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Remote sensing of selective logging in Amazonia Assessing limitations based on detailed field observations, Landsat ETM+, and textural analysis

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Abstract

We combined a detailed field study of forest canopy damage with calibrated Landsat 7 Enhanced Thematic Mapper Plus (ETM+) reflectance data and texture analysis to assess the sensitivity of basic broadband optical remote sensing to selective logging in Amazonia. Our field study encompassed measurements of ground damage and canopy gap fractions along a chronosequence of postharvest regrowth of 0.5–3.5 years. We found that canopy damage and regrowth rates varied according to the logging method used, either conventional logging or reduced impact logging. Areas used to stage felled trees prior to transport, log decks, had the largest gap fractions immediately following cutting. Log decks were quickly colonized by early successional plant species, resulting in significant gap fraction decreases within 1.5 years after site abandonment. Although log decks were the most obvious damage areas on the ground and in satellite imagery, they accounted for only 1–2% of the total harvested area of the blocks studied. Other forest damage features such as tree-fall gaps, skid trails, and roads were difficult to recognize in Landsat reflectance data or through textural analysis. These landscape features could be only crudely resolved in the most intensively logged forests and within about 0.5 years following harvest. We found that forest damage within any of the landscape strata (decks, roads, skids, tree falls) could not be resolved with Landsat reflectance or texture data when the canopy gap fraction was $<50\%$. The basic Landsat ETM+ imagery lacks the resolution of forest structural features required for quantitative studies of logging damage. Landsat textural analyses may be useful for broad delineation of logged forests, but detailed ecological and biogeochemical studies will probably need to rely on other remote sensing approaches. Until spatial gradients of canopy damage and regrowth resulting from selective logging operations in tropical forests in the Amazon region are resolved, the impacts of this land use on a continental scale will remain poorly understood.

1. Introduction

Forests of the Brazilian Amazon are undergoing continual land-use expansion through cattle ranching, logging, agriculture, and urban development. The ecological and socioeconomic impacts of clear-cutting Amazon forests for cattle pasture have been widely recognized (e.g., Fearnside & Barbosa, 1998; Uhl & Kauffman, 1990). However, selective logging of forests has now become a dominant land use in the Brazilian Amazon. Estimates of the area logged annually approach 15,000 km^2 (Nepstad et al., 1999), similar to the annual area of clear cuts (Houghton et al., 2000).

In the Brazilian Amazon, selective logging removes timber in the range of volumes up to roughly 60 m^3 ha^{-1} or about 1–9 trees ha^{-1} (Barros & Uhl, 1995). Current logging practices result in high levels of collateral damage, as up to 27 trees can be killed for every tree harvested (Verissimo, Barreto, & Mattos, 1992). Log removal and collateral damage lead to a range of ecosystem effects including changes in the light regime and forest microclimate, soil erosion and compaction, disruption of nutrient

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cycling and possibly long-term changes in tree species composition (Jonkers, 1987; McNabb et al., 1997; Ter Steege et al., 1995). These changes can affect the recruitment of timber species and the diversity of forest fauna (Hill, Hamer, Lace, & Banham, 1995; Johns, 1991; Pinard, Howlett, & Davidson, 1996; Thiollay, 1992). Selective logging also increases the susceptibility of forests to fire through modification of the understory microclimate and supply of fuel (Cochrane et al., 1999; Holdsworth & Uhl, 1997; Nepstad et al., 1999; Uhl & Buschbacher, 1985).

Few studies (e.g., Nepstad et al., 1999) have quantified the extent of selective logging in the Brazilian Amazon. The vast area of the Amazon region and the limited infrastructure within it, as well as legal issues related to logging activities, make it difficult to track this particular form of land use on the ground or through inspection of government economic statistics. Fortunately, canopy damage is highly correlated with timber volume removed across a wide range of humid tropical forest environments (Pereira, Zweede, Asner, & Keller, 2001). Quantification of canopy damage using remote sensing could therefore provide a means to estimate both the amount of biomass harvested and the biomass remaining as debris following selective logging.

Although remote sensing could play an important role in quantifying forest canopy damage resulting from selective logging in Amazonia, satellite analyses have not yet provided clear estimates of the extent or intensity of logging in the region, where intensity refers to the ground and canopy structural changes. One of the factors slowing the use of remote sensing approaches is that no detailed field studies of selective logging have been developed in the Brazilian Amazon for a systematic analysis of the biophysical sensitivity of remote sensing observations. We report on a field-based study to quantify the sensitivity of Landsat 7 Enhanced Thematic Mapper Plus (ETM+) data to the extent and intensity of selective logging and to the canopy closure that occurs in the years following logging operations. We use an intensive field survey of ground and canopy damage among logging areas with low and high levels of damage to evaluate the accuracy of the two most common methods for locating selectively logged sites with multispectral satellite data — simple band reflectance analysis and image texture analysis.

2. Methods

2.1. Site description

This study was conducted at the Fazenda Cauaxi in the Paragominas Municipality of Para State, Brazil in the eastern Amazon. The climate at Fazenda Cauaxi is humid tropical with annual precipitation averaging 2200 mm (Costa & Foley, 1998). A dry season extends from July through November (generally < 50 mm/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, and the forest is classified as tropical dense moist forest (IBGE, 1988).

Selective logging is practiced throughout the region (Fig. 1). The Tropical Forest Foundation maintains a training center for demonstration of forest management and reduced-impact logging (RIL) techniques (S3 * 43.878′, W48 * 17.438′). 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

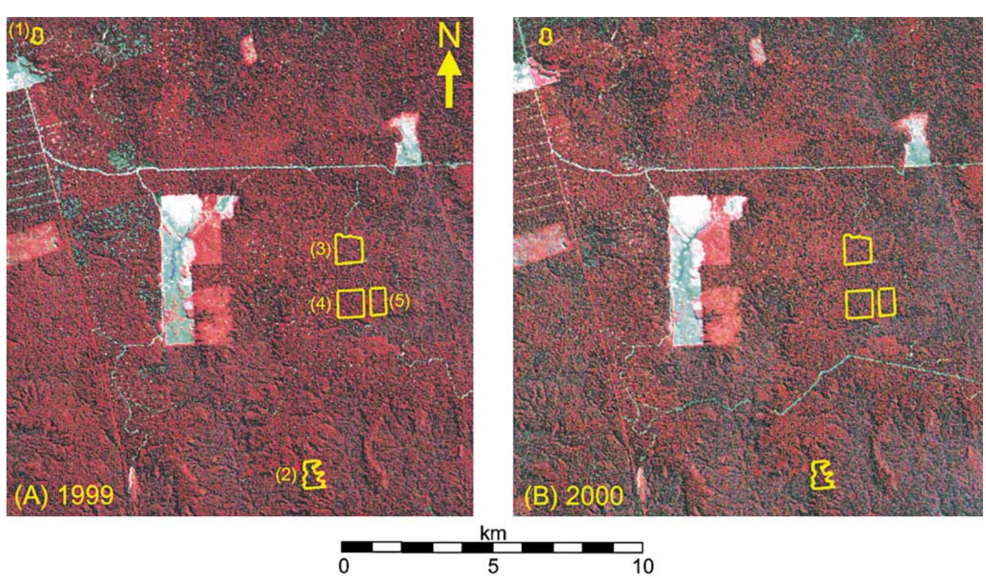

Fig. 1. Landsat 7 ETM+ imagery collected in 1999 and 2000 of the Fazenda Cauaxi area in the eastern Brazilian Amazon. Field, GIS and remote sensing analyses were carried out in the forest treatments: (1) 1998 CL, (2) 1998 RIL, (3) 1996 CL, (4) 1998 RIL, and (5) forest control.

land use or collection of nontimber forest products, although there are indicators of indigenous activity.

We studied both conventional logging (CL; high collateral damage) and RIL (low collateral damage) in order to observe a range of canopy damage intensity. Both CL and RIL practices in this region have been described previously (Johns, Barreto, & Uhl, 1996; Pereira et al., 2001; Verissimo et al., 1992). Briefly, in CL practices, woodsman marked harvest trees that were later felled by sawyers. The sawyers were, in turn, followed by operators who prepared roads and decks (log landings), skidded logs, and loaded logs onto trucks for transport. A crawler tractor without a winch 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 CL operations in the Brazilian Amazon region (Johns et al., 1996), and it plays a central role in determining ground damages resulting from selective logging operations.

In contrast to CL practices, RIL operations employed a preharvest methodology where blocks were surveyed and fully inventoried, roads were planned and built, and vines were cut from harvest trees about 1 year prior to harvest to minimize collateral damage during felling operations. Prior to harvest, crews marked trees and determined preferred felling directions. Trained sawyers felled trees using directional techniques. Skid trails were then planned and marked considering the direction of the felled trees and the structure of the residual forest. Logs were extracted using a wheeled skidder with a grapple and a winch (Caterpillar 525).

We studied four logged blocks and a natural forest area (50 ha) that had never been logged. One CL and one RIL block each were logged in 1996 and 1998. Both 1996 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. The RIL block for 1998 covered 57 ha and the CL block for 1998 covered about 14 ha.

2.2. Field studies

The two CL and two RIL blocks were inventoried and mapped prior to and following harvest operations. The number of trees felled and the total geometric volume skidded from the forest were recorded. Road, log deck, and skid lengths and areas were measured and mapped using fiberglass measuring tapes and compasses. 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 124 field GPS measurements. The GIS contained spatially explicit locations and areas of all roads, skids, log decks, and felled trees for each block (Fig. 2).

Field surveys of canopy damage were conducted in March 1999 and July 2000. This was approximately 0.5

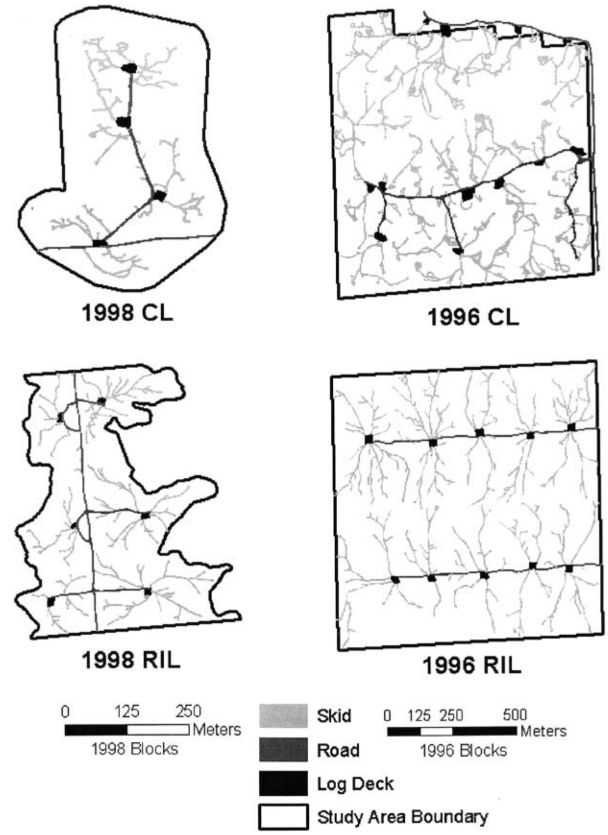

Fig. 2. Geographic information system coverages of 1996 and 1998 CL and RIL treatments. Skids, roads, and log decks were surveyed in the field, mapped to paper and digitized using DGPS ground control points.

and 1.5 years following logging in the 1998 blocks, and 2.5 and 3.5 years following logging in the 1996 blocks. Our surveys provided a means to construct logging chronosequences in both CL (high collateral damage) and RIL (low collateral damage) timber operations.

Canopy gap fraction was used as the primary indicator of forest canopy damage. 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). We measured canopy gap fraction using an optical plant canopy analyzer (LAI-2000, Licor) at 1.5 m above the ground surface. 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 & Norman, 1991). LAI is a quantity derived from the gap fraction measurement and a model of leaf angle distribution. Gap fraction is a more meaningful and repeatable result from the LAI-2000 than is LAI under conditions of highly discontinuous, spatially structured canopy coverage in this study.

The gap fraction algorithm used in the instrument assumes a diffusely lit sky; thus we restricted our measurements to about 1 h after dawn and 1 h prior to dusk (low sun angle) or to times when there was a 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° to 74°, was excluded from all analyses in order 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 the transect 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. Radii that crossed back over the skid trail, log deck or road were excluded from random selection. Gap fraction measurements for undisturbed forests were acquired in the 50-ha control plot along randomly selected 500-m transects. In total, we collected canopy gap fraction measurements over 10,000 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 a GIS. Total gap fraction (F) was calculated as (Eq. (1)):

$$F = \sum (a_i f_i)/A \qquad (1)$$

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 is 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 (Eq. (2)):

$$f = k * 10^{bx} \qquad (2)$$

where parameters k and b were estimated by least-squares regression for each harvest block (Pereira et al., 2001). 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.

2.3. Landsat ETM+ data

Landsat ETM+ imagery (Path 223, Row 63) was acquired for the study region on July 13, 1999 and July 31, 2000. These dates correspond to the beginning of the dry season, at which time the probability of a clear acquisition was maximal (Asner, 2001). The 1999 image provided a means to assess canopy damage at two time steps (0.5 and 2.5 years) following logging in both CL and RIL operations. The 2000 image allowed for an analysis of two additional time steps (1.5 and 3.5 years) after harvest.

The ETM+ data were calibrated to top-of-atmosphere radiance using the published channel response coefficients and the known solar zenith angles at the time of acquisition (44° and 45° for 1999 and 2000 images, respectively). The 2000 image was further corrected to apparent surface reflectance using three $\sim 100 \times 100$ m bare soil clearings and a ~ 500 m wide artificial lake in the region. A full-range (400–2500 nm) field spectroradiometer (ASD FR-Pro, Analytical Spectral Devices, Boulder, CO) was used to quantify the reflectance properties of the calibration targets within 2 days of the 2000 Landsat overpass. The spectra ($n = 550$ per soil site, $n = 750$ for the lake site) were collected at nadir from 1 m above the surface under clear sky conditions within 1 h of solar noon. The spectra were convolved to ETM+ optical channels, and then used to convert the 2000 imagery to surface reflectance via the empirical line calibration method (e.g., Banin, Ben-dor, & Kruse, 1994). The 1999 ETM+ were calibrated to the corrected 2000 ETM+ image using a temporally invariant surface target from a 150×150 m bare soil area (documented during 1999 and 2000 field campaigns). Both ETM+ images were geo-located with the GIS coverages (Fig. 2) using a regionally extensive and locally intensive GPS sampling scheme ($n = 124$ ground control points). Locational accuracies ranged from 3 to 15 m in the subsequent GIS and image analyses.

An image texture analysis was used to detect lateral variation in forest structure as imaged in the ETM+ data. Texture analysis is a common method for delineating surface features that cause localized variations in pixel brightness. A texture filter is passed over the image, and local variance in pixel brightness is computed according to Anys, Bannari, He, and Morin (1994). After testing filter sizes ranging from 3×3 to 15×15 pixels, we selected 3×3 for the study because larger filters lost sensitivity to highly localized surface features such as logging decks and small clearings.

In this study, we chose not to focus on Bands 1–2 because of their high susceptibility to aerosol contamination (Krueger & Fischer, 1994) and because they were often highly correlated with Band 3 (data not shown). Band 3 (red; centered at 0.67 μm) was thus used to represent the visible spectrum where vegetation is extremely dark due to strong radiation absorption by foliar chlorophyll. Soils and surface litter (including logging slash) are somewhat brighter than vegetation in Band 3 (Richardson & Wiegand, 1990). Band 4 (near-IR centered at 0.83 μm) was selected because vegetation is bright due to multiscattering of photons by foliage, while soils and litter are much darker (Asner, 1998). Band 5 (shortwave-IR centered at 1.65 μm) was analyzed because vegetation is moderately dark while soils and litter are very bright. Band 7 (shortwave-IR centered at 2.22 μm) was also selected because vegetation is extremely dark at these wavelengths while soils and litter are extremely bright. Theoretically, Band 7 reflectance should show the strongest contrast between forest canopy and gaps (soils, litter), but the signal-to-noise of this band is typically poor due to low solar irradiance in the 2.0–2.5-μm spectral region. Hence, Bands 3–5 and 7 represent differences in the biogeophysics of spectral variability as well as solar irradiance and signal strength.

Both the calibrated reflectances and calculated texture results in each ETM+ optical channel were compared against the GIS coverages of the logging blocks. This provided a means to isolate the log decks, roads, skids, and harvested tree areas in the images. Primary forest areas have natural intercrown shadowing and treefall gaps that give rise to background reflectance and textural values. We used the 50 ha forest control plot to evaluate these background values in the ETM+ imagery (Fig. 1).

3. Results and discussion

3.1. Initial ground damage

The volume of roundwood harvested from CL and RIL blocks harvested in 1996 was nearly identical (~ 23 m^3 ha^{-1}) (Table 1). No measurements of timber volume were available for the 1998 blocks, but we assume that a roughly similar volume was extracted from the 1998 RIL site. This assumption is supported by the number of individual trees extracted per hectare from the RIL treatments (3 trees ha^{-1} in 1996 RIL vs. 3.5 trees ha^{-1} in 1998 RIL). However, the intensity of logging was different between the two CL blocks. The total number of trees felled from the 1996 and 1998 conventional treatments was 415 and 88, respectively. On an area basis, the number of trees felled was 3.7 and 6.3 individuals ha^{-1}, respectively, for the two CL blocks.

Both CL and RIL logging practices affected substantial ground areas in the study blocks (Table 1). For RIL (low collateral damage logging) treatments, the proportion of ground area affected was 4.8% and 4.6% for 1996 and 1998 harvests, respectively. Among CL (high collateral damage logging) treatments, the area harvested in 1998 suffered more ground damage than the 1996 harvest area. The high density of large decks and the irregular path of the roads accounted for the higher proportion of damage in the 1998 CL block (Fig. 2). As a proportion of total area, CL practice caused about twice the ground damage as RIL practice. The distinction was particularly marked in the area of skid trails; CL harvests had more than 200% greater skid area than RIL harvests (Table 1).

3.2. Canopy damage and closure

Both CL and RIL harvest treatments produced notable canopy damage. In the undisturbed forest control plot delineated in Fig. 1, we measured a mean (± S.E.) canopy gap fraction of 3.1% (± 0.2%) in 1999 for a total sample size of 454 points spread throughout 50 ha. Repeated gap fraction measurements in 2000 yielded values of 2.6% (± 0.3%) for the forest control area. Regardless of treatment and sampling stratum (log deck, road, skid, tree fall), all of the logging areas had a greater canopy gap fraction than the forest control in both 1999 and 2000 (Table 2).

Within each sampling stratum, the 1996 treatments had lower gap fractions than the 1998 treatments because of forest regrowth. The major exception was in the 1996 log decks visited in 1999 for gap fraction measurements. At that time, the 1996 log decks in both the CL and RIL blocks had been partially cleared as a result of local training activities, leaving them unusually low in vegetation cover for 3.5-year-old postharvest treatments. Because of repeated entries by trainees and their vehicles, the log decks from the 1996 harvests should not be construed as representative of 3.5-year-old logged areas. It is notable that the gap fraction variance in these log decks increased from 1999 to 2000, indicating the spatial variability of the regrowth, which typically emanates from the forest edge into the deck area. This was observed for the 1998 CL and RIL log decks when measured in 1999 and 2000 (Table 2).

On roads and skid trails, gap fraction values were greatest at points near to log decks (data not shown). Otherwise, there were no clear spatial trends for the gap fraction along roads and skid trails. Repeated measurements in 1999 and 2000 indicated canopy closure on roads and skids among all treatment blocks (Table 2). Canopy closure occurs rapidly at first and slows as plots approach background forest canopy cover. In areas containing felled trees, the gap fraction dropped exponentially with the radial distance from the center of the downed tree crown (Pereira et al., 2001). Integrating over a 100 m radius circular area

Table 1
Ground disturbance expressed as a percentage of total area for four harvest blocks contrasting CL and RIL treatments in two different years

Year	Treatment	Area (ha)	# trees (felled)	Felled (trees/ha)	Volume (m^3)	Road area (%)	Deck area (%)	Skid area (%)	% distributed
1996	CL	112	415	3.7	2609	1.2	0.9	6.8	8.9
1996	RIL	108	325	3.0	2507	0.6	0.6	3.6	4.8
1998	CL	13.8	88	6.4	ND	2.0	1.9	7.3	11.2
1998	RIL	57.1	200	3.5	ND	1.0	0.7	2.9	4.6

The proportion of total ground disturbance [=(log deck + skid + road)/total] is reported in the column.

ND = not determined.

Table 2
Mean (S.E.) canopy gap fraction for four sampling strata in CL and RIL treatments measured in 1999 and 2000

		Deck		Road		Skid		Tree fall	
Harvest year	Treatment	1999	2000	1999	2000	1999	2000	1999	2000
1996	CL	0.97 (0.02)	0.78 (0.09)	0.50 (0.07)	0.43 (0.03)	0.44 (0.08)	0.12 (0.05)	0.20 (0.03)	0.11 (0.04)
1996	RIL	0.96 (0.03)	0.42 (0.16)	0.39 (0.06)	0.29 (0.05)	0.21 (0.06)	0.09 (0.03)	0.07 (0.02)	0.04 (0.02)
1998	CL	0.99 (0.01)	0.73 (0.11)	0.72 (0.12)	0.52 (0.16)	0.51 (0.13)	0.11 (0.06)	0.29 (0.10)	0.14 (0.04)
1998	RIL	0.97 (0.02)	0.46 (0.07)	0.36 (0.05)	0.22 (0.09)	0.27 (0.07)	0.11 (0.03)	0.13 (0.05)	0.07 (0.03)

surrounding each felled tree, canopy gap fraction ranged from 4% to 29% in the immediate tree-fall areas, depending upon logging management (CL, RIL) and regrowth time (0.5 and 2.5 years) (Table 2).

3.3. Area-integrated damage and recovery

We modeled the landscape-scale canopy gap fraction in the four logged areas by combining our field data with the actual locations of all roads, skids, log decks and tree falls as mapped and digitized in the GIS (Fig. 3). By substituting space for time among treatments, we can visualize the process of forest canopy damage and closure following selective logging events in both CL and RIL management scenarios.

Area-integrated gap fraction was largest in the 1998 CL block (21.6%) in 1999 and smallest in the 1996 RIL block (3.4%) in 2000 (Table 3). Both the intensity of canopy disturbance (Table 2) and the extent of ground disturbance (Table 1) contributed to the integrated canopy gap fraction. Although the log decks had the largest gap fraction (Table 2), their overall area was very small (Table 1), resulting in area-integrated gap fractions of only 0.3–1.1% across the entire study.

The tree-fall areas within each logging block accounted for the largest portion of the total integrated gap fraction

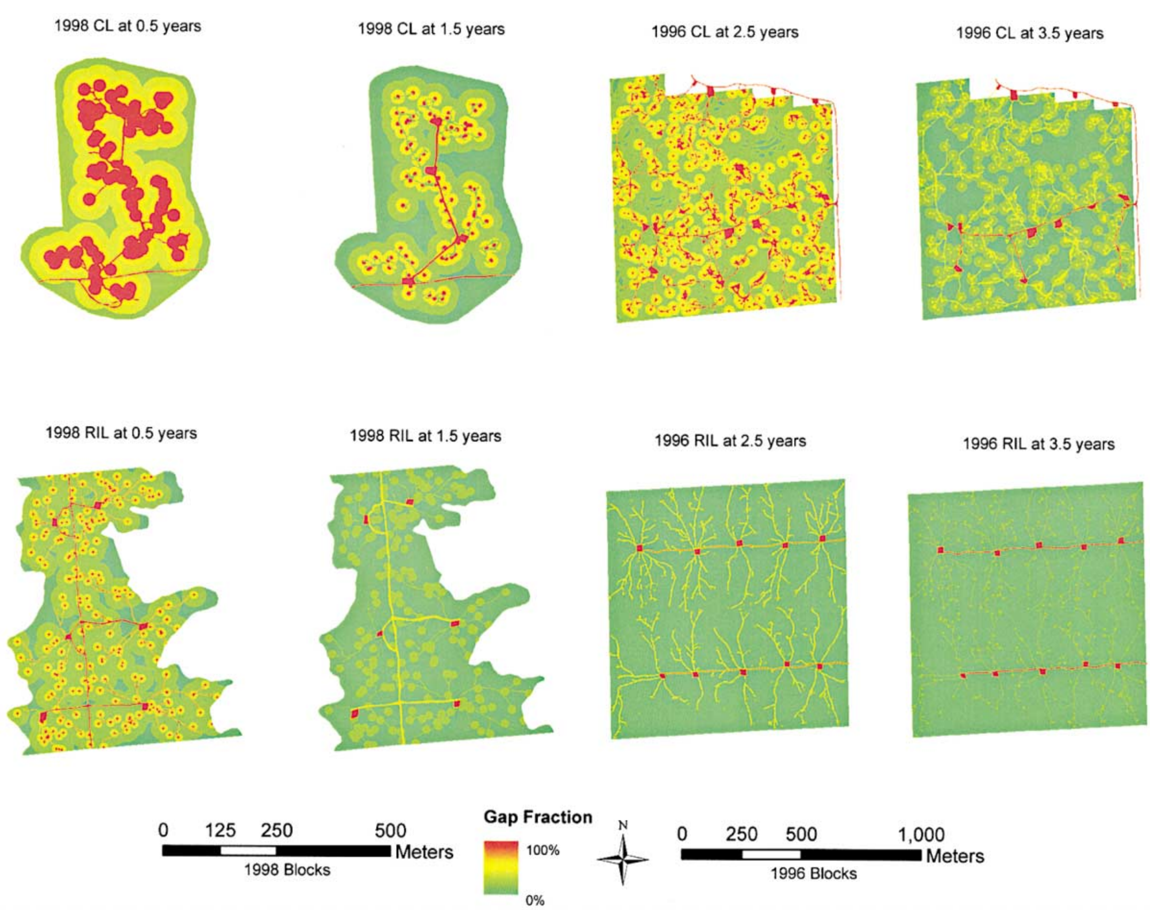

Fig. 3. Area-integrated forest canopy gap fraction for 1996/1998 CL and RIL treatments. Gap fractions are based on field measurements collected in 1999 and 2000. GIS coverages in Fig. 2 were combined with ground and canopy damage surveys (Tables 1 and 2) to estimate the spatial patterning of forest canopy gap fraction following logging and during regrowth.

Table 3
Percentage (%) of forest canopy gap fraction in 1999 and 2000 for CL and RIL treatments

		Total		Deck		Road		Skid		Tree fall	
Harvest year	Treatment	1999	2000	1999	2000	1999	2000	1999	2000	1999	2000
1996	CL	16.4	8.6	1.1	0.5	0.8	0.7	2.5	0.5	11.2	6.4
1996	RIL	4.9	3.4	0.6	0.3	0.5	0.2	0.8	0.3	3.3	2.3
1998	CL	21.6	11.8	1.0	0.7	1.2	0.9	3.4	0.9	16.9	9.7
1998	RIL	11.0	5.9	0.7	0.3	0.6	0.4	1.0	0.5	8.7	4.7

Integrated gap percentages were calculated using the GIS analysis.

(Fig. 3). In 1999, the CL treatments had two to three times higher canopy gap fraction from felled trees as did the analogous RIL treatments (Table 3). By 2000, the area-integrated gap fraction from tree falls had decreased by 30–45%, yet the CL areas continued to maintain higher absolute gap percentages than the RIL blocks.

Skid trails had modest gap fractions (Table 2) but significant spatial extent (Table 1), at times resulting in a substantial contribution to the area-integrated gap fraction of each treatment. The 1998 CL block had the largest skid-area gap fraction of 3.4% in 1999, which decreased to 0.5% by 2000 (Table 3). The 1996 RIL block had a skid-area gap content of about 0.8% in 1999 but only 0.3% by 2000. Skid-area canopy gaps in the 1998 CL and RIL blocks underwent analogous decreases from 1999 to 2000. Road areas had smaller area-integrated gaps and slower rates of closure in comparison to skids and tree-fall areas (Table 3).

Combining the ground damage surveys (Table 1) with the gap fraction measurements (Table 2) in the GIS, we draw the following conclusions that are pertinent to the problem of selective logging remote sensing. First, log decks have very small spatial extent relative to the total harvested area (0.5–2.0%), but the large gap fraction of the decks immediately following timber removal makes them useful targets for general delineation of forest areas that may subjected to selective logging (Stone & Lefebvre,1998). However, fast recolonization of log decks by vegetation increases the foliage density (lowering gap fraction) just one year after harvest. Second, tree-fall areas have the lowest gap fractions, but they are by far the most spatially extensive and variable form of canopy damage. In contrast to log decks, tree falls represent a diffusely distributed form of canopy damage, yet this damage is closely related to the volume and biomass of felled trees removed (Pereira et al., 2001). Third, roads and skid trails have spatial extents that fall between those of decks and tree-fall areas. Detection of the most obvious canopy openings, log decks, may be sufficient to identify general areas that have been logged but will not provide a measure of logging damage. Most of the damage related to biomass loss and the ability to recover biomass and ecosystem functions is concentrated in the tree-fall gaps.

3.4. Basic ETM+ observations of logging treatments

Using the field survey and GIS data, we show the first qualitative band-by-band analysis of selective logging in Amazonia using Landsat data (Figs. 4 and 5). Although basic, we assert that this first-time visual analysis of the ETM+ data relative to our GIS-based canopy damage calculations is valuable. This analysis is pertinent to ongoing research efforts in the Amazon region that will attempt to delineate selectively logged areas using visual inspection of mosaicked Landsat data (T. Krug, INPE-Brazil, personal communication). The presentation of image reflectance results is affected by the contrast stretch applied to the data; we interactively stretched each image to maximize the visibility of roads and logging decks since they are the most pronounced features on the landscape. Remote sensing analyses of selective logging may not have this option when conducted over very large spatial scales (e.g., $\sim$229 Landsat scenes for the Amazon basin).

Fig. 4 shows the 1998 CL and RIL treatments in ETM+ Bands 3–5 and 7. Among the 1998 CL and RIL treatments in both the 1999 and 2000 ETM+ imagery, there was not clear visual delineation of skid or tree-fall areas. Very heavy road damage could be seen in the 1999 and 2000 ETM+ data of the 1998 CL block. It was not possible to view roads in the 1998 RIL block in either image. Comparing these observations with road gap fractions in Table 2, we suggest a threshold of about 50% canopy gap fraction for road delineation using visual interpretation.

Logging decks could be roughly delineated in recently harvested areas, such as the 1998 CL and RIL blocks as observed in the 1999 ETM+ imagery (Fig. 4a,c). Comparing the satellite imagery in these blocks to the GIS coverages of ground infrastructure (Fig. 2) and gap fraction (Fig. 3), it appears that Bands 3, 5, and 7 were useful for visual selection of log decks in the 1998 CL and RIL blocks (Fig. 4a,c). By 2000, the log decks could not be visually selected in Band 3 in the CL blocks, but Bands 4 and 5 were useful at that time (Fig. 4b). This may indicate that visible wavelength channels are most valuable for locating log decks immediately after cutting, while longer wavelengths are more useful for aging postharvest areas. Interestingly, the log decks were not visually obvious in the 1998 RIL treatment 1.5 years following harvest (Fig. 4d), when canopy gap fraction in log decks was about 42%. Like the road analysis above, the cutoff for visual delineation of log decks thus appeared to be about 50% canopy gap fraction (see Table 2).

A precise biophysical reason for these band-dependent differences over time is difficult to determine. It is likely that the visible spectrum is useful for log-deck detection

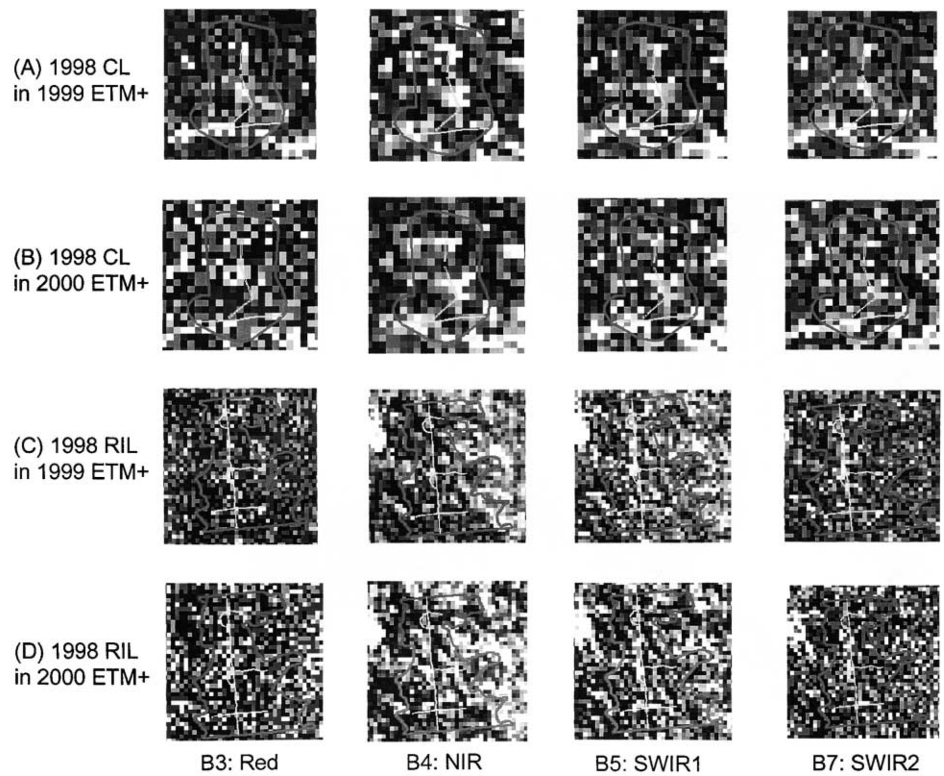

Fig. 4. Landsat ETM+ reflectance observations of 1998 logging treatments. Rows of images represent: (A) CL in 1999, (B) CL in 2000, (C) RIL in 1999, (D) RIL in 2000. Columns are for ETM+ Bands 3 (red), 4 (NIR), 5 (SWIR1), and 7 (SWIR2).

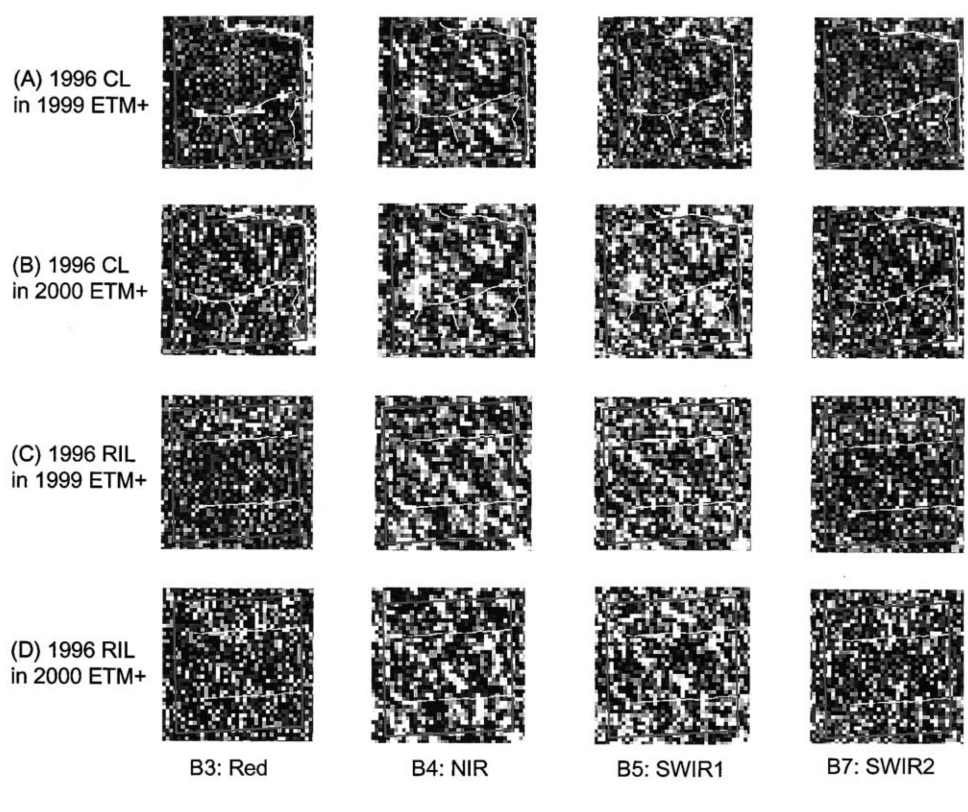

Fig. 5. Landsat ETM+ reflectance observations of 1996 logging treatments. Rows of images represent: (A) CL in 1999, (B) CL in 2000, (C) RIL in 1999, (D) RIL in 2000. Columns are for ETM+ Bands 3 (red), 4 (NIR), 5 (SWIR1), and 7 (SWIR2).

immediately after harvest because freshly bare soil is moderately bright while the surrounding forest vegetation remains extremely dark. However, as vegetation regrowth occurs in the log decks (more than 0.5 years following clearing), the visible spectrum becomes much less useful due to strong radiation absorption by chlorophyll. At this point, the near-IR and SWIR bands may show the greatest contrast between soils-litter and green vegetation because of the strong multiple scattering of photons that better carry underlying soil-litter spectral features through the early regrowth to the overhead sensor. We are currently evaluating this hypothesis using three-dimensional radiative transfer modeling techniques (Asner, Keller, & Silva, in prep).

As we found for the 1998 logging blocks, it was not possible to delineate tree-fall areas or skids in the 1996 CL and RIL blocks, representing 2.5 and 3.5 years of regrowth following selective logging (Fig. 5). In addition, no logging roads could be visually located within the treatment blocks. The gap fractions of the roads were less than 50% in all of these observations (Table 2), which again corresponds to the estimated cut-off value for gap closure.

The log decks could be seen in the 1996 CL treatment with the 1999 ETM+ observations (Fig. 5a), but as discussed, these decks were partially re-cleared prior to imaging because of visits by training courses. However, analysis of these log decks provides information on the potential for locating large forest gaps within dense forest vegetation. Band 3 was again the most useful for locating fresh bare soil areas within closed-canopy forest. Band 4 was the least useful, which is not surprising since near-IR radiation undergoes intense scattering among dense forest vegetation. Multiple scattering sharply decreases the contrast between surface features and causes a more random variation in the reflectance images of the logging blocks. Surprisingly, the log decks within the 1996 CL treatments could best be located using Bands 5 and 7 (Fig. 5a,b). The satellite observations represent about 0.5 and 1.5 years of vegetation growth following re-clearing of the log decks in 1998. These log decks had gap fractions of 97% and 78% in 1999 and 2000, respectively (Table 2), which was well above the estimated 50% cut-off for canopy gap fraction. Although difficult to see in Fig. 5, log decks within the 1996 RIL treatments were also visible in Bands 3 and 5 using the 1999 ETM+ data (gap fraction of 96%), but disappeared by 2000 when gap fractions averaged 42% (Table 2).

The above qualitative interpretations of logging infrastructure (decks and roads) using Landsat observations have limited utility since it is canopy disturbance (observed as increased gap fraction) that will best indicate logging extent and intensity in Amazon tropical forests (Pereira et al., 2001). We plotted mean gap fraction for each stratum (Table 2) against Landsat ETM+ Bands 3, 4, and 5 reflectances from the 1999 and 2000 observations (Fig. 6). We found a significant correlation only among the strata in the 1998 CL and RIL treatments as observed 0.5 years following harvest (Fig. 6a–c, closed symbols). The 1999 Landsat observations in Bands 3 and 5 could account for 53% and 55% of the variance, respectively, in gap fraction shortly after cutting. The relationship to gap fraction in both channels was severely weakened by 2000, or 1.5 years following harvest (Fig. 6e–g, closed symbols). The 2.5- and 3.5-year-old postharvest strata (1996 treatments in 1999 and 2000 ETM+) showed no relation to gap fraction in any wavelength channel (Fig. 6a–g).

3.5. Textural analysis of logging treatments

In comparison to the visual analyses described above, the 3×3 pixel textural filtering provided increased sensitivity to a broader range of canopy damage. The texture analysis results for 1998 and 1996 logging treatments are shown in Figs. 7 and 8, respectively. Textural filters are sensitive to local variation in brightness caused by changes in biophysical properties of the forest canopy, including shadowing. In these selectively logged forests, local brightness variations should be maximal in areas where canopy openings expose materials of significantly different brightness than the adjacent dark intact forest.

As discussed, forest canopy damage was by far greatest in the 1998 CL block (Tables 1 and 3). This high-damage logging resulted in clear textural indicators as shown in Fig. 7. The main roads and log decks were obvious in all 1999 Landsat observations of the 1998 CL block. By 2000, the 1998 CL blocks showed no textural sensitivity in Band 3, except for the major road crossing the south edge of the treatment. This dramatic decrease in sensitivity from 0.5 to 1.5 years following harvest is analogous to the results presented in Fig. 4 for the calibrated reflectance data. Therefore, visible wavelength channels, such a Band 3, may be most useful for isolating freshly harvested forests. In this way, the quick decrease in Band 3 sensitivity from 0.5 to 1.5 years following logging may help track the most recent logging damage with less confusion from previous years of harvesting. This is an essential element in any effort to track gross rates of forest area impacted by selecting logging in the Amazon.

In contrast to Band 3, the near-IR Band 4 and both shortwave-IR bands (5 and 7) provided strong texture sensitivity of the 1998 CL blocks in both 1999 and 2000 (Fig. 7a,b). Bands 5 and 7 showed the logged decks and roads more clearly than did Band 4 in the satellite observations of 1998 CL. This likely occurred because vegetation is very dark in the shortwave-IR, which impedes the transmittance of upwelling photons that have interacted with brighter materials, such as bare soil and slash, underlying the closing forest canopy. Thus, the significant reflectance contrast between soils/slash (bright) and foliage (dark) in the shortwave-IR results in a clearer delineation of gaps (decks, roads) and closed-canopy forest. In contrast, vegetation, soils and slash are all very bright in the near-IR (Band 4), which increases multiple scattering of photons and decreases the clarity of the observations of forest gaps.

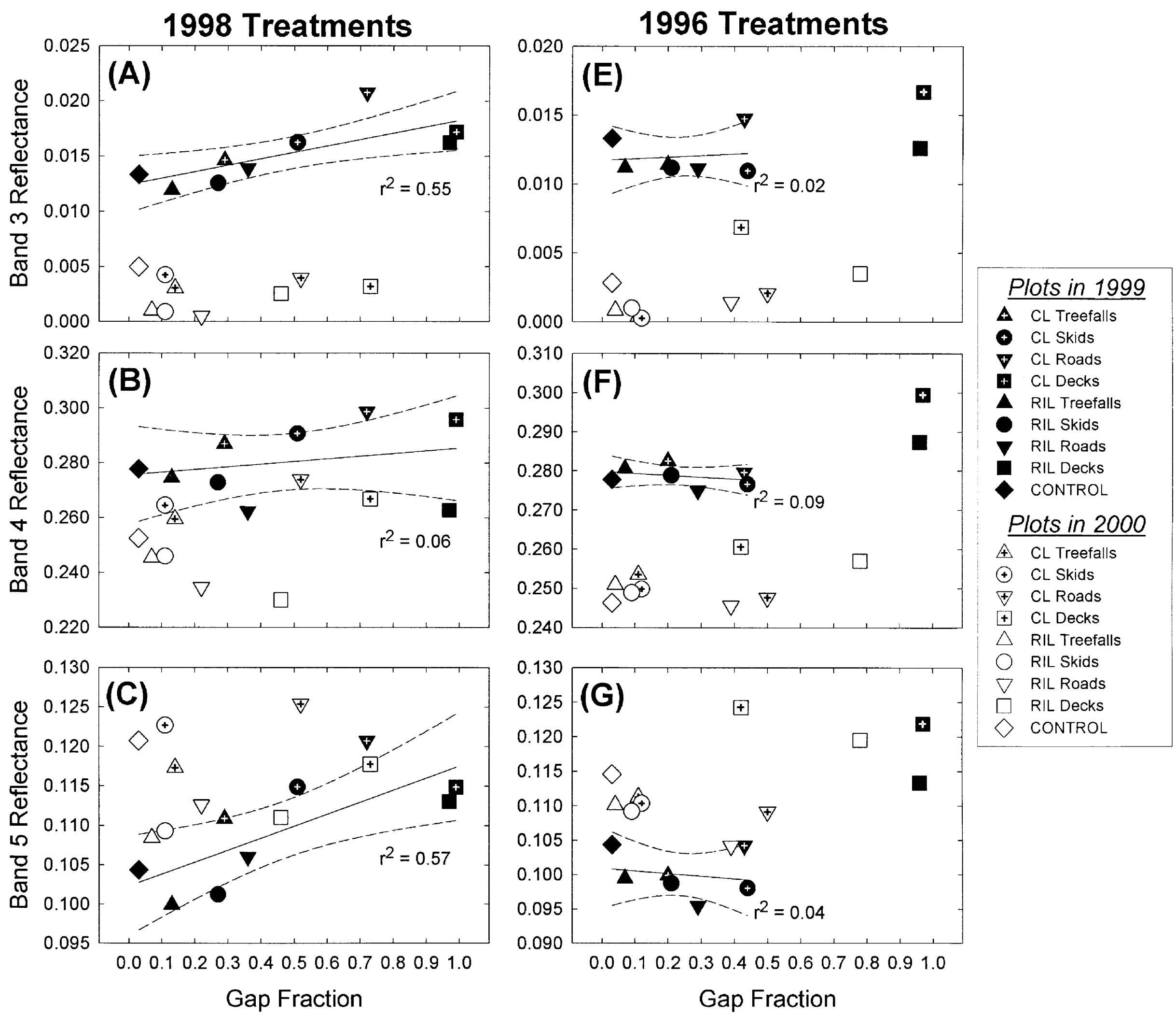

Fig. 6. Mean gap fraction of landscape strata versus Landsat ETM+ reflectance values. Open and closed symbols are for 1999 and 2000 measurements, respectively. For the 1998 CL and RIL treatments: (A) Band 3, (B) Band 4, and (C) Band 5. For the 1996 CL and RIL treatments: (D) Band 3, (E) Band 4, and (F) Band 5.

The texture analysis of the 1998 RIL treatments showed some patterns similar to those for the 1998 CL blocks but certain distinct differences as well (Fig. 7c,d). Similar to the 1998 CL blocks, the 1998 RIL roads and log decks were distinguishable in 1999 (0.5 years postharvest) using Band 3 but were not so in 2000 (1.5 years postharvest). In addition, texture with the shortwave-IR Bands 5 and 7 was sensitive to roads, log decks and skid trails in the 1999 and 2000 Landsat imagery. In contrast to 1998 CL, the texture analysis with near-IR Band 4 did not improve the discrimination of most features, including many log decks, in either the 1999 or 2000 observations. It therefore appears that only very heavily damaged logging areas (such as the 1998 CL) can be readily analyzed using a broadband near-IR channel. Texture analysis using the visible (e.g., Band 3) spectral range is useful for observing canopy damage only immediately following both low (RIL) and high (CL) intensity logging. The shortwave-IR (Bands 5 and 7) were the most useful for observing canopy damage from roads and log decks up to 1.5 years following harvest.

The conclusions drawn from the 1998 treatments (Fig. 7) are further supported in the texture analyses of the 1996 logging blocks (Fig. 8). These blocks were imaged 2.5 and 3.5 years following harvest, and no canopy damage from tree falls, roads or skid trails could be detected using texture analysis in any wavelength channel. The exception was for the log decks in the 1996 CL treatment, as these decks had been re-cleared in 1998. As for the 1998 blocks, the texture analysis was able to accentuate the log decks 0.5 years following re-clearing in the 1996 CL blocks (Fig. 8a) but less so at 1.5 years (Fig. 8b). Band 3 was useful for locating log decks and the main road (left side of image) in the 1999 Landsat observations (Fig. 8a) but not so in 2000 (Fig. 8b). We were unable to observe the 1996 CL log decks in either 1999 or 2000 observations using Band 4 (near-IR). However, the texture analysis with shortwave-IR Bands 5 and 7 could be used to delineate the 1996 CL log decks in both

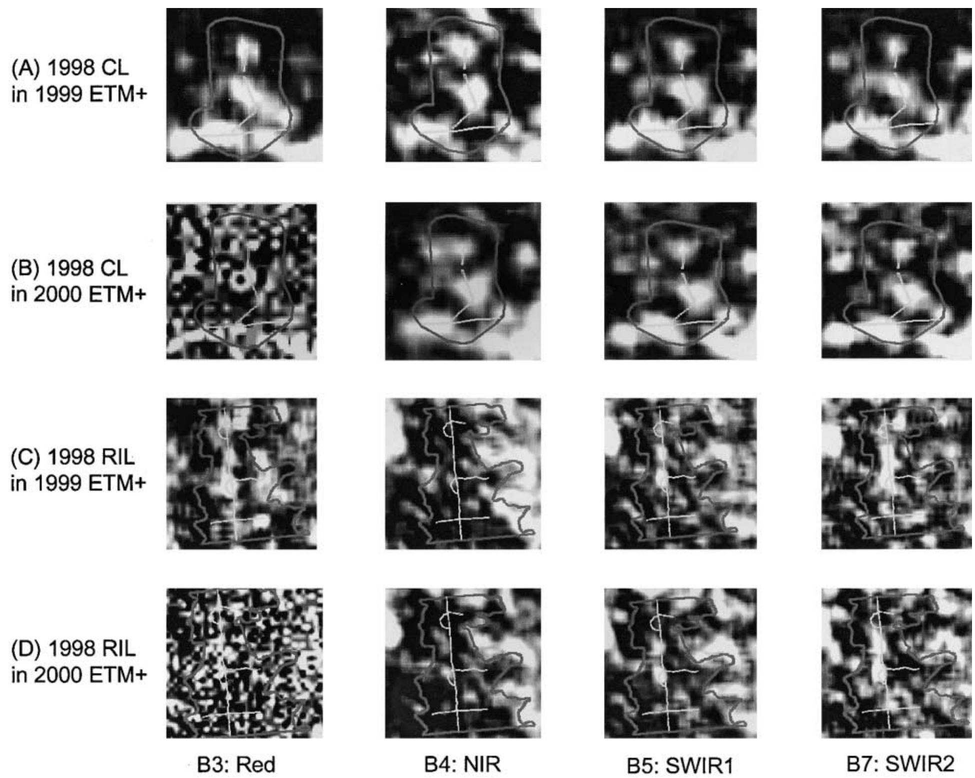

Fig. 7. Textural analysis of 1998 logging treatments. Rows of images represent: (A) 1998 CL in 1999, (B) CL in 2000, (C) RIL in 1999, (D) RIL in 2000. Columns are for ETM+ Bands 3 (red), 4 (NIR), 5 (SWIR1), and 7 (SWIR2).

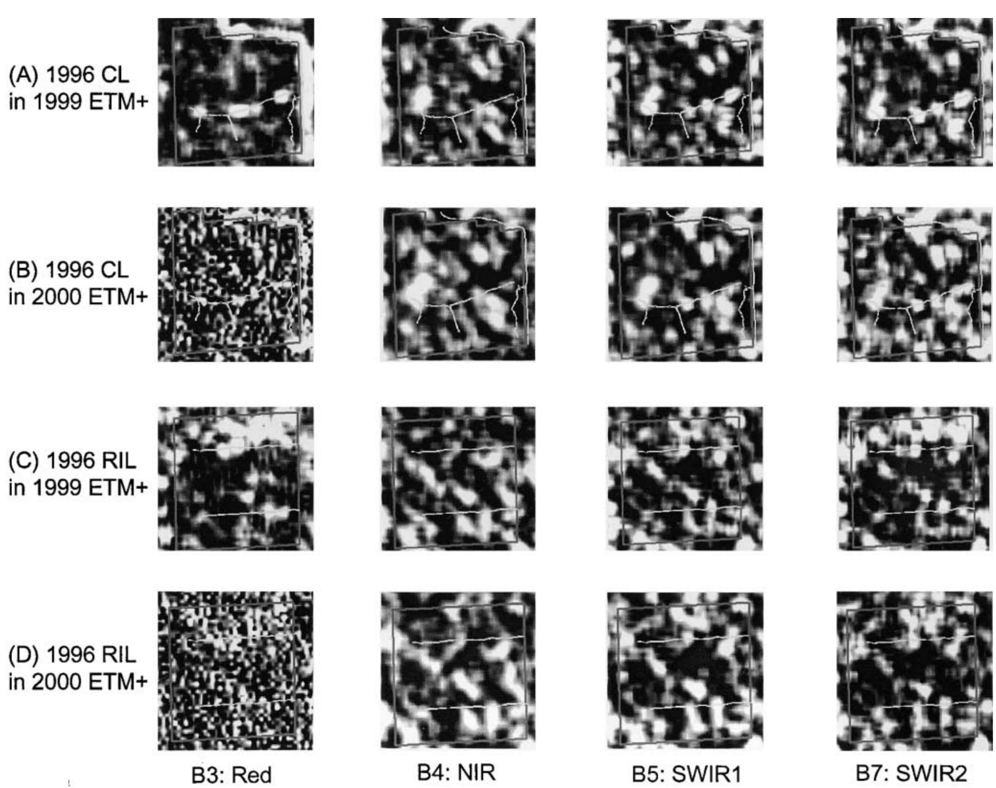

Fig. 8. Textural analysis of 1996 logging treatments. Rows of images represent: (A) CL in 1999, (B) CL in 2000, (C) RIL in 1999, (D) RIL in 2000. Columns are for ETM+ Bands 3 (red), 4 (NIR), 5 (SWIR1), and 7 (SWIR2).

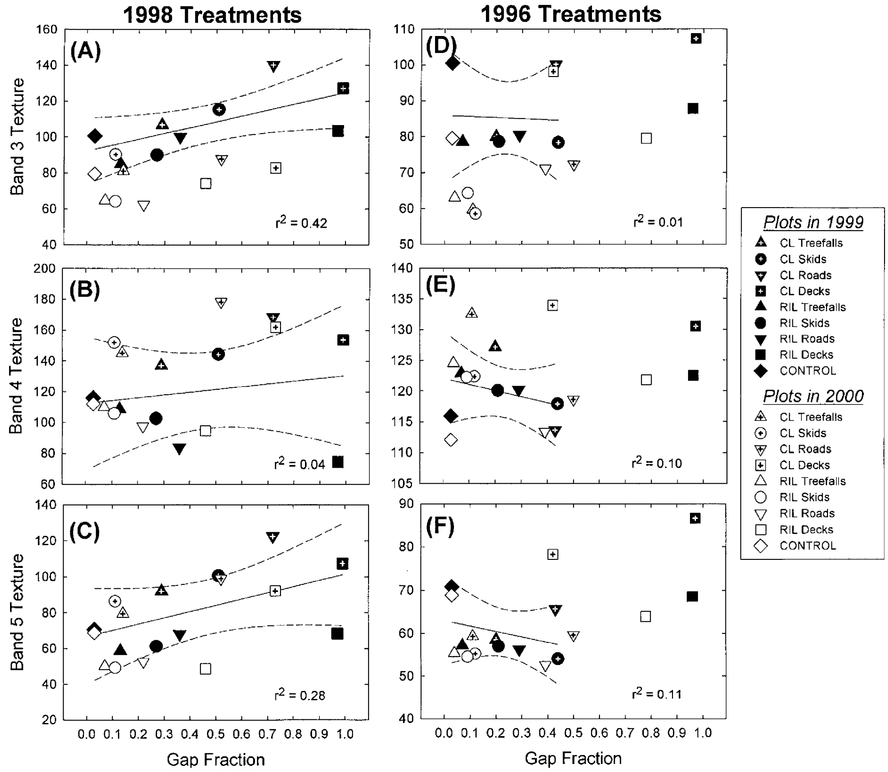

Fig. 9. Mean gap fraction of landscape strata versus textural analysis values. Open and closed symbols are for 1999 and 2000 measurements, respectively. For the 1998 CL and RIL treatments: (A) Band 3, (B) Band 4, and (C) Band 5. For the 1996 CL and RIL treatments: (D) Band 3, (E) Band 4, and (F) Band 5.

1999 and 2000 Landsat imagery. At most, a few log decks were possibly distinguishable in the 1996 RIL logging blocks using the shortwave-IR channels (Fig. 8c,d).

Plotting field-based gap fractions of roads, skids, log deck, and tree-fall areas (Table 2) against the Landsat texture data indicated the sensitivity of this method to a range of canopy damage values (Fig. 9). Similar to the reflectance data results (Fig. 6), the Channel 3 image texture analysis of the 1998 logging blocks was able to provide some information on the degree of canopy opening when observed 0.5 years after harvest (Fig. 9a; $r^2=.42$). It is important to note that the log decks in CL and RIL treatments and the CL roads were the dominant contributors to the correlation in Fig. 9a. Eliminating them from the regression resulted in r^2 values of only 0.14. This emphasizes that only the log decks and, at times, the roads can indicate canopy gap fractions associated with selective logging operations using multispectral reflectance data (Fig. 6a) or texture analysis of those data (Fig. 9a), even immediately following harvest.

By 2000 or 1.5 years postharvest, the texture filter lost sensitivity to all gap fractions under 50%, and the correlation for all strata weakened significantly (r^2=.11). Band 5 observations in 1999 had a somewhat weaker relationship with gap fractions among the 1998 logging blocks (r^2=.28), which also diminished to insignificant values by 2000 (Fig. 9c). The near-IR Band 4 could never consistently represent the range of canopy gap fractions resulting from logging activities in either year of observation (Fig. 9b).

Texture analyses of the 1996 logging treatments showed no sensitivity to the range of canopy gap fractions found among roads, skids trails or tree-fall areas (Fig. 9d–f). The log decks represented artificially high gap fractions for 2.5- and 3.5-year-old harvests due to re-clearing for other purposes. Therefore, we did not include the log decks in the regressions depicted in Fig. 9d–f.

4. Conclusions

Selective logging has become a dominant land use in the Brazilian Amazon. Today, the spatial extent of selective logging activities is thought to rival that of the forest clearing (Nepstad et al., 1999). While there are research efforts underway to locate and map selective logging in Amazonia using Landsat imagery, no studies up until now have quantified the sensitivity of multispectral observations to variations in canopy damage associated with harvest intensity or forest regrowth. The spatial variability of logging extent, pattern, and methodology create a complex mosaic of forest canopy openings. The heterogeneity of forest damage must be spatially and temporally resolved to understand the effects of selective logging on ecological and biogeochemical processes.

We combined a detailed field study of forest canopy damage with calibrated Landsat 7 ETM+ reflectance data and texture analysis to assess the sensitivity of broadband optical remote sensing to selective logging in Amazonia. Our field study encompassed measurements of ground damage and canopy gap fractions along a chronosequence of logging intensity and postharvest regrowth of 0.5–3.5 years. We found that canopy damage and regrowth rates varied by harvest method.

Within each harvest treatment, the log decks had the largest gap fractions immediately following cutting. These log decks were quickly colonized by pioneer plant species, resulting in significant gap fraction decreases just 1.5 years after site abandonment. Although log decks are the most obvious damage type on the ground and in satellite imagery, they accounted for only 1–2% of the total harvest area. Because most of the Amazon basin can only be imaged about one time per year (Asner, 2001), the fast regrowth and small area of log decks limits their use as a means to locate areas of selective logging over time. In addition, despite their accessibility from Landsat data, the presence of logging decks is not necessarily correlated with the degree of forest damage and volume of wood removed. Log decks were just as obvious in the Landsat imagery of our RIL sites as in the conventionally logged areas. Counting the number or area of decks per harvested area is not a strong indicator of logging damage intensity because of variations in forest structure, skid layout and felling methods. Moreover, much logging in Amazonia is illegal (Nepstad et al., 1999), and often log decks are not constructed in such clear patterns as they were in our study sites. In some operations, logs are loaded directly onto trucks with minimal deck construction. Frequently decks may be located only near main roads. Log decks along main roads may not be specifically identified as related to logging activity.

The specific areas of the forest containing tree-fall gaps, skid trails, and roads are usually difficult to resolve in calibrated Landsat reflectance data or texture analysis. At best, these landscape features can be only crudely resolved in the most intensively logged forests and immediately following harvest. Our 1998 conventionally logged forest contained an exceedingly large amount of canopy damage (Table 1), which is rarely matched by other logging operations in the eastern Amazon (e.g., Pereira et al., 2001; Verissimo et al., 1992) and worldwide (e.g., Jonkers, 1987). Only in this 1998 CL treatment could we argue that roads, skids and tree-falls gap may have been resolved using the basic reflectance data or texture analysis.

It is important to note that we were able to recognize these features in our bottom-up scaling analysis; that is, we knew what features to look for in the imagery. In regional, top-down monitoring efforts using Landsat, it would be very difficult to recognize all but the highest canopy damage classes. In general, we found that forest damage within any of the landscape strata (decks, roads, skids, tree falls) could not be resolved with basic Landsat reflectance or texture analysis when the forest gap fraction exceeded 50%.

Although the general forest regions undergoing timber harvest could be seen in the basic Landsat ETM+ imagery (Fig. 1), the basic reflectance data lack the structural resolution required for sufficiently quantitative studies and monitoring of logging activities in the Amazon. Landsat textural analysis may be useful for broad delineation of logged forests, as is needed for law enforcement activities in the Brazilian Amazon, but it is far from optimal for ecological, biogeochemical, and socioeconomic studies because the intensity of damage cannot be assessed. Until we can resolve the spatial gradients of canopy damage and regrowth that result from selective logging operations in tropical forests, the impacts of this land use will remain poorly understood. Potential approaches include very high spatial resolution observations (e.g., IKONOS) or spectral mixture analysis of multispectral or hyperspectral imagery.

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