gaps, which averaged 0.32–0.49 after initial CL harvests but only 0.22–0.34 following initial RIL harvests, or 44–91% less than in CL (multiple *t*-tests; $P < 0.05$). Skids were also clearly different between treatment pairs, averaging 58–278% greater in CL blocks 0.5 years following harvest. The lowest gap fractions at 0.5 years postharvest were in tree crown areas, with values of 0.22 ± 0.12 and 0.22 ± 0.05 for 1999 and 2000 RIL treatments, respectively.

Gap fractions were high in the 1996 CL and RIL log decks even at 2.5 years postharvest because those areas had been recleared for use in training courses conducted by the Fundaçao Floresta Tropical (Asner *et al*., 2002). Thus these few log deck measurements conducted in 1999 were more representative of gap fractions in log decks 0.5 years after timber cutting, and were treated as such in subsequent analyses.

With one exception, CL harvest treatments employed crawler tractors to move logs from felling points to log decks. For the 2000 harvests, one of the 2000 CL treatments used a wheeled skidder with a winch (CL-b; Tables 1 and 3). We found that the use of tractors resulted in canopy gap fractions that were 20%, 170% and 172% larger in log decks, roads and skids, respectively, over those created using a skidder ($P < 0.05$). Initial canopy gaps in the 2000 CL-b treatment were at times lower than those from recent RIL blocks (e.g., 1998 and 1999 RIL roads and skids), but were at times higher as well (e.g., 2000 RIL decks, roads and skids).

Canopy gaps over time

Field measurements of forest canopy gap fraction from Table 3 were combined into classes of 0.5, 1.5, 2.5 and 3.5 years postharvest, and by CL vs. RIL methods (Fig. 3). The forest control area had a mean ($\pm$ SD) gap fraction of 0.03 ($\pm$ 0.01), consistent during all field campaigns. In contrast to this area, all landscape strata measured in areas of selective logging had much higher gap fractions, even up to 3.5 years following timber extraction. Log decks in RIL (0.93 ± 0.09) and CL (0.83 ± 0.22) treatments were not significantly different at 0.5 years postharvest. However, CL road and skid gap fractions were significantly higher (93% and 75%,

Table 3 Mean (± standard deviation) of canopy gap fraction by logging treatment type, harvest year (1996–2000), and measurement year (1999–2001) for log decks, roads, skids and felled tree crowns

Treatment	Harvest (year)	Log decks 99	00	01	Roads 99	00	01	Skids 99	00	01	Tree crowns 99	00	01
CL	1996	0.97 (0.02)	0.78 (0.20)	–	0.44 (0.19)	0.12 (0.11)	–	0.50 (0.06)	0.43 (0.11)	–	0.30 (0.05)	0.16 (0.06)	–
RIL	1996	0.96 (0.03)	0.42 (0.14)	–	0.21 (0.13)	0.09 (0.04)	–	0.39 (0.01)	0.29 (0.10)	–	0.08 (0.01)	0.06 (0.02)	–
CL	1998	0.99 (0.01)	0.73 (0.17)	0.49 (0.01)	0.51 (0.26)	0.11 (0.13)	0.04 (0.01)	0.72 (0.22)	0.52 (0.13)	0.09 (0.02)	0.49 (0.13)	0.31 (0.15)	0.17 (0.10)
RIL	1998	0.97 (0.02)	0.46 (0.14)	0.42 (0.06)	0.27 (0.14)	0.11 (0.15)	0.08 (0.01)	0.36 (0.12)	0.22 (0.06)	0.19 (0.01)	0.34 (0.13)	0.10 (0.03)	0.12 (0.07)
CL	1999	–	0.99 (0.03)	0.66 (0.03)	–	0.28 (0.18)	0.15 (0.01)	–	0.41 (0.12)	0.38 (0.01)	–	0.42 (0.16)	0.33 (0.15)
RIL	1999	–	0.94 (0.02)	0.51 (0.07)	–	0.20 (0.09)	0.16 (0.01)	–	0.26 (0.13)	0.24 (0.02)	–	0.22 (0.12)	0.29 (0.07)
CL	2000	–	–	0.94 (0.06)	–	–	0.43 (0.02)	–	–	0.68 (0.04)	–	–	0.32 (0.17)
CL-b	2000	–	–	0.79 (0.13)	–	–	0.16 (0.01)	–	–	0.25 (0.01)	–	–	–
RIL	2000	–	–	0.58 (0.12)	–	–	0.12 (0.01)	–	–	0.18 (0.01)	–	–	0.22 (0.05)

Cl, contrasting conventional logging; RIL, reduced-impact logging.

respectively) than in RIL treatments after 0.5 years of regrowth ($P<0.05$).

At 1.5 years following harvest, canopy gap fractions in log decks and roads remained significantly larger in CL than in RIL treatments ($P<0.01$; Fig. 3). Skid-area gap fractions were, however, similar at this time and remained similar after 2.5 and 3.5 years of forest regrowth ($P>0.10$). Canopy gaps within the CL decks appeared slightly higher than in RIL decks at 2.5 and 3.5 years postharvest, but these differences were not statistically significant. It took 2.5 years of regrowth in the CL road areas to match the gaps at 0.5 and 1.5 years of regrowth in RIL areas.

Calculated rates of canopy closure indicated high variability by treatment type and by year since harvest (Fig. 4). Initial (0.5–1.5 years) closure rates in log decks were greater for RIL (42%) than for CL (25%) ($P=0.01$), but were lower for RIL in subsequent periods (1.5–2.5 and 2.5–3.5 years; $P<0.05$). The resultant long-term (0.5–3.5 years) closure rate on log decks was nearly equal in RIL (49%) and CL (48%) treatments. Gap-closure rates were initially similar in CL and RIL road areas (0.5–1.5 years), but were later much lower in RIL treatments (Fig. 4). This resulted in a long-term rate of change estimated at 14% in RIL and 55% in CL areas ($P<0.01$). In comparison to roads, the skid areas showed nearly opposite trends in canopy closure rates with time and treatment type (Fig. 4). Gaps closure was twice as high in CL (62%) than in RIL (31%) treatments during 0.5–1.5 years postharvest, but switched to lower values in CL (14%) than in RIL (38%) in the 2.5–3.5 years regrowth period ($P<0.01$). Over the long-term (0.5–3.5 years), canopy closure rates were higher in CL (65%) than RIL (54%) skids ($P=0.04$).

Canopy openings in tree-fall areas were largest at the location of the felled crowns, and decreased with distance from the crowns (Fig. 5). At 0.5 years after harvest, tree-fall gap fractions in CL areas were significantly larger than in RIL treatments at all transect sampling points (0–100 m from crowns; $P<0.05$; Fig. 5a). Initially following harvest, tree-fall gaps in CL and RIL areas decreased to closed-canopy levels at 50 and 20 m, respectively. Canopy gaps in the 0–20 m radius surrounding felled crowns were $\sim 56\%$ larger in CL than in RIL treatments, but the difference was 96–225% at 30–100 m radial distances. RIL canopy gaps more than 50 m from felled crowns averaged 0.03 (± 0.02) just 0.5 years following harvest (Fig. 5a), a value not significantly different from the background gaps in the forest control (Fig. 3). In contrast, initial CL tree-fall gaps (0.08–0.12) remained well above background forest levels even 80–100 m from the felled crowns.

Tree-fall gap fractions were almost always higher in CL than in RIL treatments at all time-steps in the

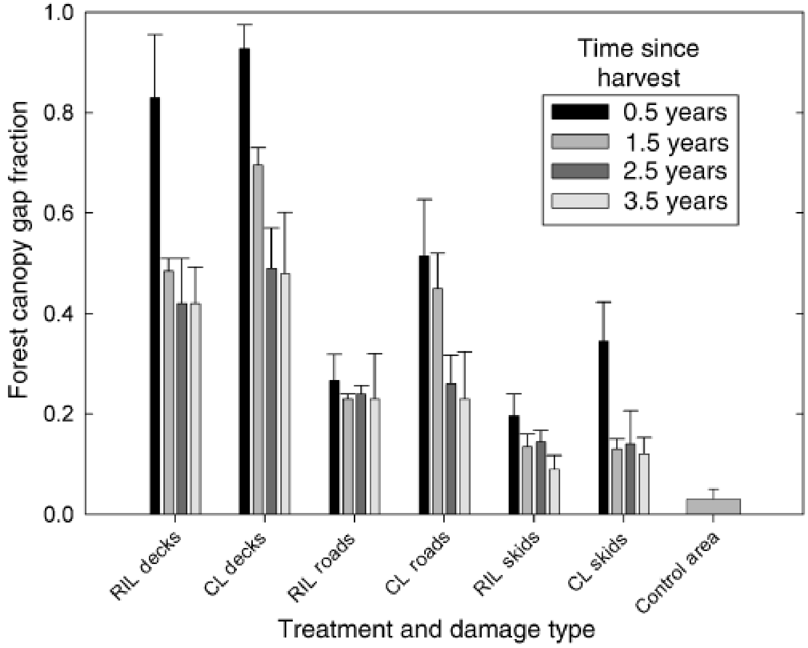

Fig. 3 Mean (± SD) canopy gap fraction for landscape strata organized by postharvest year and by conventional logging (CL) or reduced-impact logging (RIL) methods. Forest control area also shown.

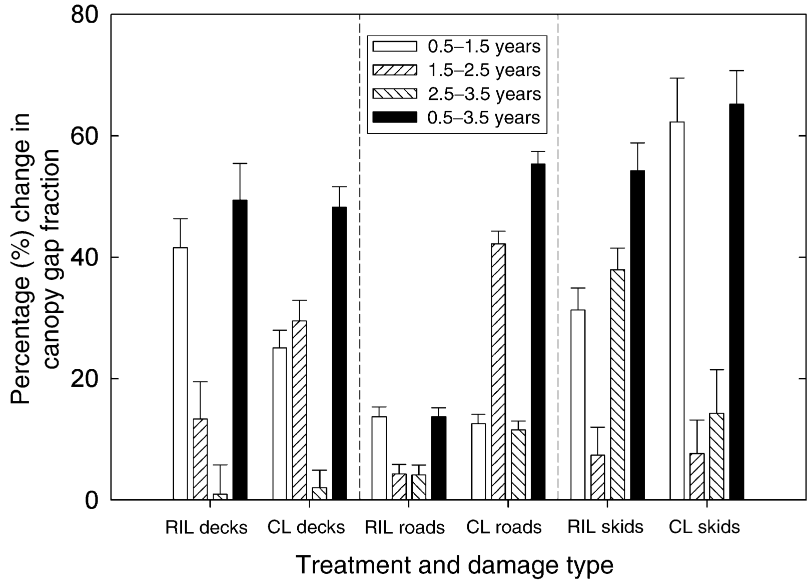

Fig. 4 Percentage change in forest canopy gap fraction following each chronosequence increment for conventional logging (CL) and reduced-impact logging (RIL) treatments. Mean (± SD) given for log decks, roads and skids.

chronosequence (Fig. 5a–d). Over this period, canopy gaps at the felled tree crowns went from 0.26(± 0.07) to 0.20(± 0.09) to 0.13(± 0.05) to 0.10(± 0.03) in RIL areas. Crown gaps in CL treatments changed from 0.41(± 0.09) to 0.32(± 0.03) to 0.21(± 0.09) to 0.16(± 0.04). Gap closure rates at the felled crowns were therefore similar, averaging 23–35% for RIL and 22–35% for CL throughout the 3.5 years recovery period.

During the entire period represented in the study and in terms of gap fraction levels, the area around each felled crown affected by harvesting decreased quickly from 50 m radius at 0.5 years, to 20 m at 1.5/2.5 years and to 10 m at 3.5 years in RIL treatments (Fig. 5). In contrast, the affected area in CL treatments went from roughly 100 to 80 to 50 to 40 m at each time increment.

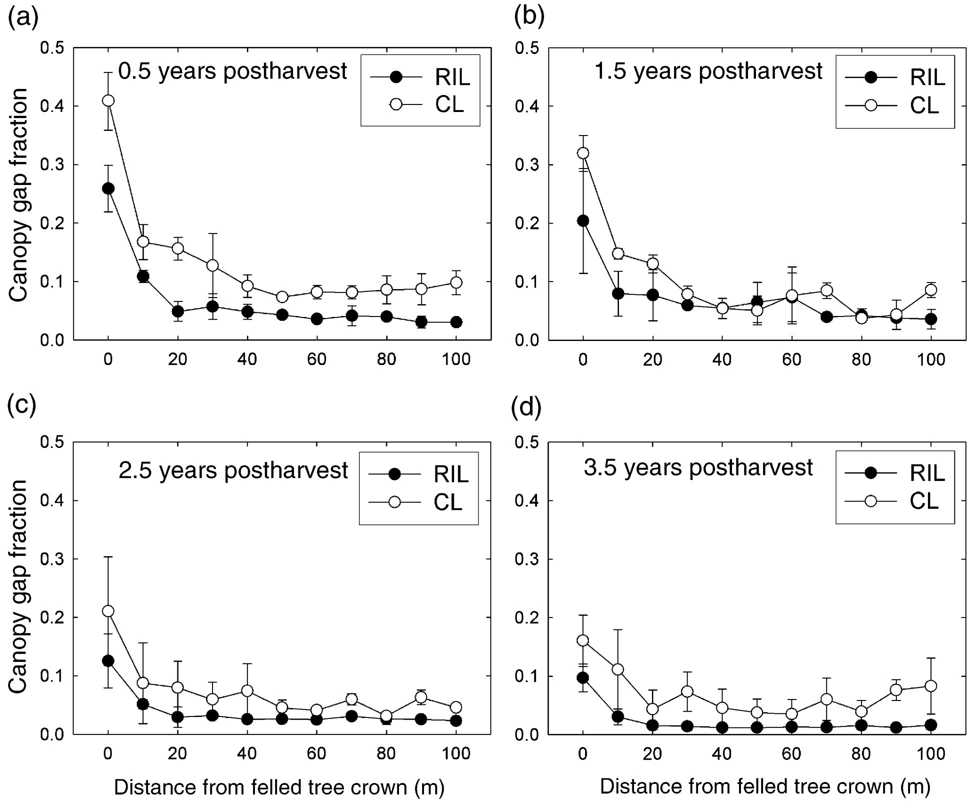

Fig. 5 Mean (± SD) forest canopy gap fraction in conventional logging (CL) and reduced-impact logging (RIL) treatments with distance (m) from felled tree crowns. (a) 0.5 years, (b) 1.5 years, (c) 2.5 years and (d) 3.5 years postharvest.

Area-integrated gap fraction

GIS analysis was used to combine ground damage data (Table 2) with canopy gap fraction results for the individual landscape strata (Table 3) and tree-fall transects (Fig. 5). Average gap fraction values for log decks, roads, skids and tree falls were spatially distributed in the GIS for each treatment type and time since harvest. The resulting GIS models are shown in Figs 6–9, and they simulate the spatial distribution of forest canopy opening for each harvest block during the various measurement campaigns (see Table 1). Areas of high gap fraction (> 0.8) are in red, medium gap (0.2–0.8) in yellow and low gap opening (< 0.2) in green. The GIS models were needed to calculate area-integrated gap results, but they also provided an important visual perspective on the spatial distribution and temporal changes in canopy opening following timber harvest.

Six logging treatments were measured at 0.5 years following harvest (Fig. 6), and are shown as the GIS models with the highest area-integrated gap fractions. The 1998 CL treatment (Fig. 6a) had the highest calculated total gap fraction of 24.2% at 0.5 years (Table 4), which was the location and time of the highest recorded damage levels in the study. The 1999 and 2000 CL sites had lower total canopy openings at 0.5 years postharvest (Fig. 6c, e). Mean (± SD) area gap fraction for these 0.5 years CL sites was 19.7 ± 4.0, much of which was accounted for by the gap fraction and spatial extent of tree-fall areas (Table 4).

Tree-fall gaps, calculated as the 100 m radius around each harvested tree (Fig. 5), comprised more than two-thirds of the canopy opening to the 1998 CL area at 0.5 years postharvest. Although 1999 CL (16.4%) and 2000 CL (18.6%) had less damage per unit area than 1998 CL, tree-fall gaps also contributed about two-thirds to these area-integrated gap levels (Table 4). Skids were the second most important contributor to the area-integrated gaps in newly harvested sites, with values for CL treatments of 2.5–5.2%. In comparison, roads (0.4–0.7% gap) and log decks (0.6–1.9%) were very minor contributors to the landscape-level canopy opening at 0.5 years postharvest.

At 0.5 years following harvest, RIL areas had substantially lower area-integrated gap opening in comparison to CL treatments (Fig. 6). Despite comparable harvest intensity levels between CL and RIL areas (Table 2), the initial damage levels were significantly lower in RIL log deck, road, skid, tree-fall and total area classes ($P = 0.02$–0.05; Fig. 6). Similar to CL results,

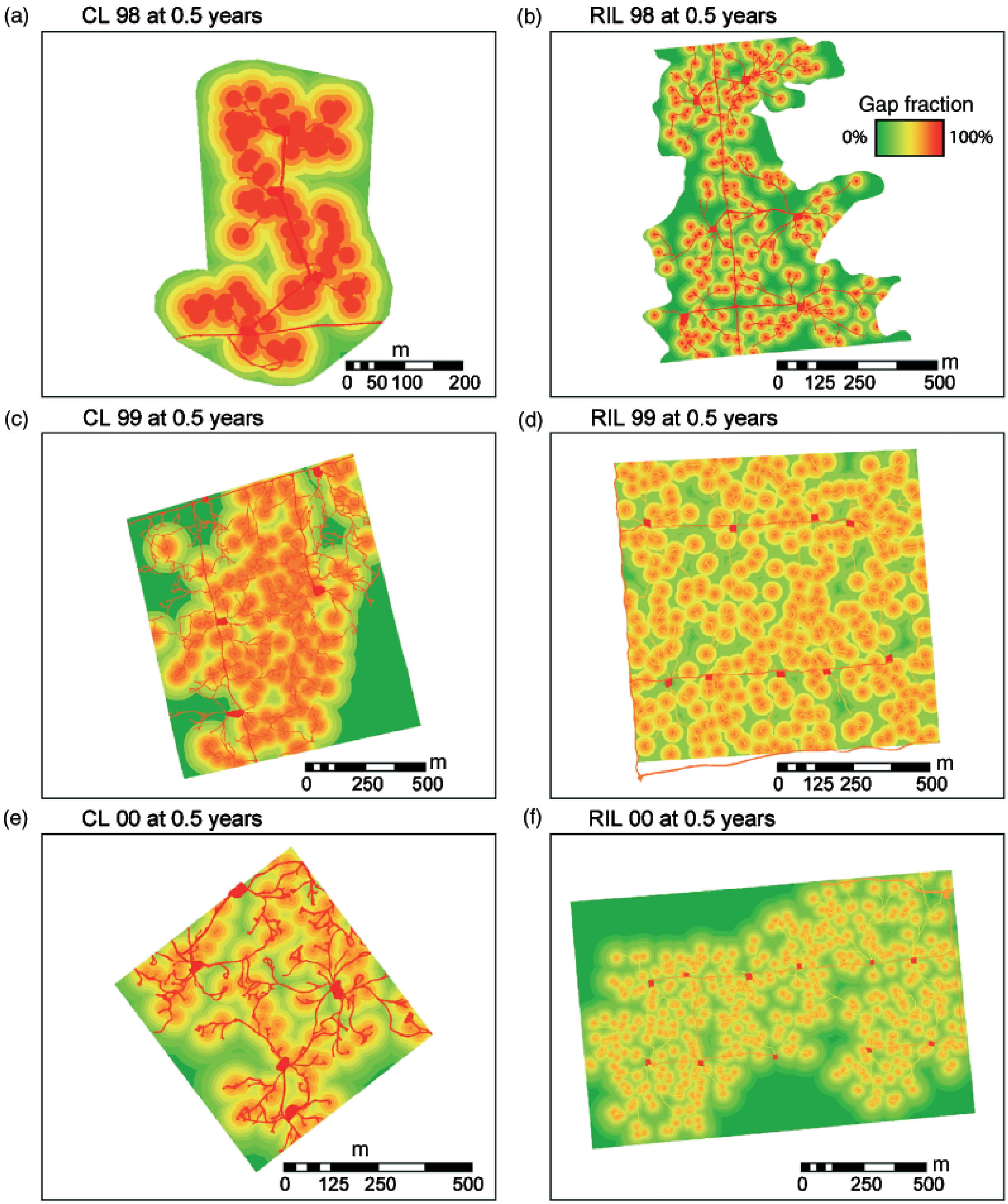

Fig. 6 Geographic information system models of forest canopy gap fraction at 0.5 years postharvest for conventional logging (CL) and reduced-impact logging (RIL) treatments. Models show the location of treatment boundaries, roads, skids and felled trees, with their respective gap fractions as measured during field campaigns (Table 3).

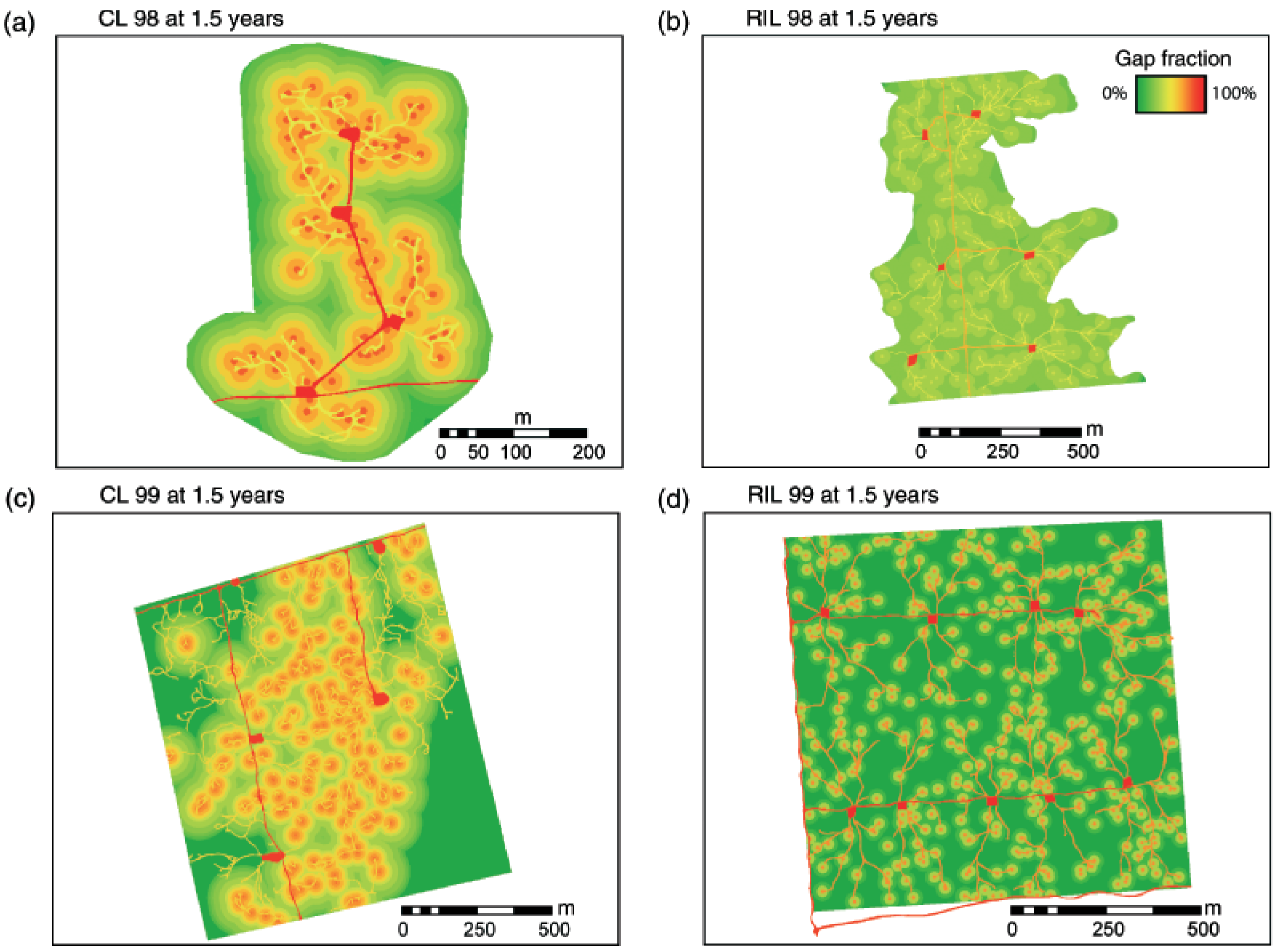

Fig. 7 Geographic information system models of forest canopy gap fraction at 1.5 years postharvest for conventional logging (CL) and reduced-impact logging (RIL) blocks. Other descriptive information is given in Fig. 6.

contributions from log decks (0.2–0.7%), roads (0.2–0.4%) and skids (0.4–1.3%) were minor in comparison to the contribution from trees targeted for harvest (7.1–12.9%; Table 4). In fact, tree-fall gaps accounted for 98% and 89% of the total gap area for 1999 and 2000 RIL treatments, respectively.

There was pronounced spatial variability in the GIS-modeled canopy gap fractions and recovery, as depicted at time-steps 1.5, 2.5 and 3.5 years postharvest (Figs 7–9). The simulations showed that the forest canopy varied in initial gap fractions (Fig. 6), as well as in the patterns and rates of canopy closure (Figs 7–9). Individual treatment blocks had consistent patterns of decreasing canopy gap over time (Table 4). For example, the 1998 CL block decreased in area-integrated gap fraction by 11.2% and 7.0% (absolute) from 0.5–1.5 to 1.5–2.5 years following harvest, respectively. In contrast, the 1998 RIL gaps decreased 2.7% and 1.3% during the same periods, although RIL values were much lower than CL treatments.

Where possible, we grouped the area-integrated gap results from Figs 6–9 and Table 4 into classes of 0.5, 1.5, 2.5 and 3.5 years postharvest (Fig. 10). We acknowledge that this dataset ranges from relatively rich in 0.5 years treatments (1998–2000 CL and RIL) to a single pair of 3.5 years areas (1996 CL and RIL); however, some basic trends were evident. First, there was a significant decrease in area-integrated gap fraction from 0.5 to 1.5 years postharvest in CL and RIL treatments (*t*-tests, $P<0.05$). After 1.5 years, this trend ceased to occur on an annual basis in the CL blocks (Fig. 10a), but it continued to the 3.5 years mark in RIL areas (sequential *t*-tests, $P<0.05$; Fig. 10b). Second, area-integrated gaps for log decks, roads, skids and tree falls tended to decrease over time in CL treatments, although few of trends were significant from period to period in the chronosequence. However, trends were significant over the entire time-course of the chronosequence (0.5–3.5 years); area-gap fraction decreased a total of 48% and 76% in CL and RIL treatments, respectively ($P<0.05$).

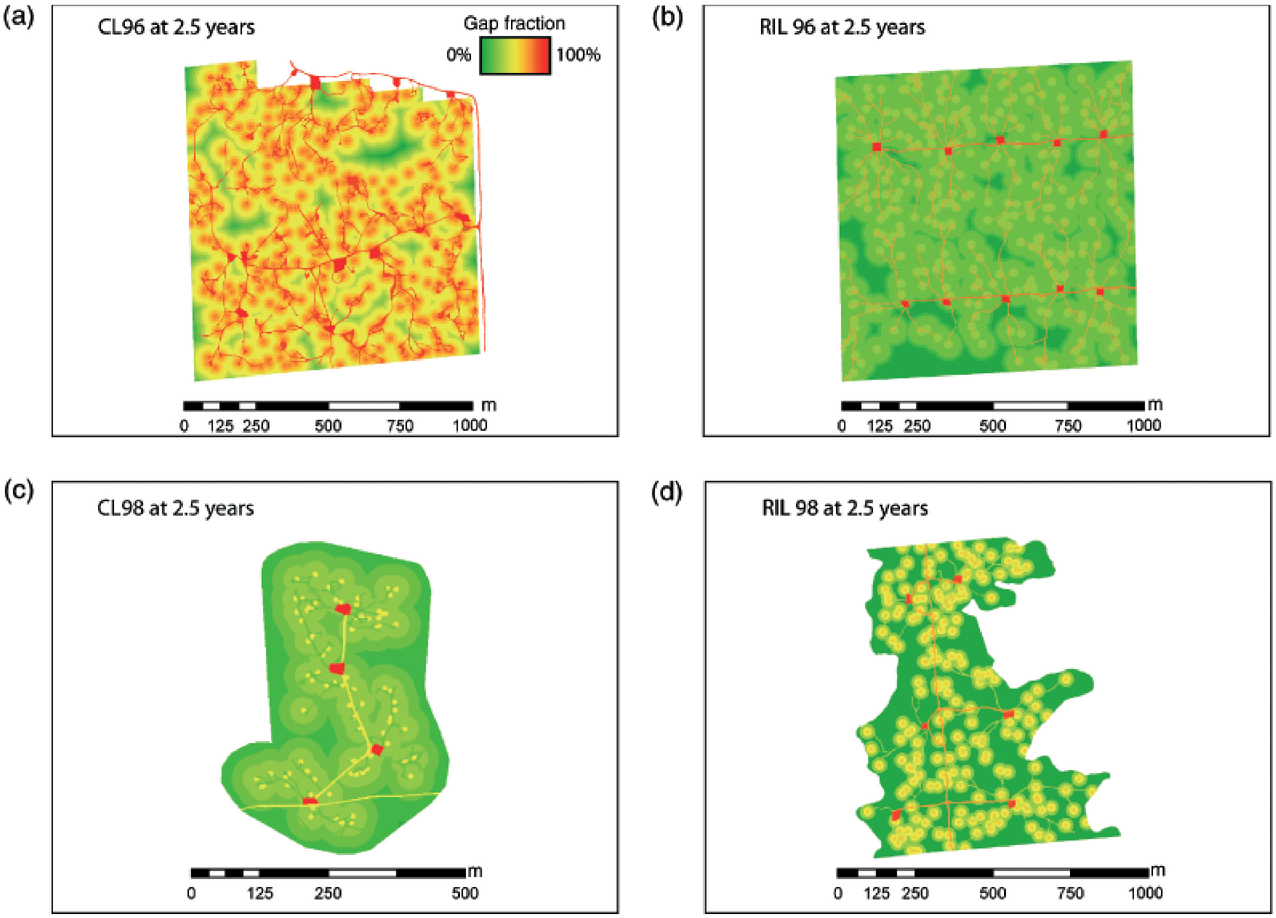

Fig. 8 Geographic information system models of forest canopy gap fraction at 2.5 years postharvest for conventional logging (CL) and reduced-impact logging (RIL) blocks. Other descriptive information is given in Fig. 6.

Likewise, changes in area-integrated log deck, road, skid and tree-fall gaps over the 3.5-year period of regrowth were −48%, −33%, −79% and −37%, respectively, in CL areas. In comparison, RIL treatments underwent less change over the same time period for the same landscape strata (−31%, −1%, −64% and −48%). Hence, the rate of change in CL areas was greater than for RIL, although the integrated gap areas were always lower in the RIL treatments.

Discussion

Vegetation structure exerts control over the transfer of materials and energy in ecosystems, and in turn, it is responsive to these transfers. Changes in vegetation structure therefore result in functional changes in the canopy and throughout the ecosystem. Selective logging causes an instantaneous (days) change in forest structure relative to the timescales of forest canopy growth, biomass accumulation and mortality (years to centuries). From the perspective of vegetation structure, neither the short- nor the long-term effects of selective logging are well understood in tropical forests, especially in a spatially detailed context.

The effects of selective logging on forest structure can be, for convenience, broken down into three major components: (1) the ground damage incurred by harvest operations, (2) temporal patterns of canopy gap fraction within each ground damage category and (3) temporal changes in gap fraction associated with felled trees throughout the landscape. Canopy gap fraction represents the integrated effect of several scale-dependent biophysical properties such as vegetation height, vertical and horizontal crown size and shape, leaf angle distribution and the spatial density or spacing of the plants. Although gap fraction does not determine the relative importance of these properties individually, it is informative because it is sensitive to the integrated effects of structural change. It is also sufficiently simple to allow for the collection and interpretation of many observations throughout a landscape. We capitalized on this capability by repeatedly

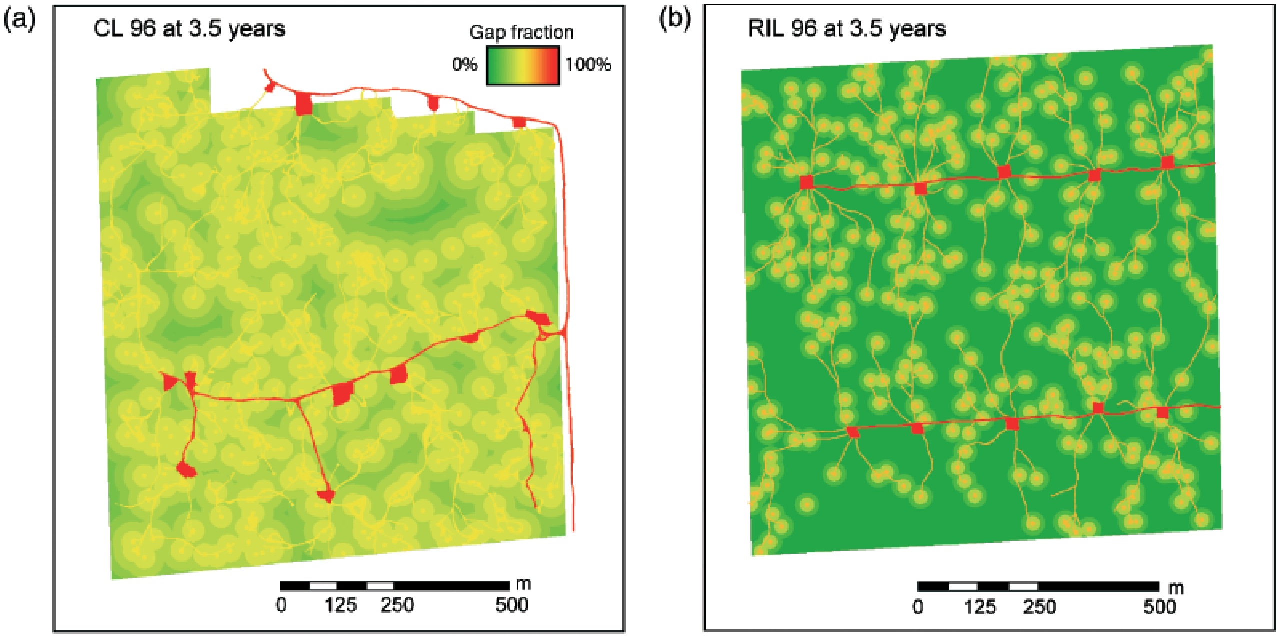

Fig. 9 Geographic information system models of forest canopy gap fraction at 3.5 years postharvest for conventional logging (CL) and reduced-impact logging (RIL) blocks. Other descriptive information is given in Fig. 6.

Table 4 Area-integrated canopy gap fraction (%) by logging treatment type, harvest year (1996–2000) and measurement year (1999–2001) for total block, log deck, roads, skids and felled tree areas

		Total			Log decks			Roads			Skids			Tree crowns		
Treatment	Harvest (year)	99	00	01	99	00	01	99	00	01	99	00	01	99	00	01
CL	1996	17.7	10.3	–	0.9	0.7	–	0.4	0.4	–	3.0	0.8	–	13.4	8.4	–
RIL	1996	5.6	2.4	–	0.6	0.3	–	0.3	0.3	–	0.8	0.3	–	4.0	1.6	–
CL	1998	24.2	13.0	6.0	1.9	1.4	0.9	0.7	0.5	0.1	3.7	0.8	0.3	17.9	10.3	4.7
RIL	1998	9.0	6.3	5.0	0.7	0.3	0.3	0.4	0.2	0.2	0.8	0.3	0.2	7.2	5.5	4.3
CL	1999	–	16.4	9.9	–	0.6	0.4	–	0.4	0.4	–	2.5	1.3	–	11.1	7.8
RIL	1999	–	13.1	5.6	–	0.4	0.2	–	0.3	0.2	–	1.3	1.0	–	12.9	4.1
CL	2000	–	–	18.6	–	–	1.5	–	–	0.7	–	–	5.2	–	–	11.2
RIL	2000	–	–	8.0	–	–	0.2	–	–	0.2	–	–	0.4	–	–	7.1

Cl, contrasting conventional logging; RIL, reduced-impact logging.

collecting thousands of gap fraction measurements among the landscape strata most pertinent to selective logging regimes – log decks, roads, skids and tree-fall areas. This approach permitted us to model the contributions of these strata to the spatial and temporal dynamics of canopy gaps at the stand level.

Ground damage

Across a wide range of harvest areas (14–158 ha) and extraction intensities (2.6–6.4 felled trees ha^{-1}), skid trails were consistently the largest contributor to the overall ground damage found in CL (7–12%) and RIL (3–6.5%) treatments. In contrast, log decks and roads were small components of the ground damage, usually averaging less than 1% and 2%, respectively, of the total harvest area. Whereas the differences in log decks and road areas between CL and RIL were statistically significant, they were nonetheless very low in both types of logging relative to skids.

During our field studies, we often observed that surface (detrital and soil) organic matter was removed from log decks and roads, whereas it often remained in the skid areas. Although we did not quantify the severity of soil disturbance, other reports indicate that such differences are important determinants of forest

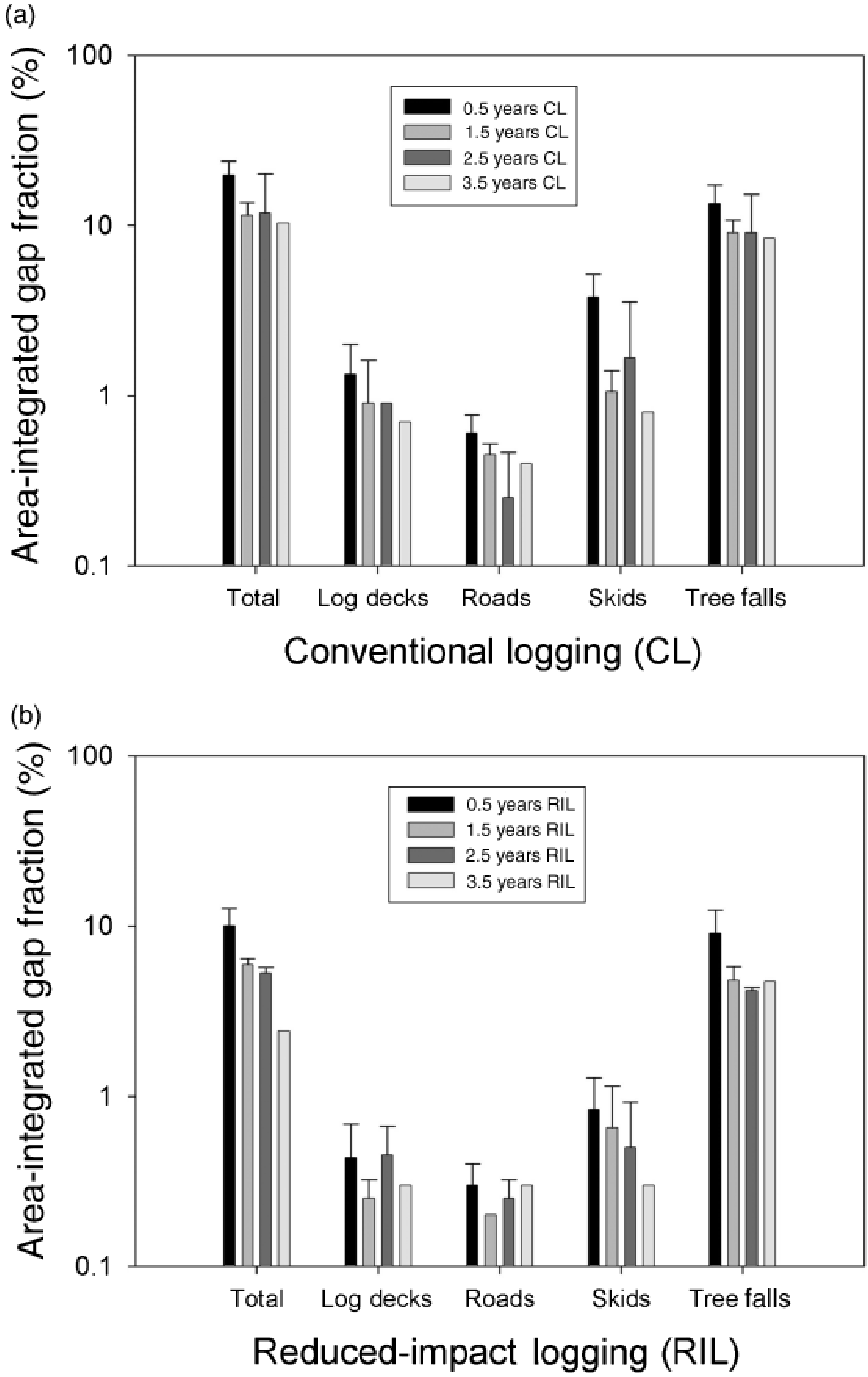

Fig. 10 Area-integrated gap fractions organized 0.5, 1.5, 2.5 and 3.5 years postharvest for: (a) conventional logging– (CL) and (b) reduced-impact logging (RIL).

regeneration (Gullison & Hardner, 1993; Ter Steege *et al*., 1994; Pinard *et al*., 1996). Our work compliments previous studies of ground damage by showing that, independent of surface/soil disturbance levels, selective logging in the eastern Amazon produces a diffuse spatial pattern of ground damage dominated by skid areas but punctuated by small areas (log decks and roads) of more severe damage.

Currently the most common approach for estimating logged areas and damage levels is by counting log decks and/or by assigning buffers around log decks indicating the area affected by timber harvests (*sensu*

Stone & Lefebvre, 1998; Cochrane *et al*., 2002). Our study found that neither the number of log decks nor their individual or summed area per harvest block was well correlated with the number of trees removed or the intensity of tree harvesting (trees ha^{-1}). While the correlation between log deck variables and damage levels was low on an inter-site basis, the ground damage area per tree felled was significantly higher in CL than in RIL. However, the number of log decks employed was significantly lower in CL than in RIL treatments. The percentage area of skids, however, was well correlated with ground area damaged (m^2) per tree felled ($r = 0.92$, $P < 0.05$; Pearson's product moment correlation). These results indicate that the forest area affected by timber harvest or the spatial density of forest damage per felled tree cannot be accurately quantified via field- or satellite-based counts of log decks or sizes. Remote sensing approaches must therefore continue to improve if the canopy damage and ecological consequences of selective logging are to be determined and monitored at the regional scale (Asner *et al*., 2002, in press).

Canopy opening and closure

The landscape categories of log decks, roads and skids are a convenient means to organize field measurements and to report ground damage from selective logging. However, these categories do not incorporate the forest area directly impacted by the felling of trees for timber, the primary goal of this land use. Canopy gap fraction measurements in log decks and along roads and skids were straightforward to acquire, but quantifying the area affected by tree felling was less certain. Our strategy involved measuring gap fractions in 100 m radii extending from randomly selected tree crowns on the forest floor. Combined with GIS locations of each felled tree, this sampling method provided insight to the spatial dynamics of canopy gap fraction over the major area affected by the harvests.

The spatial characteristics of forest canopy gap fractions were relatively clear at 0.5 years postharvest. Gap fractions were highest in log decks (0.58–0.99; Table 3) and lowest in tree-fall areas (0.22–0.49 at the felled crown; Fig. 5). Roads and skids had intermediate gap fractions initially following timber extraction. However, due to the small surface area of log decks, their contribution to the total area-integrated forest gap fraction was small (Table 4). In contrast, the relatively small gap fractions caused by tree falls were dispersed throughout the forest, which when integrated over area, resulted in a large contribution to the total stand-level canopy gap fraction. The relative importance log deck, road, skid and tree-fall gaps on the total canopy openness of recently harvested forests is most apparent in the GIS analyses presented in Fig. 6. At this point in time, the landscape was dominated by a diffuse distribution of gap fractions from felled trees.

Temporal patterns of canopy gap closure varied dramatically by landscape stratum. In log decks, rapid initial decreases in gap fraction during the first 1.5 years of forest regrowth diminished in subsequent years, as gap levels stabilized. Plant establishment was initially much faster in RIL than in CL decks (0.5–1.5 years), and gap fractions decreased very early in the RIL chronosequences. In later years (1.5–3.5 years), changes in gap fraction were much slower in RIL than in CL decks, suggesting the onset of light limitation in the RIL decks. Differences in the speed of plant establishment and growth in log decks is likely related to the initial size of decks, which was usually smaller in RIL treatments (Table 2). Additional studies are required to understand the biological and physical (e.g., temperature, moisture) determinants of plant colonization and growing in log decks.

Whereas the course of vegetation reestablishment and gap fraction change was clear in log decks, the trends were much more variable in roads and skids. However, some consistent patterns could be discerned. Low initial light levels in RIL roads and skids precluded any major decrease in canopy gap fraction in the chronosequence. Relative to RIL treatments, canopy gap fractions in CL roads and skids were high at 0.5 years postharvest, and thus decreased rapidly in the following 1–2 years of regrowth. It is noteworthy that by endpoint of the chronosequences, the canopy gap fractions of decks, roads or skids in RIL were not significantly different from those in CL.

Canopy gap fractions decreased with distance from each felled tree crown. Initially following harvest, the area with a measurable impact by tree felling was at least 100 m in radius in CL and about 50 m in RIL. During the 3-year period of forest recovery, tree-fall gap fractions were always higher in CL than in RIL treatments. Canopy gap area affected by each felled tree decreased from 100 to 40 m in CL, and from 50 to 10 m in RIL. Moreover, throughout the chronosequence, we observed that additional gaps would periodically form in the CL treatments from previously standing dead and damaged trees. This likely accounts for the greater variability of CL canopy gap in the 50–100 m range along the 2.5 and 3.5 years postharvest transects (Fig. 5c, d), although we did not quantify the rate of collateral gap formation. In general, these results strongly suggest that not only is the initial impact area of logging dominated by tree felling, but the temporal dynamics of gap closure are dominated in tree-fall areas as well.

Our canopy gap fraction measurements of a 50 ha primary forest site were 0.03 ($\pm$ 0.01), which is within the typical range of values reported for Amazônia and other tropical forests (e.g., Chazdon & Fetcher, 1984; Denslow, 1987; Herbert & Fownes, 1997). Estimates of the initial canopy opening and gap fraction changes in harvested areas could be compared to this control site. An important finding was that gap fractions remained higher in log decks, roads and skids of CL and RIL treatments than in the control area, even after 3.5 years of forest recovery (Fig. 3). This indicates that the high degree of light scavenging (and likely, light limitation) normally found in tropical forests takes many years to re-establish following selective logging.

Other implications

The findings presented here have wide ranging implications for studies of the Amazon basin and of humid tropical forests worldwide. These studies can be categorized into at least four topical areas mentioned throughout the paper: ecological, physical and biogeochemical processes plus remote sensing. In addition, our results highlight differences in CL and RIL operations and thus forest management.

In general, the scientific implications of our results can be linked to two of the more important findings presented in this paper: (1) forest canopy gap dynamics are dominated by a spatially diffuse, moderate amount of canopy opening caused by tree felling, and not by the construction of log decks and roads; (2) the degree and rate of canopy closure depends largely upon initial gap fractions following timber harvest. The most direct impact of these results relate to canopy structure and light penetration, with secondary effects on the temperature and moisture regime of vegetation and soils (Kammesheidt *et al*., 2002). These changes subsequently affect carbon fluxes of net primary production (NPP) and heterotrophic respiration (Monteith, 1972; Silva *et al*., 1995, Pinard & Cropper, 2000), as well as nutrient dynamics and trace gas emissions (Brouwer, 1996; Keller *et al*., 1997; McNabb *et al*., 1997; Martinelli *et al*., 2000). Changes in NPP can lead to altered fruiting and flowering phenology, affecting herbivore and ultimately carnivore populations (Johns, 1991; Johns, 1992; Thiollay, 1992; Hill *et al*., 1995). The dynamics of canopy gap opening and closure also bear closely on the changing fire dynamics of the Amazon basin (Nepstad *et al*., this issue). In sum, spatially extensive thinning and recovery of the forest canopy exerts a ripple effect crossing a wide range of ecological, physical and biogeochemical processes.

Clearly selective logging techniques have a major impact on initial canopy opening. CL methods resulted in consistently more ground damage and higher canopy gap fractions than did RIL. At times, the rate of canopy closure was faster in CL, but at other times, it was more rapid in RIL. As compared to CL, RIL harvests produced a consistent pattern of lower initial gap fraction among landscape strata and lower area-integrated gap fraction following 3 years of recovery. RIL methods have been established with the goal of increased sustainability of tropical forest resources (Healey *et al*., 2000; Sist, 2000; Pereira *et al*., 2002). This study provides detailed spatial and temporal information showing that RIL methods decrease ground and canopy damage without a decrease in harvest intensity.

Conclusions

Canopy gap fraction is a relatively simple, integrative measure of forest structure, providing information on canopy openness following selective logging. We used repeated gap fraction measurements to estimate rates of canopy closure and recovery following logging disturbance. We combined gap fraction measurements with field mapping of infrastructure to quantify spatial and temporal dynamics of forest canopy opening in ways that are otherwise inaccessible. We distributed our measurements and modeling across chronosequences of CL (high damage) and RIL (low damage) areas in tropical forest stands of eastern Pará, Brazil. Our study offers the following conclusions:

- Across a wide range of harvest areas (14–158 ha) and intensities (2.6–6.4 felled trees ha^{-1}), the majority of ground damage resulting from selective logging occurs as skid trails (4–12%). On an areal basis, log decks and roads are only a small contributor to the total ground damage ($<2\%$). Despite similar timber harvest intensities, CL results in significantly more ground damage than does RIL.
- Neither the number of log decks nor their individual or total area is well correlated with the number of trees removed or intensity of tree harvesting (trees ha^{-1}). The percentage area of skids is well correlated with ground area damaged per tree felled (m^2).
- In recently logged forest (0.5 years postharvest), canopy gap fractions are highest in log decks (0.58–0.99) and lowest in tree-fall areas (0.22–0.49 at the downed crown). However, due to the small surface area of log decks, their contribution to the total area-integrated forest gap fraction is minor. In contrast, the moderate gap fractions associated with tree falls are widely spread throughout the forest, resulting in a large contribution of these areas to the total stand-level canopy gap fraction.

- After 3.5 years of forest regrowth, canopy gaps in log decks, roads, skids and at downed tree crowns remain higher than in intact forest areas. For each of the logged-landscape strata, initial decreases in gap fraction during the first 1.5 years of forest regrowth diminish in subsequent years, as gap levels stabilize. Over a 3.5-year period following selective logging, canopy gap closure rates are higher in high-damage (CL) than in low-damage (RIL) areas.
- Canopy openings decrease in size with distance from each felled tree crown. In recently logged forest, the area initially affected by harvesting of each tree is at least 100 m in radius for CL and about 50 m for RIL. Throughout the 3.5-year period of forest recovery, tree-fall gap fractions remain higher in CL than in RIL treatments. On a per-tree basis during a 3-year recovery, the canopy gap area affected by each felled tree decreases from 100 to 40 m in CL, and from 50 to 10 m in RIL.

An accounting of the spatial distribution of landscape features and their respective canopy gap fractions is required to understand the dynamics of canopy damage in logged tropical forests. This study highlights both the substantial spatial variation in forest canopy gaps and the consistent temporal trends in canopy gap characteristics in years following timber harvest. The former issue of spatial complexity challenges regional carbon, climate and biogeochemical studies, and it calls for much improved remote sensing studies of selective logging, canopy opening and recovery (Asner *et al*., 2002). Locations of log decks alone will not provide an accurate assessment of the total area impacted by selective logging, nor will it be closely correlated to damage levels and canopy gap closure rates.

Quantitative information on the spatial and temporal characteristics of canopy gaps following selective timber harvests in the eastern Amazon are useful for studies of carbon cycling, mesoscale climate dynamics, local and regional biogeochemical process studies, forest management and wildlife research, and fire (e.g., Jonkers, 1987; Johns, 1991; Brouwer, 1996; McNabb *et al*., 1997; Cochrane *et al*., 1999; Houghton *et al*., 2000; Pereira *et al*., 2002; Nepstad *et al*., this issue). Additional spatially explicit, multi-temporal studies of forest canopy gaps are needed in other parts of the Amazon and for tropical forests worldwide, as this information remains scarce.

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