Canopy Damage and Recovery Following Selective Logging in an Amazon Forest: Integrating Field and Satellite Studies

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Abstract

We combined a detailed field study of forest canopy gap fraction with spectral mixture analyses of Landsat 7 ETM+ satellite imagery to assess landscape and regional dynamics of canopy damage following selective logging in Amazonia. Our field studies encompassed measurements of ground damage and canopy gap fractions along multi-temporal sequences of post-harvest regrowth of 0.5-3.5 years. Areas used to stage harvested logs prior to transport, called log decks, had the largest forest gap fractions, but their contribution to the landscape-level gap dynamics was minor. Tree falls were spatially the most extensive form of canopy damage following selective logging, but the canopy gap fractions resulting from them were small. Reduced-impact logging consistently resulted in less damage to the forest canopy than did conventional logging practices. This was true at the level of individual landscape strata such as roads, skids and tree falls as well as at the area-integrated scale.

A probabilistic spectral mixture model, *AutoMCU*, was developed that utilizes bundles of the field spectral reflectance measurements with Monte Carlo analysis to estimate sub-pixel cover of forest canopies, exposed non-photosynthetic vegetation and soils in the Landsat ETM+ imagery. The method proved highly useful for quantifying forest canopy cover fraction in log decks, roads, skids and tree-fall areas. The information derived from this approach allowed tracking of forest canopy damage up to 3.5 y post-harvest. Forest canopy cover fraction data derived from the satellite observations were highly and inversely correlated with field-based canopy gap fraction. Subsequent regional-scale estimates of forest canopy gap fraction were derived from the combination of field- and satellite-based measurements. A preliminary 400 km^2 study of gap fraction showed that approximately one-half of the canopy opening caused by logging is closed within one year of regrowth following timber harvests. This is the first regional-scale study utilizing field measurements, satellite observations and models to quantify forest canopy damage and recovery following selective logging in the Amazon.

Keywords: Amazon basin, Brazil, canopy damage, gap fraction, selective logging, spectral mixture analysis, timber harvest

Introduction

The Amazon Basin contains the world's largest contiguous area of tropical forest. This area has been subject to continual deforestation and land-use expansion that is typical of tropical forests worldwide. Common land-use practices in the Brazilian Amazon include cattle ranching, logging, agriculture, mining, and urbanization. Conversion of forest to cattle pasture has received the most attention in ecological and geographical studies (e.g. Uhl and Kauffman 1990, Moran et al. 1994, Fearnside and Barbosa 1998). Recently, Nepstad et al. (1999) pointed out that selective logging has become a dominant land use in the Brazilian Amazon. According to this study, the total logged area in 1996-1997 (10,000-15,000 km^2) was nearly equal to the area of forest converted to pasture or agriculture. These rates of selective logging could have major implications for biogeochemical processes – including carbon sequestration – and for the long-term sustainability of forest productivity in the region.

Selective logging practices in the Brazilian Amazon result in high levels of collateral forest damage. Canopy opening on three logging plots in the Paragominas area of the eastern Amazon ranged from 25 to 45% of the total logged area (Verissimo et al. 1992). An average of 27 trees were damaged for each tree harvested. Logging can result is substantial carbon losses from tropical forests (Pinard and Putz 1996). Canopy opening and the concentration of logging debris may lead to greater flammability (Uhl and Kauffman 1990). In addition, timber harvesting leads to a variety of short-lived and long-lived effects including changes in the forest microclimate, erosion, soil compaction, and disruption of nutrient cycling (Ter Steege et al. 1995, Jonkers 1987, McNabb et al. 1997, Brouwer 1996). These changes can affect the recruitment of forest plant species and may lead to long-term changes in tree species composition and the diversity and abundance of forest fauna (Pinard et al. 1996, Hill et al. 1995, Thiollay 1992).

While the potential impacts of selective logging on ecological and biogeochemical processes in the Amazon are recognized, these impacts have not been well quantified at the regional level. Barriers to regional studies include natural spatial variability in forest structure and socio-economically driven variations in logging intensity and methods. It is difficult to track the diverse range of structural and functional effects of logging activities in the Amazon region without the use of remotely sensed data.

Detection and quantification of selective logging with remote sensing in the Amazon region is difficult because tree species diversity in the Brazilian Amazon is very high, and most species are locally rare. Logging is selective because markets accept only a few species for timber use. In areas far from markets, sometimes only a single species (e.g., mahogany) will be cut (Verissimo et al. 1995). In contrast, over 80 species are acceptable in other areas supplying lumber to the national Brazilian markets (Uhl et al. 1997). These dramatic differences in logging intensity result in concomitant variation of forest canopy disturbance and collateral damages caused by harvesting activities. Forest disturbance also varies even under the same market conditions for a given locale because of logging practices. The very best harvesting practices (often referred to as Reduced Impact Logging – RIL) adopted by a few large-scale commercial operations can diminish canopy damage by nearly half compared to conventional practices (Pereira et al. 2001).

To date, remote sensing has not provided clear estimates of the extent or intensity of selective logging operations in the Amazon basin, where intensity refers to the level of ground and canopy structural damage and subsequent biomass losses. Few studies have quantified the accuracy of remote sensing for tracking changes in canopy structure and gap fraction during regrowth following selective logging (Asner et al. *in press*). One of the primary factors slowing the use of quantitative remote sensing approaches is the lack of detailed and systematic multi-temporal observations of selectively logged sites with quantification of conditions on the ground.

We combined a spatially explicit field study of forest canopy gap fraction with spectral mixture analyses of Landsat 7 ETM+ satellite imagery to assess landscape and regional dynamics of canopy damage following selective logging in Amazonia. Our field studies encompassed measurements of ground damage and canopy gap fractions along multi-temporal sequences of post-harvest regrowth of 0.5-3.5 years. We focused on the measurement of canopy gap fraction because of its functional link to important ecological processes such as energy balance and gas exchange and because of the obvious linkage of canopy cover to optical remote sensing analysis. We present a probabilistic spectral mixture model that provides estimates of forest canopy cover fraction within Landsat image pixels, a scale commensurate with logging activities on the ground and with field measurement capabilities. The approach is applied in a bottom-up scaling study across a multi-temporal sequence of selectively logged sites spanning a range of harvest intensities. The study is then extended in a top-down analysis of regional patterns of forest gap fraction changes following logging activities.

Methods

Site Description

This study was conducted at the Fazenda Cauaxi and surrounding areas in the Paragominas Municipality of Para State, Brazil in the eastern Amazon (Figure 1). The climate of the Cauaxi region is humid tropical with annual precipitation averaging 2200 mm (Costa and Foley 1998). A dry season extends from July through November (generally < 50 mm/mo.), 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 by a few large companies and many small land-holders, resulting in a wide range of logging intensities and methodologies. The Tropical Forest Foundation maintains a training center for demonstration of forest management and reduced-impact logging (RIL) techniques (S 3° 43.878', W 48° 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 land use, although there are indicators of indigenous activity.

[INSERT FIGURE 1]

We studied both conventional logging (CL; high collateral damage) and reduced-impact logging (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 (Verissimo et al 1992, Johns et al. 1996, Pereira et al. 2001). 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) and who skidded 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 conventional logging 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 (Pereira et al. 2001).

In contrast to CL practices, RIL operations employed a pre-harvest methodology where blocks were surveyed and fully inventoried, roads were planned and built, and vines were cut from harvest trees about one 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 six 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, 1998 and 1999. The areas of the blocks ranged from 14 to 120 ha (Table 1). The 1999 CL logging block covered a total area of 120 ha, but the field surveys of ground damage were taken from a 49 ha inset of that treatment (Table 1).

Field Studies

The three CL and three RIL blocks were inventoried and mapped prior to and following harvest operations following the techniques used by Pereira et al (2001). 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 261 field GPS measurements. The GIS contained spatially explicit locations and areas of all roads, skids, log decks, and felled trees for each block.

Field surveys of canopy damage were conducted in March 1999 and July 2000. This was approximately 0.5 and 1.5 y following logging in the 1998 blocks, and 2.5 and 3.5 y following logging in the 1996 blocks. It was also about 0.5 y following selective logging in the 1999 blocks. Our surveys provided a means to construct multi-temporal sequences in both CL and RIL timber operations.

Our primary indicator of forest canopy damage was canopy gap fraction. Gap fraction (range 0 to 1) is defined as the proportion of the upward-facing hemisphere with a clear view of the sky (no interfering plant canopy). We measured canopy gap fraction using optical plant canopy analyzers (LAI-2000, Licor, Inc.) at ~1.5 m above the ground surface. Although these canopy analyzers are often used to estimate leaf area index (LAI), we choose to report gap fraction, which the basic measurement of the instrument (Welles and 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 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 lit sky, so we restricted our measurements to 1 hr after dawn or 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 61-74^{o}, were 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 8 cardinal directions. Radii that crossed back over the skid trail, log deck or road were excluded. Gap fraction measurements for undisturbed forest were acquired in the 50 ha control plot along non-overlapping randomly selected 500 m transects. In total, we collected canopy gap fraction measurements over 14,000 m of transect in this study.

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

$$F = \Sigma (a_i f_i) / A \quad (1)$$

where a_i and f_i are the area and gap fraction measured for particular sampling strata (decks, roads, skids, tree falls, and background area) and A 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:

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

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. This results in a conservative estimate of damage because gap fraction did not reach background forest levels within 100 m of tree falls (Pereira et al. 2001). Where tree falls overlapped with one another or with decks, roads, or skids, the greatest gap fraction was selected. We applied no additive effects. Again, this results in a conservative damage estimate.

Landsat ETM+ Data

Landsat 7 Enhanced Thematic Mapper Plus (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 is maximal (Asner 2001). The 1999 image provided a means to assess canopy damage at two time steps (0.5 and 2.5 y) following logging in both CL and RIL operations. The 2000 image allowed for an analysis of two additional time steps (1.5, 3.5 y) after harvest as well as 0.5 y post-harvest again for the 1999 logging sites.

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^o and 45^o for 1999 and 2000 images, respectively). The 2000 image was further corrected to apparent surface reflectance using three ~100 x 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 two 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 one hour 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 et al. 1994). The 1999 ETM+ were calibrated to the corrected 2000 ETM+ image using a temporally invariant surface target from a 150 x 150 m bare soil area (documented during 1999 and 2000 field campaigns). Both ETM+ images were geo-located with the GIS coverages using a regionally extensive and locally intensive GPS sampling scheme (n = 261 ground control points). Geo-location accuracies ranged from 3-15 m in the subsequent GIS and image analyses.

Spectral Mixture Analysis

We employed a general, probabilistic model for decomposing optical reflectance measurements into sub-pixel estimates of photosynthetic vegetation (PV), non-photosynthetic vegetation (NPV), and bare soil covers. This model, *AutoMCU*, is based on an algorithm developed for savanna and shrubland ecosystems (Asner and Lobell 2000, Asner and Heidebrecht *in press*). It is fully automated and uses a Monte Carlo approach to derive uncertainty estimates of the sub-pixel cover fraction values. *AutoMCU* uses three spectral endmember "bundles" (Bateson et al. 2000), derived from field measurements and satellite imagery, to decompose each image pixel using the following linear equation:

$$\rho(\lambda)_{pixel} = \Sigma [C_e \bullet \rho(\lambda)_e] + \varepsilon = [C_{pv} \bullet \rho(\lambda)_{pv} + C_{soil} \bullet \rho(\lambda)_{soil} + C_{npv} \bullet \rho(\lambda)_{npv}] + \varepsilon \quad (3)$$

where $\rho(\lambda)_e$ is the reflectance of each land-cover endmember (e) at wavelength λ and ε is an error term. The sub-pixel cover fractions (C_e) of each endmember are PV, NPV, and bare soil. Solving for the sub-pixel cover fractions (C_e) therefore requires that the observations (in this case, reflectance or $\rho(\lambda)_{pixel}$) contain enough information to solve a set of linear equations, each of the form in equation (3) but at a different wavelength (λ).

Few spectral signatures of green and senescent vegetation and bare soil have been collected in the Amazon basin. The *AutoMCU* algorithm requires spectral reflectance bundles that encompass the common variation in canopy and soil properties. We collected these spectral data during visits in 1999 and 2000. The spectral endmember database encompassed the common variation in materials found throughout the region. For soils, we attempted to collect spectra across a diverse range of soil types, surface organic matter levels, and moisture status. Spectral collections for NPV included logging residues (slash) from a wide range of species and decomposition stages as well as surface litter from foliage deposition on the forest floor. The photosynthetic vegetation (PV) spectra were collected directly from the Landsat images in areas of known intact forest including our 50 ha control site. This approach was necessary because the vegetation height (> 20 m) precluded collection of the spectra in the field. These green vegetation spectra thus inherently included the variable effects of intra- and inter-crown shadowing, which is so prevalent in tropical forests (Gastellu-Etchegorry et al. 1999). The total number of spectra retained in the final endmember bundles for the *AutoMCU* algorithm was 252, 611, and 434 for PV, NPV and soil, respectively (Figure 2).

[INSERT FIGURE 2]

Bottom-up and Top-down Analyses

Analyses of field, GIS, and satellite data were completed using both bottom-up and top-down approaches. Field-based measurements of ground and canopy damage were projected spatially using the GIS. The resulting area-integrated gap fraction maps were then used to estimate landscape-scale impacts of conventional and reduced-impact logging operations. The maps provided a means to evaluate the spatial patterns of forest canopy closure in the years follows timber harvesting. Spatial and temporal trends in the GIS models were directly comparable to satellite-based estimates of forest canopy cover fraction derived from the spectral mixture analysis. This provided a means to evaluate the performance of spectral mixture studies for selective logging detection and quantification.

The bottom-up scaling studies were complemented with top-down analyses of logging extent throughout the 400 km^2 Cauaxi region. These studies involved the use of Landsat mixture model results to evaluate regional patterns of logging intensity and associated forest canopy gap fraction.

Results

Ground Damage

Both conventional and RIL logging operations used for creating log decks, skids, and roads substantially impacted forest areas (Figure 3). However, the ground damage (defined as the ground area subject to mechanical disturbance – roads, decks and skid trails) differed dramatically between conventional logging (CL) and reduced-impact logging (RIL) treatments. As reported by Pereira et al. (2001), the percentage area disturbed in CL (8.9%) was nearly double that of RIL (4.8%) for the 1996 harvests (Table 1). For the 1998 harvests, CL practice resulted in more than two times the damage as RIL (11.2% vs. 4.6%, respectively). There was only a 20% difference in ground damage between the 1999 CL (10.5%) and RIL (8.6%) blocks. However, calculating the area damaged per tree harvested (Table 1) revealed that CL was consistently more damaging than RIL, even in the 1999 harvests.

[INSERT FIGURE 3]

Skid areas contributed the most to the overall ground damage (2.9-8.8% of treatment areas). Skid damage from CL (6.8-8.8%) was always greater than for RIL (2.9-6.5%). Roads and log decks contributed much less to the total area of ground damage. Percentage area ground damage from log decks was consistently higher in CL (0.6-1.9%) then in RIL (0.4-0.7%). Road damage was also greater in the 1996 and 1998 CL sites but not in the 1999 logging blocks.

[INSERT TABLE 1]

Canopy Damage and Closure

In the undisturbed forest block, we measured a mean (± s.d.) canopy gap fraction of 3.1% (0.2%) in 1999 (n = 454) and 2.6% (0.3%) in 2000 (n = 396). Both CL and RIL operations produced significant canopy damage. Regardless of treatment and sampling stratum (deck, road, skid, tree fall), all of the logging areas sampled had a greater canopy gap fraction than the intact forest (Table 2).

[INSERT TABLE 2]

The degree of canopy damage as indicated by gap fraction measurements was the highest in road and deck areas (Table 2). Gap fractions were largest in log decks at 0.5 y post-harvest (e.g., 1998 harvests measured in 1999). Mean (± 1 s.d.) gap fractions for these "fresh" log decks ranged from 0.94 (0.02) to 0.99 (0.01). Gap fraction values for log decks in the 1996 treatments were also very large in 1999 because these decks were re-cleared in 1998 for use in forestry courses ongoing in the region (Table 2; Pereira et al. 2001).

Re-establishment of vegetation in the log decks led to notable decreases in canopy gap fraction 1.5 y following clearing (Table 2). The rates of canopy closure among RIL treatments were much different from those of CL blocks. In the log decks of the 1996 RIL sites, gap fractions decreased from 0.96 (± 0.03) at 0.5 y post-clearing to 0.42 (0.16) at 1.5 y. Similarly, the 1998 RIL log decks decreased from 0.99 (0.01) to 0.46 (0.07). In contrast, gap fraction decreased much less in conventional logging decks, from 0.97 (0.02) to 0.78 (0.09) for 1996 CL and from 0.99 (0.01) to 0.73 (0.11) for 1998 CL.

Other landscape strata such as roads, skids and tree fall areas had large canopy gap fractions 0.5 y following harvest (Table 2). Gap fraction was almost always lower in RIL sites than in CL areas. For example, roads in the 1998 CL site had a mean (± s.d.) gap fraction of 0.72 (0.12) at 0.5 y post-harvest in comparison to 0.36 (0.05) for 1998 RIL. Roads in the 1996 blocks that had undergone 2.5 y of regrowth (1999 survey) still had large gap fractions of 39% (RIL) and 50% (CL). Canopy closure proceeded at only a slower pace in these older logging treatments (14% and 25% of the 1996 gap fraction for CL and RIL, respectively) than in newer harvest areas (28% and 39% of the 1998 gap fraction for CL and RIL). In contrast, rates of canopy closure over skid areas were comparable between new and old CL or RIL pairs. For instance, there was a 73% decrease in skid gap fraction in the 1996 CL block during a year of regrowth between 1999 and 2000 (Table 2). The same year of regrowth in the 1998 CL site brought a 78% decrease in gap fraction between 1999 and 2000.

By far, the tree-fall areas had the lowest canopy gap fractions of the disturbed strata. Values for CL at 0.5 y post-harvest had gap fractions ranging from 0.11 (0.05) in the 1999 block to 0.29 (0.10) in the 1998 block (Table 2). While the gap fraction values for tree fall areas in the 1999 RIL site (0.12±0.04) were comparable to those of the 1999 CL block, the values for the 1998 RIL (0.13±0.05) were much lower than those in the 1998 CL site. This emphasizes the variability by year and by site, and it highlights the difficulty in studying canopy damage at the regional scale.

Area-Integrated Damage and Recovery

Modeled landscape-scale canopy gap fractions in the six logged areas allowed us to assess spatial patterns of forest canopy damage and closure following selective logging events in both CL and RIL management (Figures 4-6). The area-integrated forest canopy gap fractions were derived from these spatial models (Table 3). These results differ from those of Table 2 as they depict the contribution of each landscape stratum to the overall area-integrated gap fraction.

[INSERT FIGURES 4, 5, 6]
[INSERT TABLE 3]

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 (Figure 3) contributed to the integrated gap fraction. Although the log decks had the largest measured gap fractions (Table 2), their overall area was very small, resulting in integrated gap fractions of only 0.3-1.1% across all studied blocks. Skid trails had modest gap fractions (Table 2) but significant spatial extent (Figure 3), at times resulting in substantial contributions to the integrated gap fraction of each treatment (0.3% to 3.4%). Integrated gap fraction for skids was consistently higher in CL than in RIL treatment (Table 3). Road areas had a smaller contribution to the area-integrated gap fraction than skid trails. The tree-fall areas within each logging block accounted for the largest portion of the total integrated gap fraction (Figures 4-6). In both 1999 and 2000, the CL treatments had 2-3 times greater canopy gap fraction from felled trees than the RIL treatments (Table 3).

One year of regrowth decreased canopy gap fractions within all sampling strata, resulting in area-integrated decreases in gap fraction as well. The greatest contribution to the area-wide recovery of the canopy occurred within the tree-fall areas. For the 1996 CL treatment, integrated gap fraction decreased by 43% from 2.5 y (1999) to 3.5 y (2000) post-harvest within tree-fall areas. For the 1998 CL block, integrated gap fraction in tree-fall areas decreased from 16.9% in 1999 to 9.7% in 2000, or a fractional decrease also of

43%. The 1996 RIL treatment saw a decrease in gap fraction throughout tree-fall areas of only 30%, but the overall gap fraction was extremely low at 3.3% (1999) and 2.3% (2000). In contrast, the 1998 RIL site had a 46% decrease in integrated gap fraction for tree-fall areas, and these remained higher than the intact forest control area (Table 3).

Other sampling strata had for the most part even greater rates of canopy recovery although they contributed less to the area-wide integration. The 1998 CL block had the largest skid-area gap fraction of 3.4% in 1999, which decreased to 0.5% by 2000. The 1996 RIL block had an integrated skids-area gap fraction decrease from 0.8% in 1999 to 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 integrated gaps and slower rates of closure in comparison to skids and tree-fall areas (Table 3).

Regional-scale Analysis with Landsat ETM+

Quantitative analysis of selective logging areas throughout the 400 km^2 region was made possible using the Landsat 7 ETM+ imagery with the Monte Carlo spectral unmixing model, *AutoMCU*. Figure 7 shows a color composite of the three sub-pixel cover fractions for photosynthetic vegetation (forest canopy including shade), exposed non-photosynthetic vegetation (NPV) and bare soil. Larger roads are seen in red, indicating significant levels of bare soil. Deforested areas such as cattle pastures have high levels of bare soil (red) or mixtures of bare soil and green vegetation (yellow). Areas where canopy gaps allow underlying NPV to be exposed within image pixels are shown in blue tones. Close inspection of new selective logging harvests indicated a patchwork of log decks with exposed soil (red) and roads/skids with exposed NPV or slash (blue). Closure in the canopy gaps created by selective logging can be followed by comparing the 1999 and 2000 *AutoMCU* results. New areas of logging in the northwest corner of the region can also be seen in 2000.

[INSERT FIGURE 7]

Using the GIS models shown in Figures 4-6 as a spatial and temporal guide, we extracted the sub-pixel cover fraction data for the landscape strata located in the logging study areas. For the 1999 Landsat observations, we found consistent patterns in forest canopy, NPV and bare soil exposure (Figure 8a). The

1999 CL site had not yet been harvested, and thus the forest canopy gap fraction was similar to that of the forest control area. Although timber harvesting had not yet occurred in the 1999 RIL area, log decks and some roads had been established prior to the 1999 Landsat acquisition. This is shown in the sub-pixel forest cover fraction result of 0.73 ($\pm$0.04) for log decks and 0.93 ($\pm$0.03) for roads (Figure 8a). In addition, significant levels of NPV were found in the 1999 RIL log decks prior to harvest (0.27$\pm$0.04).

[INSERT FIGURE 8]

In general, the order of increasing forest canopy cover was log decks < roads < skids < tree-fall areas. For example, the 1998 CL and RIL treatments had the lowest forest canopy cover fractions, with log decks showing minima at 0.57$\pm$0.01 and tree-fall areas having the highest values at 0.95$\pm$0.01 (Figure 8). Reciprocally, bare soil or NPV were highest in the log decks and lowest in the tree fall areas. Other than log decks, almost all landscape strata in the 1996 treatments had forest canopy cover fractions near in value to intact forest values.

In the sub-pixel cover fractions from the 2000 Landsat imagery, the 1999 CL and RIL treatments had the lowest forest canopy covers and the highest soil and NPV exposure (Figure 8b). Forest cover was consistently lower in the CL logging areas than in RIL, independent of the time since harvest. All landscape strata in the 1996 and 1998 harvests showed higher forest canopy cover fractions in 2000 than in 1999.

There were significant inverse correlations between the forest canopy gap fractions derived from field studies and the forest canopy cover estimates from satellite data analysis (Figures 9-10). Comparison of the 1999 Landsat imagery and ground surveys of gap fraction from 1998 logging blocks yielded a very high correlation for log decks, roads, skids, tree fall areas, and the intact forest control block ($r^2 = 0.96$, $p < 0.01$; Figure 9a). The 1999 observations of the older 1996 harvests yielded a less robust but still statistically significant correlation ($r^2 = 0.78$, $p < 0.05$); however, the correlation was leveraged somewhat artificially by the more recently cleared log decks within these treatments (Figure 9b). Closer inspection showed that the remaining strata (except for CL roads) were of similar forest canopy cover in the satellite results.

[INSERT FIGURE 9]

Relations between field- and satellite-based canopy properties in the 2000 observations followed the same pattern found in 1999 (Figure 10). Canopy openings in the most recently harvested 1999 CL and RIL treatments were readily predicted from the spectral mixture analyses (Figure 10a). The strength of the correlation grew weaker with time as the canopy closed (Figure 10b,c). As mentioned above, the apparent high correlation between field and satellite observations in the 1996 treatments (3.5 y post-harvest) was driven by the log decks that were re-cleared in 1998. Removal of these decks from the analysis yielded r^2 values of only 0.24 ($p < 0.05$; Figure 10c). Grouping all landscape strata from logging blocks imaged less than one year following harvest operations yielded a highly significant correlation between satellite-based forest canopy cover fraction and field-based gap fraction ($r^2 = 0.95$, $p < 0.01$).

[INSERT FIGURE 10]

Discussion

Canopy Damage and Closure

Selective logging has a highly variable impact on tropical forest canopies in the eastern Amazon. Among the forest sites in this study, the amount of canopy damage depended primarily upon the management practices employed at the harvest site. Conventional logging (CL) consistently resulted in greater canopy damage than did reduced-impact logging (RIL), independent of the number of trees harvested per hectare (Table 1). Initial canopy gap fractions were lower in RIL than in CL immediately following timber extraction. However, the rate of canopy closure in CL blocks was equal to or greater than that of RIL treatments. This is apparent in the GIS-integrated gap maps shown in Figures 4-6 and Table 3. These maps also depict the extreme spatial variation in gap fraction between sites as well as the differences in the rate at which the forest canopy closes in roads, skids and tree-fall areas.

From the spatially integrated GIS analyses of ground and canopy damage, we summarize results that are pertinent to understanding forest canopy gap dynamics following selective logging in the eastern Amazon. These results are also key to determining the role of remote sensing in studies of land-use change and the ecology of logged forests in the region. First, log decks have very small spatial extent relative to the total harvested area (0.4-1.9%), 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 and Lefebvre 1998). However, fast re-colonization 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). Tree-fall areas open up the canopy 300-400% immediately following harvest, but the gap fraction and thus the light regime changes rapidly thereafter. Third, roads and skid trails have spatial extents that fall between those of decks and tree-fall areas. Their contributions to changes in the forest light regime are intermediate to those of log decks and tree falls.

It is important to acknowledge that much of the canopy closure, particularly in the CL plots in the 0.5-3.5 y following harvest, occurs as low-stature secondary species. Our closure rates should not be construed as a general forest biomass recovery, but rather recovery of leaf area that primarily affects the canopy light and thermal radiation regime. Understanding of the components of canopy recovery (understory versus residual canopy) will be important both for carbon balance as well as for other ecological and biogeochemical functions of the system.

Spectral Mixture Analysis

The spectral mixture analyses of the Landsat ETM+ imagery were sensitive to spatial and temporal variation of forest canopy gap fraction (Figures 9,10). This result contrasted sharply with the relatively low sensitivity of previous methods that employ the basic Landsat reflectance bands or textural analysis with those bands (Stone and Lefebvre 1998, Asner et al. *in press*). The mixture modeling presented in this study provided sufficiently high precision to allow multi-temporal tracking of canopy closure over time. These results suggest that the sub-pixel heterogeneity of forest canopy properties is relevant to not only the problem of selective logging detection and quantification, but also to the value of such analyses for studying other components of forest structure in the Amazon (Cochrane and Souza 1998).

While the internal precision of the spectral mixture modeling was very high, the accuracy of the approach seemed poor when comparing sub-pixel forest cover fraction to canopy gap fraction (Figures 9,10). Specifically forest gap values from satellite observations (= $1 - C_{pv}$; from eq. 3) were systematically lower than the field gap fraction measurements. Although the field and satellite measurements were highly correlated, there are several reasons why these measurements are not directly comparable. The optical canopy analyzers used in this study (LAI-2000s; Licor, Inc.) view the forest canopy throughout nearly the entire skyward-pointing hemisphere. Gap fraction is a spherical measurement collected from below the canopy. In contrast, forest cover derived from the satellite observations is based upon planar measurements from above.

Apparent shadowing is also directly related to the difference in the field and satellite measurements. Field-based gap fraction measurements are acquired when viewing the canopy with a diffusely illuminated sky in the background. Intra- and inter-crown shadows are not as apparent from the ground vantage point. In contrast, the particular spectral mixture analysis approach employed in this study combines the green leaf canopy with the shadows, which are apparent from the satellite downward-looking vantage point. Another reason for the mismatch between field and satellite data involves the difficulty in co-locating gap measurements to image pixels. Satellite image pixels do not necessary fall exactly within log decks; the pixels likely overlap to some degree with adjacent forest canopy. A related effect of this adjacency involves multiple scattering of light between gap and non-gap areas, both within and between satellite pixels (Townshend et al. 2000). This multiple scattering decreases the spectral distinction between the neighboring pixels.

Despite these sources of error in comparing field gap fraction and satellite fractional cover, the two measures were often highly and inversely correlated. This provided a means to analyze the time-dependence of canopy gap fraction for recently harvested areas throughout the 400 km^2 region. We estimated gap fractions based on the unmixing results from the 1999 and 2000 Landsat images for recently harvested areas using a combination of data provided in Figures 9a and 10a (gap = $1.02 - 0.43C_{pv}$; $r^2 = 0.95$, $p < 0.01$). Then we integrated the gap fractions spatially for selected regions recently harvested prior to the 1999 image acquisition (white boxes in Figure 7). We repeated the procedure for the same areas in 2000. We compared area-integrated forest canopy gap fraction at 0.5 y and 1.5 y post-harvest (Figure 11). We found a 50% decrease in gap fraction values for intensively logged areas after a year of forest regrowth. This result agrees well with ground-based measurements of the 1998 CL and RIL study blocks that recovered approximately 50% of the canopy area lost between 0.5 and 1.5 years following logging.

[INSERT FIGURE 11]

To our knowledge, this is the first regional-scale analysis of forest canopy gap fraction and closure following selective logging in the Amazon basin. Leaf cover, inversely correlated with gap fraction, is one of the most important factors controlling net primary production (NPP) in humid tropical forests. The rate of carbon uptake following human disturbance is a major unknown in this region of the world (Houghton et al. 2000). However, gap fraction alone cannot be used to infer NPP following logging damage. The age structure of the forest and the type of canopy recovery (low secondary vegetation versus canopy trees) is also important. Remote sensing observations can provide some of this needed information when the sub-pixel structure of forests can be estimated (Hall et al. 1995).

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 site-level 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. Regional forest canopy damage monitoring can provide information pertinent to other aspects of the carbon cycle such as the location of respiration hotspots likely to result from coarse woody debris (slash) and severed roots.

Selectively logged forests are highly susceptible to fire in the eastern Amazon (Uhl and Buschbacher 1985, Uhl and Kauffman 1990, Nepstad et al. 1999). Regional disturbance monitoring can be used to predict the location of fire-prone sites (*sensu* Cochrane et al. 1999). Sub-pixel gap fraction monitoring in particular can be employed as an input to models simulating thermal and evaporative conditions at the site level in relation to fire susceptibility. Regional-scale gap fraction assessments can play a role in ecological research efforts beyond that of the carbon cycle and fire prediction. The spatial and temporal dynamics of faunal species such as birds, reptiles, and mammals can be linked to forest disturbance (e.g., Johns 1991, Johns 1992, Thiollay 1992).

Conclusions

We employed detailed field studies of ground and canopy damage to estimate the area-integrated impact of selective logging on tropical forests in the eastern Amazon basin. Repeated surveys of the forest sites in 1999 and 2000 provided initial estimates of canopy gap closure rates in the years following timber harvests. Continued visits to these and other sites will eventually yield more information on the temporal dynamics of canopy gap fraction after logging. Until then, this study offers several conclusions regarding canopy gap dynamics:

- Log decks are the sites of the largest forest gap fractions following selective logging activities, but their contribution to the landscape-level gap dynamics is minor. Thus, they are useful for locating logged areas in remotely sensed data but are likely less important for describing the energy balance, fire susceptibility or carbon dynamics of the harvested region.
- Tree falls are spatially the most extensive form of canopy damage following selective logging, but the canopy gap fractions resulting from them are small. This impedes the detection of selective logging from remote sensing observations, and it challenges regional studies of logging intensity and forest recovery.
- Reduced-impact logging results in less damage to the forest canopy than does conventionally logging practices. This is true at the level of individual landscape strata such as roads, skids and tree falls as well as at the area-integrated scale.

Spectral mixture analyses of the Landsat ETM+ data indicate the following:

- The *AutoMCU* algorithm, along with a combination of field- and image-derived spectral endmember bundles, provides detailed information on forest canopy damage following selective logging. The information derived from this method allows tracking of forest canopy damage up to 3.5 y post-harvest.

- Sub-pixel forest canopy cover fraction derived from satellite data is highly and inversely correlated with field-based canopy gap fraction.
- Regional-scale estimates of forest canopy gap fraction can be derived from a combination of field- and satellite-based measurements. Regional gap fraction studies can be used to quantify logging damage, intensity and canopy closure following timber harvests.
- Approximately 50% of the canopy opening caused by selective logging becomes closed within one year of regrowth following timber harvests.

This is the first large-scale study of forest canopy recovery following selective logging in Amazonia. The results from this study pave the way for larger-scale analyses of canopy gap fraction. We are currently undertaking this effort for the greater part of the eastern Amazon.

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Table 1. Ground disturbance expressed as a percentage of total area for six harvest blocks contrasting conventional logging (CL) and reduced-impact logging (RIL) treatments. Values are derived from GIS analysis presented in Figure 3. The proportion of total ground disturbance [= (log deck+skid+road)/total] and area ground disturbed per tree harvested are also provided.

Year	**Treatment**	**Area (ha)**	**# Trees Felled**	**Felled Trees/ha**	**Road Area %**	**Deck Area %**	**Skid Area %**	**% Disturbed**	**m^2 Ground Damage per Tree Harvested**
1996	CL	112	415	3.7	1.2	0.9	6.8	8.9	240
1996	RIL	108	325	3.0	0.6	0.6	3.6	4.8	160
1998	CL	14	88	6.4	2.0	1.9	7.3	11.2	180
1998	RIL	57	200	3.5	1.0	0.7	2.9	4.6	130
1999	CL	49[+] (120)	128[+] (185)	2.6[+]	1.1	0.6	8.8	10.5	400
1999	RIL	99	379	3.8	1.7	0.4	6.5	8.6	230

[+] Tree harvest statistics for 1999 CL taken from sub-area of 100% survey coverage in Figure 6. Values in parentheses indicate results for the total block area as used in subsequent satellite analyses.

Table 2. Mean (± 1 s.d.) canopy gap fraction for four landscape strata in conventional logging (CL) and reduced-impact logging (RIL) treatments measured in 1999 and 2000. All values derived from *in situ* field measurements.

Harvest		**Deck**		**Road**		**Skid**		**Tree Fall**	
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)
1999	CL	---	0.99 (0.02)	---	0.41 (0.08)	---	0.28 (0.06)	---	0.11 (0.05)
1999	RIL	---	0.94 (0.02)	---	0.26 (0.04)	---	0.20 (0.03)	---	0.12 (0.04)

* Log decks in 1996 CL and RIL blocks were re-cleared in 1998

Table 3. Area-integrated forest canopy gap fraction in 1999 and 2000 for conventional logging (CL) and reduced-impact logging (RIL) treatments. Integrated gap percentages were calculated using the GIS analyses presented in Figures 4-6.

Harvest		**TOTAL**		**Deck**		**Road**		**Skid**		**Tree Fall**	
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
1999	CL	--	11.7	--	0.6	--	0.5	--	2.5	--	8.1
1999	RIL	--	6.6	--	0.5	--	0.4	--	1.3	--	4.4

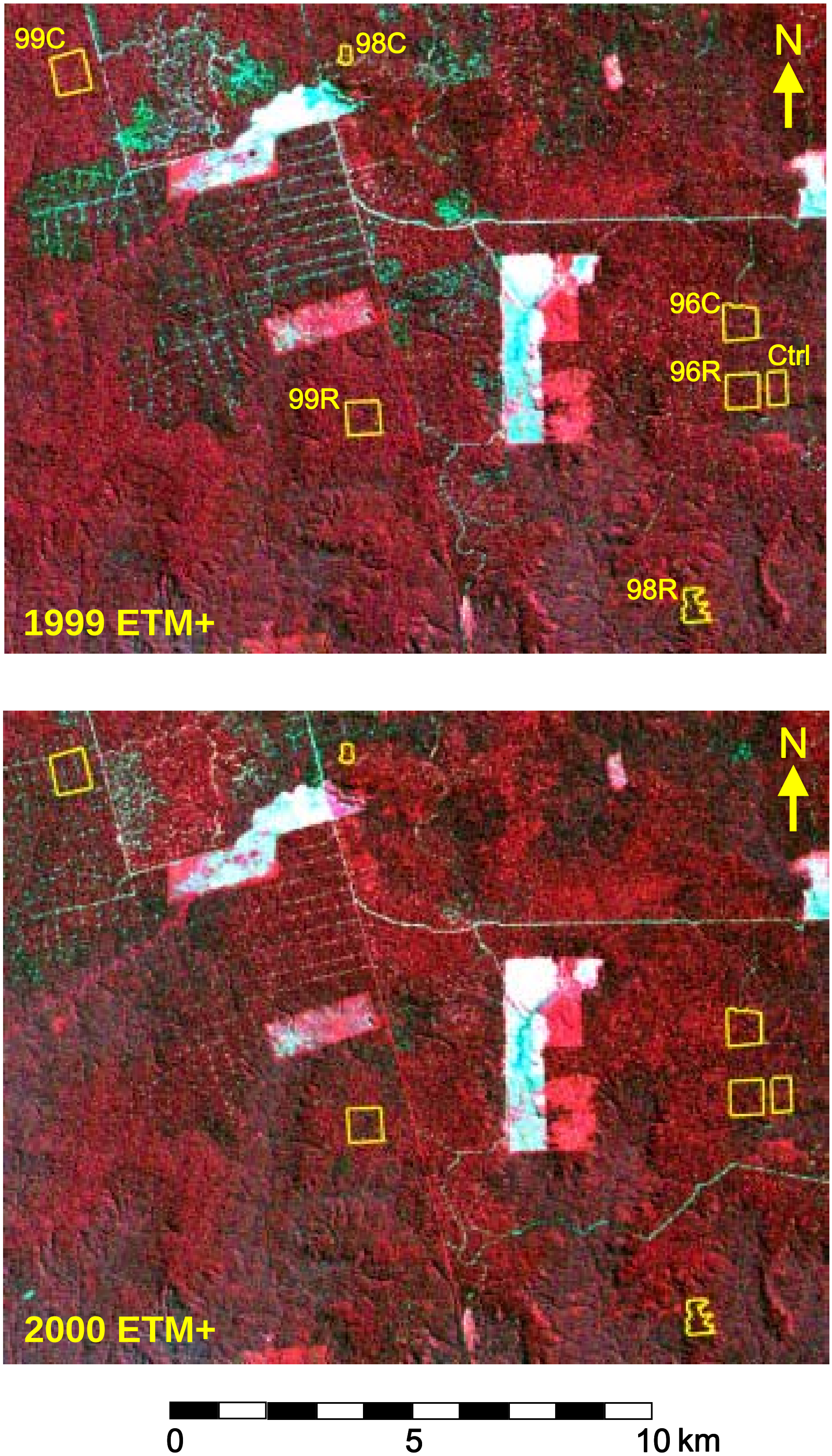

Figure 1. Landsat ETM+ imagery collected in 1999 and 2000 over the Fazenda Cauaxi-CIKEL area in the eastern Amazon. Images show color composite of near-infrared (band 4), red (band 3) and green (band 2) channels. Study boundaries for 1996, 1998 and 1999 conventional (C) and reduced-impact (R) logging sites are show. An un-logged control site (Ctrl) is also shown. Extremely heavy logging damage can be readily seen in the northwest corner of the 1999 image.

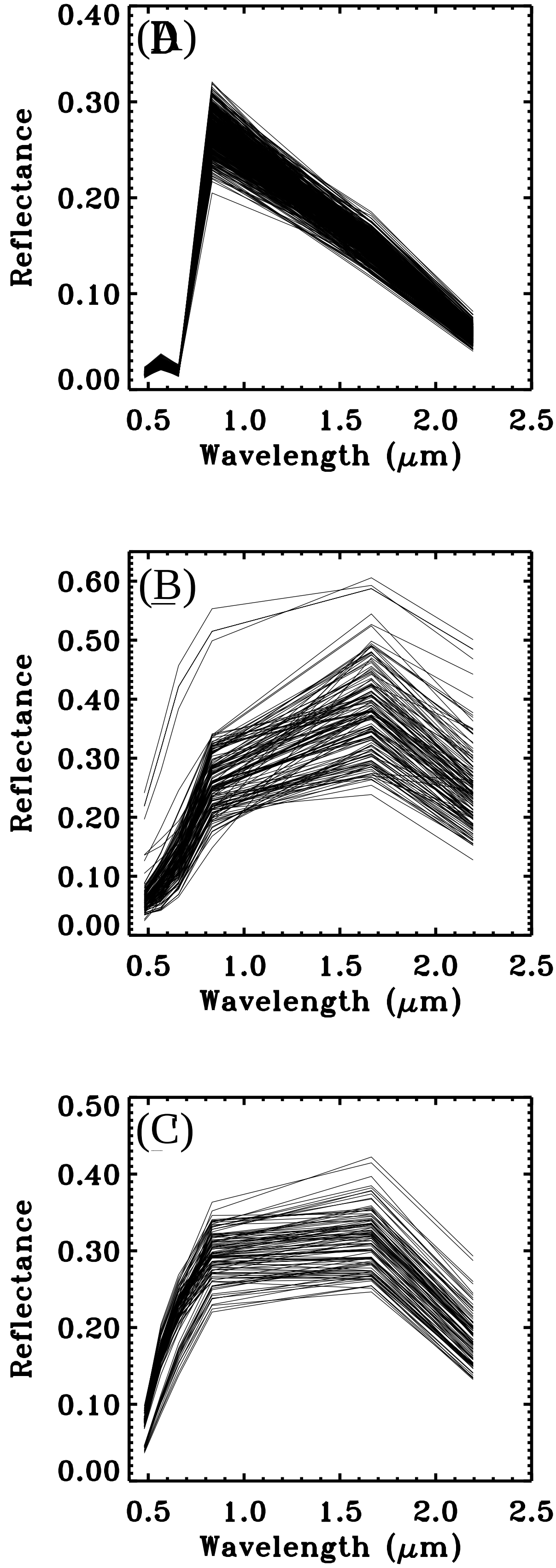

Figure 2. Spectral reflectance endmembers collected throughout study region and used for AutoMCU analysis. Panels A-C show bundles for photosynthetic vegetation (PV) including shade, non-photosynthetic vegetation (NPV) and bare soil, respectively. PV bundle was derived from selected image pixels containing closed-canopy forest cover (n = 252). NPV (n = 611) and soil (n = 434) bundles were derived from field surveys throughout the region.

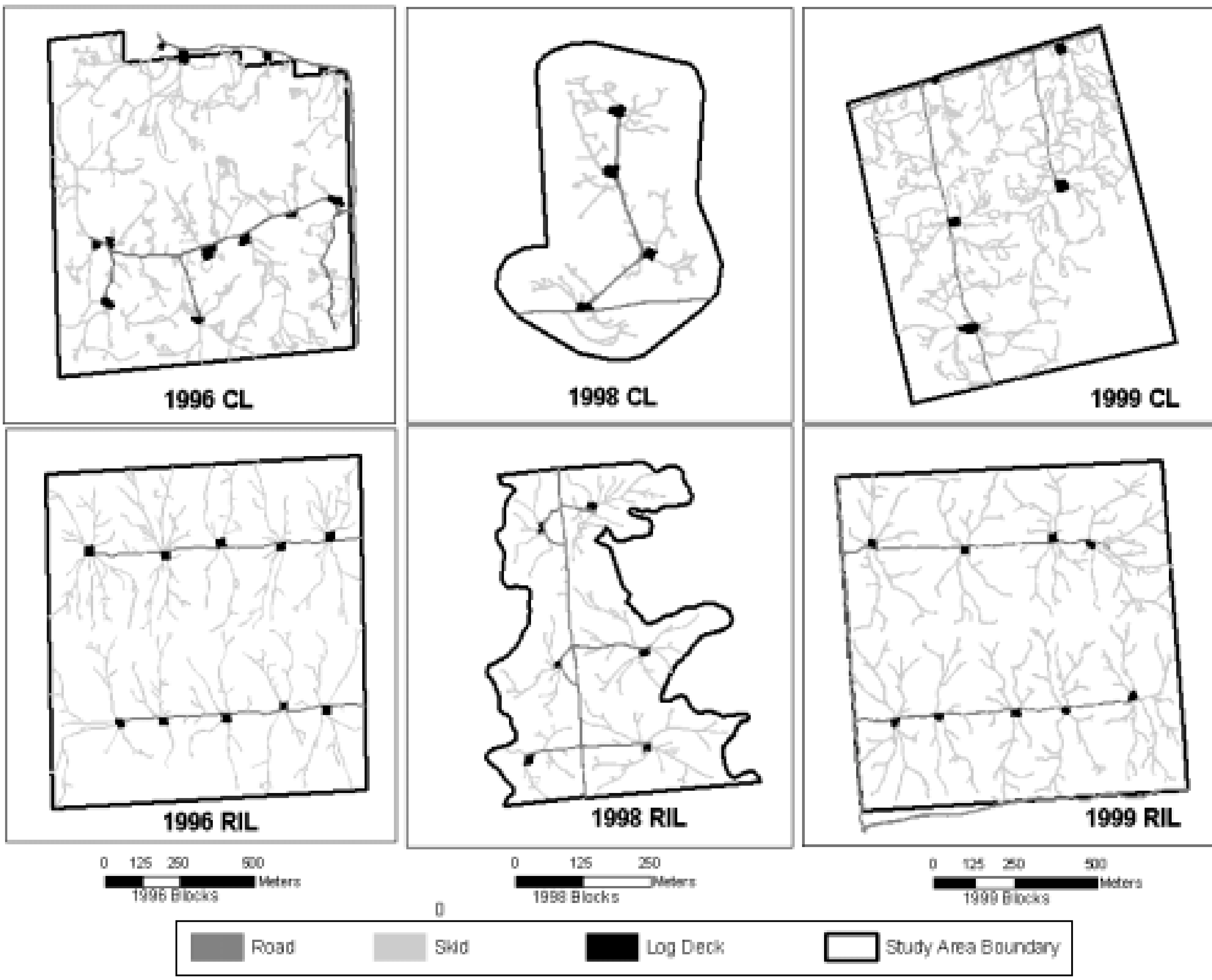

Figure 3. Geographic information system coverages of 1996, 1998 and 1999 conventional logging (CL) and reduced-impact logging (RIL) treatments. Skids, roads, log decks, and felled trees (not shown) were surveyed in the field, mapped to paper and digitized using DGPS ground control points.

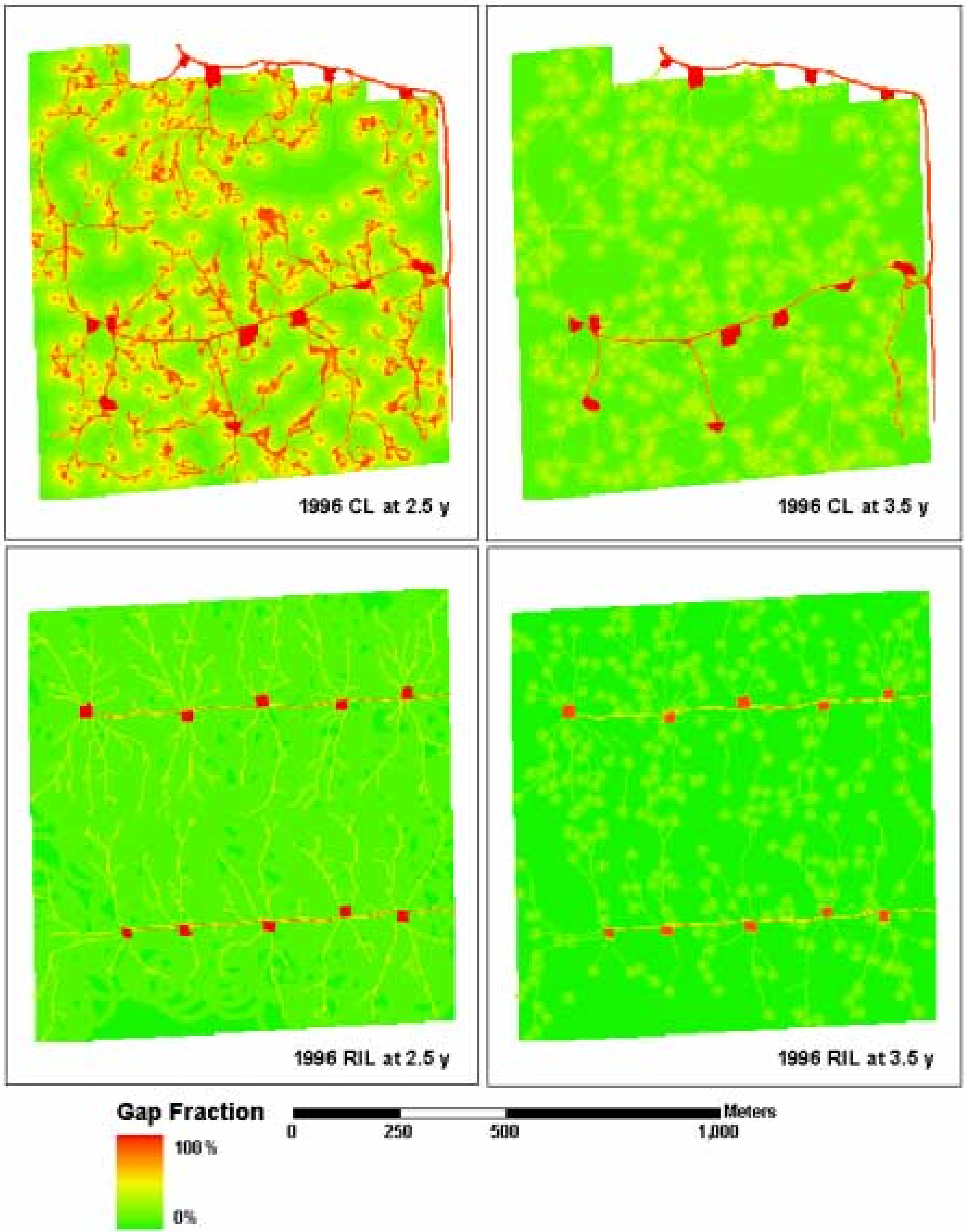

Figure 4. Area-integrated forest canopy gap fraction for 1996 CL and RIL treatments. Gap fractions are based on field measurements collected in 1999 (2.5 y post-harvest) and 2000 (3.5 y post-harvest), coincident with Landsat overpasses. GIS coverage of ground damage in Figure 3 was combined with field survey of felled tree locations and with canopy gap surveys (Tables 2) to estimate the spatial patterning of forest canopy gap fraction following logging and during regrowth.

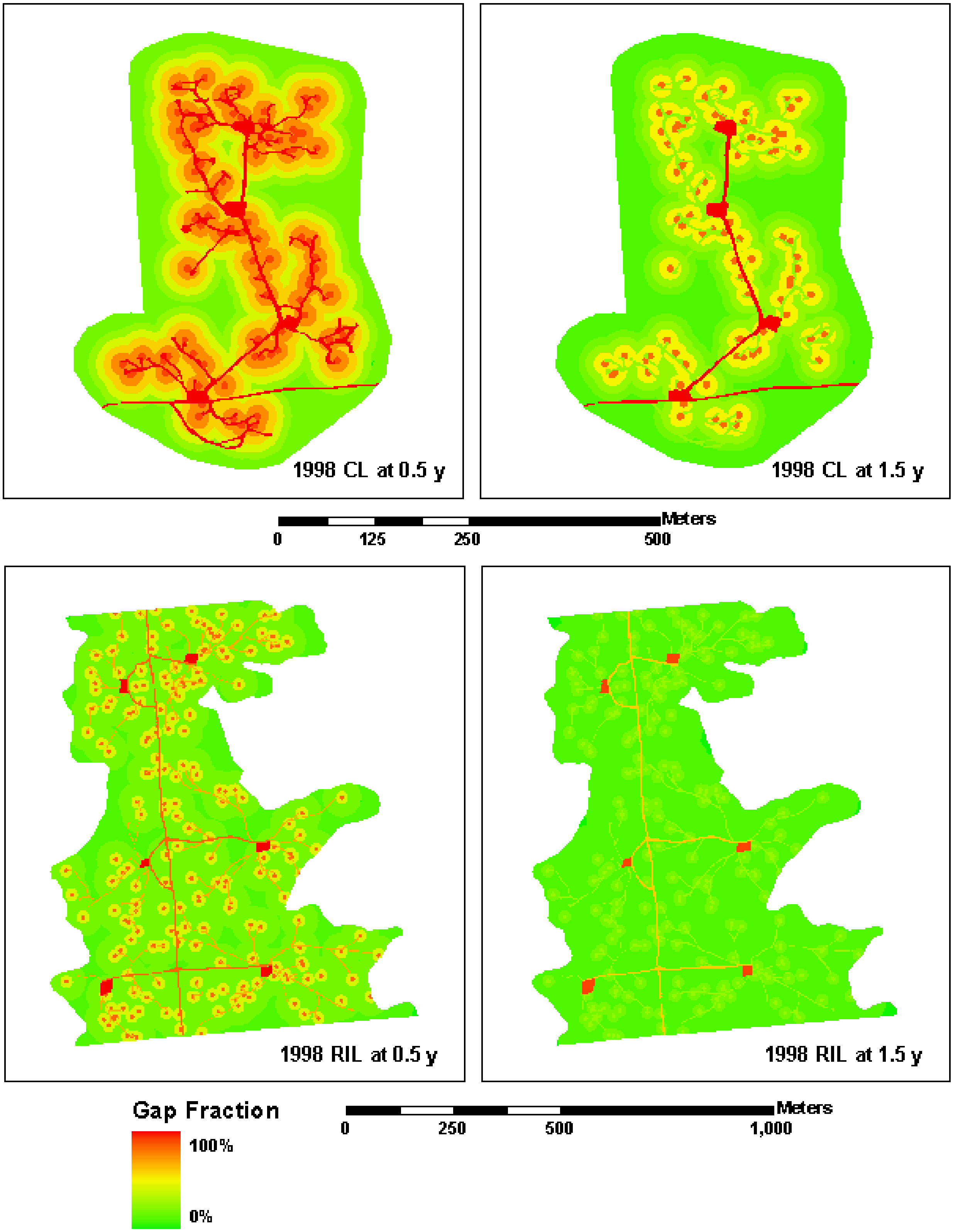

Figure 5. Same as Figure 4 but for 1998 CL and RIL logging blocks in 1999 (0.5 y post-harvest) and 2000 (1.5 y post-harvest).

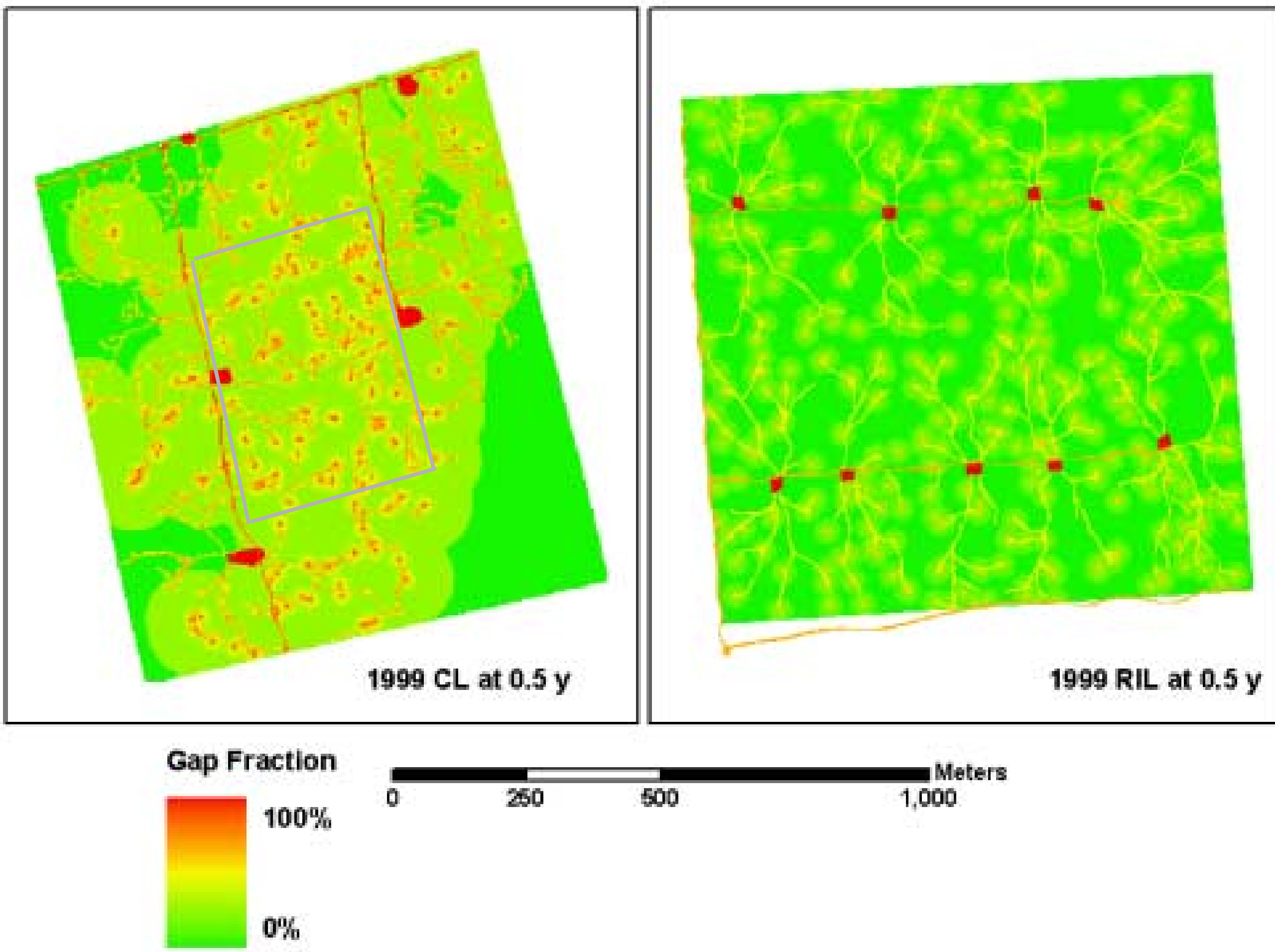

Figure 6. Same as Figure 4 but for 1999 CL and RIL logging blocks in 2000 (0.5 y post-harvest). Gray box within the 1999 CL block depicts area of 100% tree harvest survey used to generate harvest intensity statistics in Table 1.

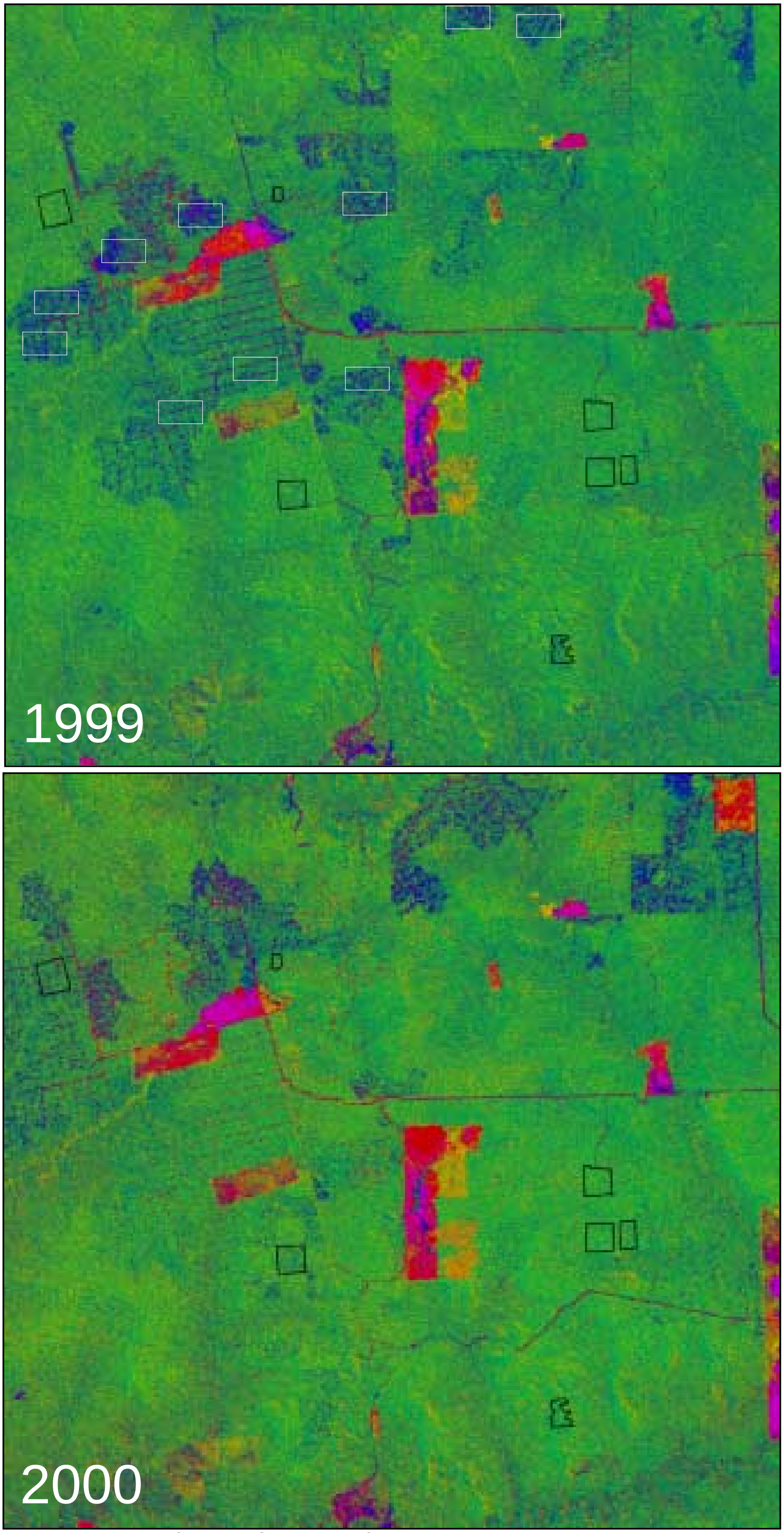

Figure 7. Color composite images of AutoMCU output for 1999 and 2000. Red colors show bare soil, green shows forest canopy with shading, and blue shows exposed non-photosynthetic vegetation (slash in logged areas). Logging research areas used for bottom-up analyses are delineated in black. Larger areas of 1999 heavy logging used for top-down analyses are shown in white boxes.

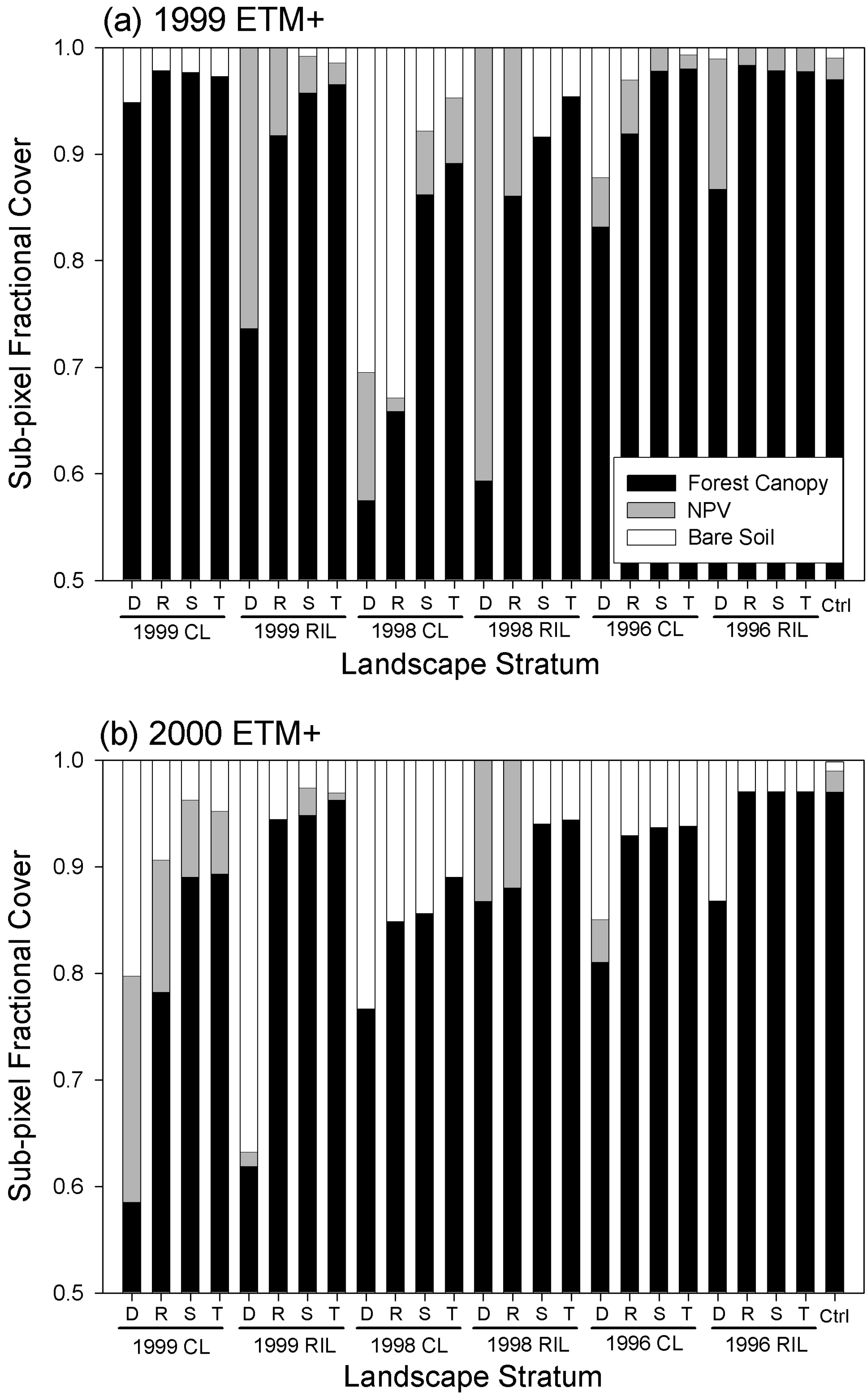

Figure 8. Mean fractional cover of forest canopy (PV + shade), non-photosynthetic vegetation (NPV) and bare soil in Monte Carlo spectral mixture analysis of (a) 1999 and (b) 2000 Landsat imagery. Results are given for logging decks (D), roads (R), skids (S), and tree fall areas (T). Data are partitioned by harvest year (1996-1999) and management (CL vs. RIL). Results from the forest control block (Ctrl) are also provided.

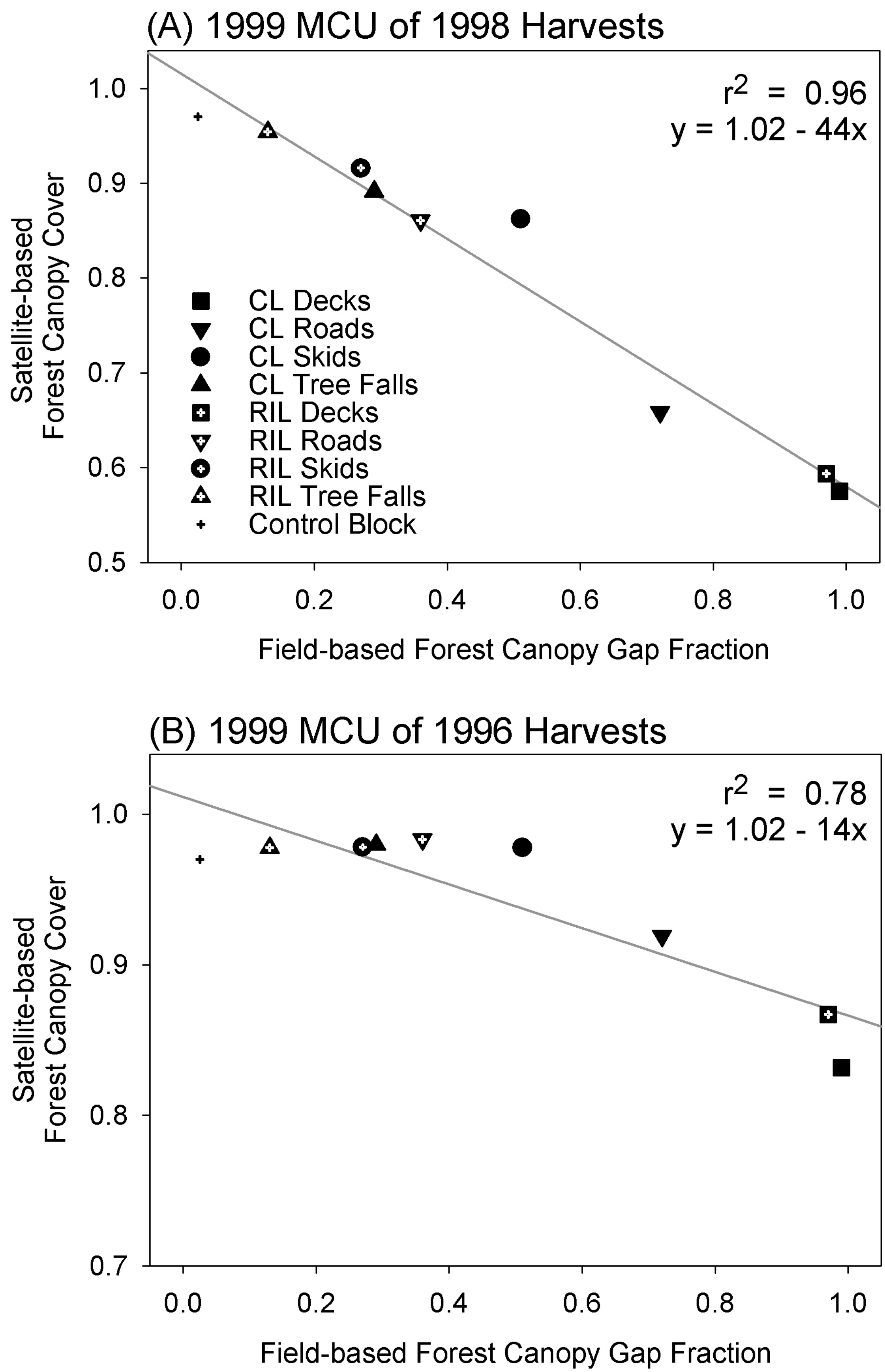

Figure 9. Correlation between field-based canopy gap fraction and satellite-based canopy cover for (A) 1998 harvests and (B) 1996 harvests, as imaged in 1999.

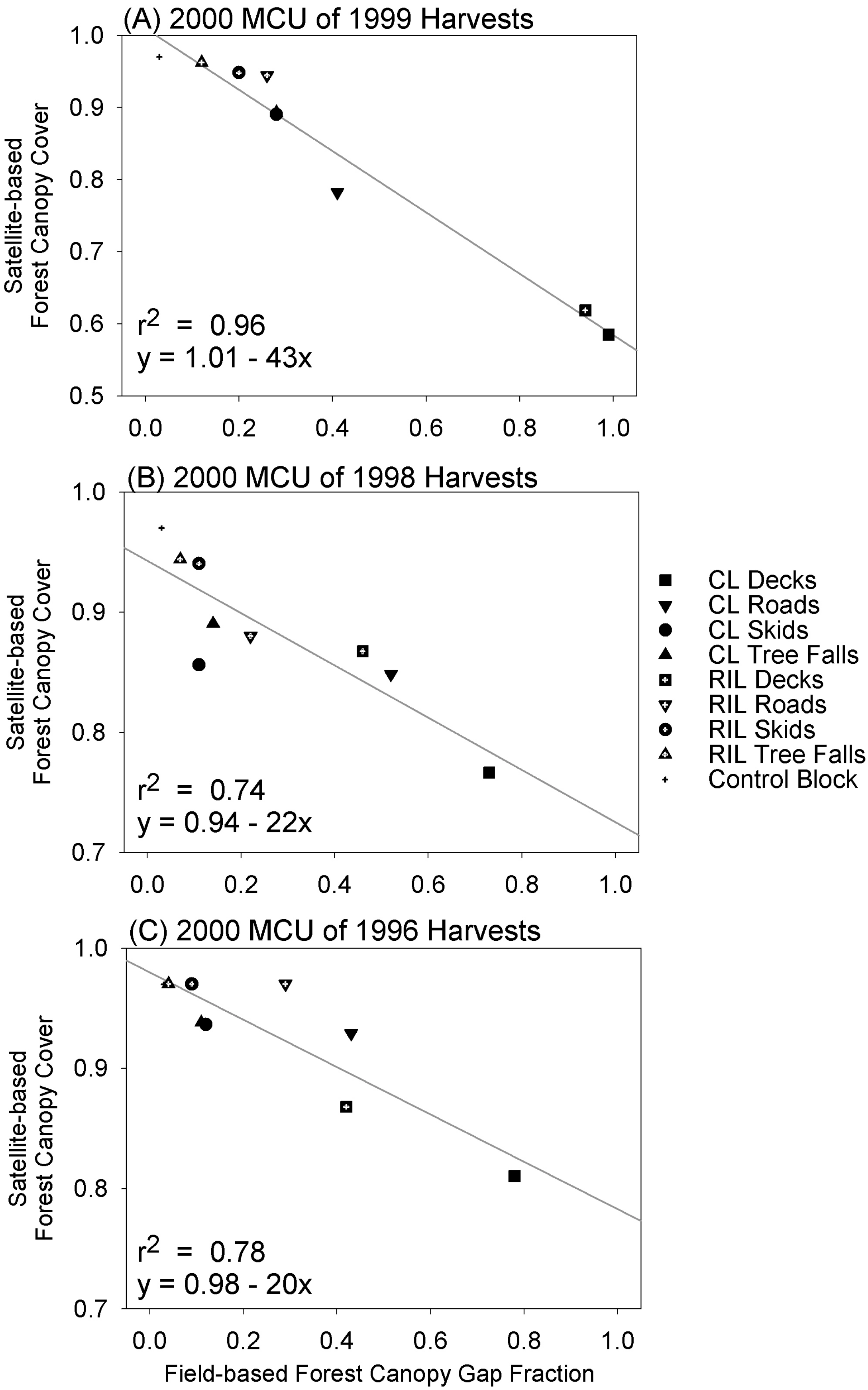

Figure 10. Correlation between field-based canopy gap fraction and satellite-based canopy cover for (A) 1999 harvests, (B) 1998 harvests and (C) 1996 harvests, as imaged in 2000.

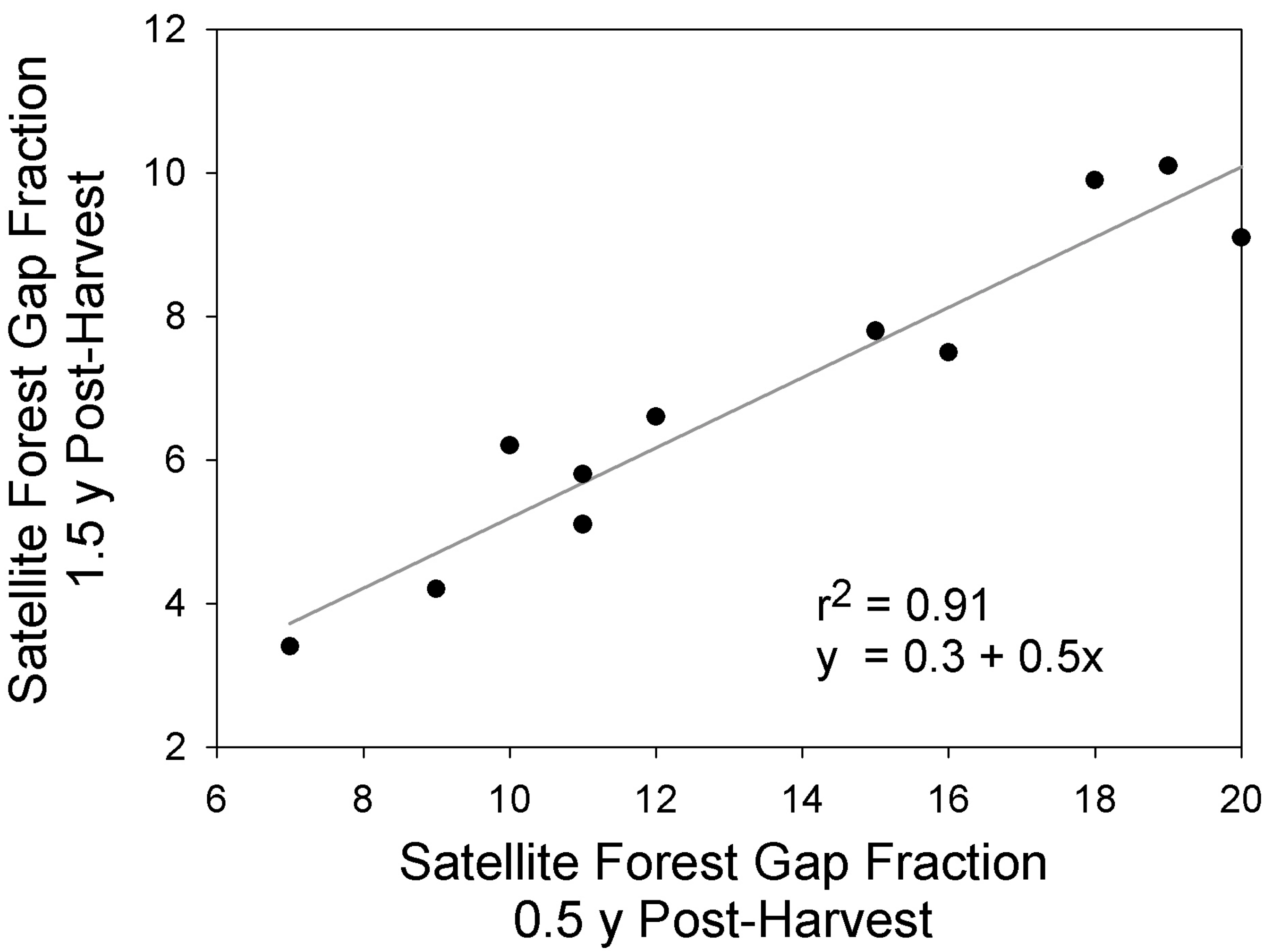

Figure 11. Satellite-based area integrated forest gap fraction at 0.5 y vs. 1.5 y post-harvest. Relationship was derived by applying equation (gap = 1.02 – 0.43C_{pv}; r^2 = 0.95, $p < 0.01$) relating gap fraction to sub-pixel forest cover fraction on a pixel-by-pixel basis to selected areas (white boxes) in Figure 7.