Monitoring Selective Logging in Tropical Evergreen Forests Using Landsat: Multitemporal Regional Analyses in Mato Grosso, Brazil

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ABSTRACT: Selective logging degrades tropical forests. Logging operations vary in timing, location, and intensity. Evidence of this land use is rapidly obscured by forest regeneration and ongoing deforestation. A detailed study of selective logging operations was conducted near Sinop, State of Mato Grosso, Brazil, one of the key Amazonian logging centers. An 11-yr series of annual Landsat images (1992–2002) was used to detect and track logged forests across the landscape. A semiautomated method was applied and compared to both visual interpretation and field data. Although visual detection provided precise delineation of some logged areas, it missed many areas. The semiautomated technique provided the best estimates of logging extent that are largely independent of potential user bias. Multitemporal analyses allowed the authors to analyze the annual variations in logging and deforestation, as well as the interaction between them. It is shown that, because of both rapid regrowth and deforestation, evidence of logging activities often disappeared within 1–3 yr.

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During the 1992–2002 interval, a total of 11 449 km$^2$ of forest was selectively logged. Around 17% of these logged forests had been deforested by 2002. An intra-annual analysis was also conducted using four images spread over a single year. Nearly 3% of logged forests were rapidly deforested during the year in which logging occurred, indicating that even annual monitoring will underestimate logging extent. Great care will need to be taken when inferring logging rates from observations greater than a year apart because of the partial detection of previous years of logging activity.

**KEYWORDS:** Forest degradation; Selective logging; Brazilian Amazon

### 1. Introduction

Tropical timber operations are global in scale and pervasive in most of the world’s remaining tropical forests. Despite the known importance of tropical logging operations in directly and indirectly causing forest impoverishment (Curran et al. 1999; Siegert et al. 2001), there are no systematic tools for monitoring these activities remotely. The Amazon is the largest remaining tract of unlogged forest and is coming under increasing development pressure (Laurance et al. 2001; Veríssimo et al. 2002). Logging operations are well developed and increasingly widespread (Smeraldi and Veríssimo 1999; Matricardi 2003). Although there is an ongoing effort by the Brazilian government to establish large-scale sustainable forestry in a system of national forests (Veríssimo et al. 2002), these efforts will be wasted if there is no way to monitor where and when logging operations are taking place.

In tropical logging operations, forests are rarely clear-cut since so few of the standing trees have market value. Instead, selective logging is practiced wherein the loggers crisscross forests, often with bulldozers, looking for valuable trees. Although selective logging activities only harvest a portion of the forest, they can damage a large proportion of the remaining trees (Uhl et al. 1991; Veríssimo et al. 1992; Pinard and Putz 1996; Huth and Ditzer 2001). Damages caused by selective logging vary as a function of the timber extraction intensity and management practices and affect the postharvest forest recovery to varying degrees. Poor felling techniques can kill up to six trees for every one that is cut down. The remaining forests become highly degraded, with up to 40%–50% of the canopy cover being destroyed by the logging operations (Uhl and Vieira 1989; Veríssimo et al. 1992). The effects of unmanaged selective logging include increased fire susceptibility (Holdsworth and Uhl 1997), damage to nearby trees and soils (Johns et al. 1996; Veríssimo et al. 1992), increased risk of local species extirpation (Martini et al. 1994), and emissions of carbon (Houghton 1996). Logged forests are increasingly being revisited multiple times to harvest additional tree species (Uhl et al. 1997; Veríssimo et al. 1995), exacerbating such problems.

Timber extraction is a major land-use activity in the Brazilian Amazon, representing 90% of Brazil’s native wood production (Veríssimo and Smeraldi 1999). Frontier logging operations catalyze deforestation by opening roads into unoccupied government lands and protected areas that are subsequently colonized by ranchers and farmers (Veríssimo et al. 1995). The results of such unconstrained activities have devastated forests throughout much of the southern Amazon (Gas-
con et al. 1998; Schneider et al. 2000). The exhaustion of timber in older frontier areas is now resulting in a chaotic migration of loggers to new frontier areas in western Pará and southern Amazonas (Veríssimo et al. 2002).

In spite of the damages and consequences of tropical logging, few attempts have been made to systematically detect and quantify areas impacted by selective logging using remote sensing techniques. In this research, we applied remote sensing and geographic information system (GIS) techniques to detect and measure the extent of forests impacted by selective logging in a study region in the Amazon state of Mato Grosso, Brazil. Logged forests were mapped using satellite imagery from different sensors [Landsat Thematic Mapper (TM), Landsat Enhanced Thematic Mapper Plus (ETM+), and IKONOS]. We applied an improved version of the semiautomated technique used by Janeczek (Janeczek 1999) to detect patios (clearings where logs are temporarily stored) within selectively logged forests and used the 180-m patio buffer radius, suggested by Souza and Barreto (Souza and Barreto 2000), to estimate the area affected by logging. We compared these results against those derived from visual interpretation of the Landsat imagery and evaluated the accuracy of both methods using ground-verified high-spatial-resolution IKONOS imagery. We also performed annual analyses of logging for the period of 1992 to 2002 using Landsat imagery and conducted an intra-annual analysis of logging-related land-cover dynamics during one year using four images between May 2001 and April 2002 and complementary field validation. The analysis was designed to assess the relative utility of the semiautomated detection and estimation method as compared to more laborious and subjective visual interpretation for monitoring selective logging. Multitemporal analyses allowed us to define the annual rates of selective logging within the study area (scene 226/68) and quantify the land-use and land-cover changes associated with forest harvest activities within the study area.

2. Earlier studies

Previous remote sensing studies of selective logging in tropical forests have generally been limited in scope and more technically oriented. Stone and Lefebvre (Stone and Lefebvre 1998) used both supervised and unsupervised classification and visual interpretation techniques to detect selective logging, using Landsat imagery, in a case study in the state of Pará. The authors were able to visually quantify areas impacted by selective logging in two areas (2459 and 3183 km²) but only for images acquired shortly after the logging activities. Even though selective logging impacts were quite evident in field observations, a few years after the logging operations, it was not possible to distinguish between any of the logged and undisturbed forests in the satellite imagery three years following harvest (Stone and Lefebvre 1998).

Souza and Barreto (Souza and Barreto 2000) developed an alternate approach for estimating selective logging areas in another case study (0.825 km²) in the state of Pará. Based on field studies, they used Landsat-based linear mixture modeling to detect logging patios. Subsequently, a field-calibrated 180-m buffer radius around the patios was employed to estimate the actual area affected by selective logging operations that was not directly visible on the satellite imagery. They reported that log landings (patios and access roads) rapidly became undetectable.
due to rapid forest regeneration in the areas with bare soils. The detection rate for patios decreased with time to virtually zero within 3–4 yr. Hence, they suggested that, ideally, monitoring of selective logging operations must be done with images acquired no more than two years apart.

Asner et al. (Asner et al. 2002) compared field data with Landsat textural analysis to determine if it was possible to directly assess canopy damage caused by selective logging in yet another case study (4.50 km²) in the state of Pará, Brazil. The authors concluded that even though textural analysis was useful for broad delineation of logged forest, the technique could not estimate the extent of canopy damage. They suggested that new approaches should be attempted using high-spatial-resolution and hyperspectral satellite imagery in order to improve assessments of selective logging impacts.

More recently, Asner et al. (Asner et al. 2004) conducted another study (∼7.8 km²) in the state of Pará, at Cauaxí Ranch. The authors combined a map of logging infrastructure and gap fraction measurements to assess forest degradation and regeneration following both conventional and reduced-impact selective logging. The authors concluded that the area of degradation caused by logging activities could not be accurately estimated based on the presence of patios. However, this directly contradicts Souza and Barreto (Souza and Barreto 2000), who previously demonstrated accurate logging area estimation based on detected patios. Asner et al. (Asner et al. 2004) did not address these findings, apparently being unaware of the work by Souza and Barreto (Souza and Barreto 2000). Asner et al. (Asner et al. 2004) used a substitution of space for time in logged areas of different ages to simulate a multitemporal assessment. Image-based detection of patios and subsequent area estimations were never actually conducted or tested. What they did show was that the number and area of logging patios was not well correlated with the number of trees removed or intensity of the harvesting methods. Therefore, the claim that accurate estimation of area affected by logging cannot be achieved, based on patio detections, is not supported.

Souza et al. (Souza et al. 2003) applied spectral mixture models to calculate fraction images from Satellite Pour L’Observation de la Terre (SPOT4) imagery. Fraction images were subsequently used to classify forest degradation in a study site of approximately 3600 km² in the state of Pará, Brazil. This approach required a previous definition of the spectral signatures or end members for each fraction (green vegetation, nonphotosynthetic vegetation, soils, and shade). Based on visual analysis of Landsat imagery and field observation, they created four classes of forests: undisturbed forests, selectively logged forests, highly degraded forests, and forest regeneration. Using a decision tree classifier, they were able to classify the satellite image with 86% overall accuracy. The authors concluded that more studies are needed for selective logging assessment in other regions with different types of forests such as in the state of Mato Grosso, Brazil.

In a broader study, Janeczek (Janeczek 1999) applied visual interpretation and indirect estimation of the area of selective logging through in the Brazilian Amazon using Landsat imagery from 1992. Janeczek (Janeczek 1999) tested a textural algorithm, individually using Landsat bands 3, 4, and 5 (red, near-infrared, and middle infrared, respectively) to detect patios. Patios were identified most effectively with band 5, because dry bare soil reflects more incoming radiation at those wavelengths than vegetation, resulting in good contrast on the images. The accu-
racy of the resulting data was not assessed because of the lack of field data, but Janecek (Janecek 1999) concluded that these techniques could be improved by integrating high-spatial-resolution satellite imagery, such as that provided by IKONOS, to assess mapping accuracy of detecting selectively logged forests.

Santos et al. (Santos et al. 2003) tested Landsat imagery and linear spectral mixture modeling to detect deforestation and selective logging in the Brazilian Amazon. Similarly to Souza et al. (Souza et al. 2003), these authors applied linear mixture models to calculate “soil” fraction images, which could be used to enhance logging patio locations within logged forests. They suggested that area impacted by logging could be reliably estimated using appropriate buffer sizes around detected patios and provide accurate monitoring of this activity in tropical forests.

3. Regional setting: Southern Brazilian Amazon

This study was conducted using one Landsat scene (path 226 and row 068) that encompassed approximately 30 105 km², in the Sinop region, State of Mato Grosso, Brazil (Figure 1), a major logging center in the Amazon. A composite of the clouds, cloud shadows, and dense smoke from all years (1992–2002) were masked out of the study region, reducing the total area of analysis by 972 km². A further 36 km² of water bodies were also removed from the subsequent analyses.

The climate in the study area is humid tropical with an average annual precipitation of 2000 mm. The mean annual temperature is 26°C. A dry season of much reduced rainfall extends from June through September. This area was originally completely covered by semideciduous forest with an emergent canopy. The predominant soil type is dystrophic red–yellow latossols (BRASIL 1980).

In the State of Mato Grosso, land use has significantly changed the natural vegetation. The landscape now consists of fragmented forests interspersed with pastures and agricultural lands. Land-use activities within this state have increased deforestation from 20 000 km² in 1978 to 143 900 km² in 2000, an increase of 719% in 22 yr (INPE 2004). According to government records, between 1990 and 2001 approximately 36 × 10⁶ m³ of round wood was logged from natural forest in the state of Mato Grosso (IBGE 2004).

4. Methods

4.1. Dataset

The imagery and products used in this study were drawn from the Tropical Rain Forest Information Center (http://bsrsi.msu.edu/trfic/home.html) at the Center for Global Change and Earth Observations (CGCEO), Michigan State University. This included deforestation layers and digital IKONOS, Landsat TM, and Landsat ETM+ images. Landsat images from 1992 to 2002 were examined for evidence of selective logging as part of the multiannual analyses. Three additional interspersed Landsat images, acquired in 2001, were used for the intra-annual analyses (Table 1).

A high-resolution IKONOS image, acquired on 30 April 2000, was used to assess the accuracy of the Landsat-based logging detection techniques. The
IKONOS scene (po_44060) encompasses 4893 ha (approximately 7 km × 7 km), located 45 km north of Sinop, where fieldwork was conducted.

The deforestation GIS layers are standard products, generated at the CGCEO. The method used is based on an initial unsupervised classification of the Landsat imagery that is subsequently reviewed and updated using visual interpretation and manual edits. Although there are multiple nonforest land-cover classes (e.g., cerrado, deforestation, water, etc.), we lumped all of these classes together to create a nonforest mask. The masking operation was done to simplify the scene by leaving only forested areas, selectively logged or not, on both the IKONOS and Landsat images. The cumulative clouds, smoke, and shadows for the time series

Figure 1. Study site location (Landsat scene, path 226 and row 068).
were masked out of all of the Landsat imagery to provide a common area of analysis.

4.2. Field study

A field study within the study region was conducted during July 2002. We conducted a field verification of selectively logged forests encompassed by the IKONOS image, acquired in 2002. We dated the time of logging activity of these areas through interviews with the local landowners. Forest damage such as tree-fall gaps, stumps, logging access roads, skidder trails, and patios were quite evident from 3 to 5 yr after logging and most of the damaged forests exhibited strong secondary regrowth. In some cases of severe impacts by logging activities, continued soil exposure (roads and patios) were observable even 5 yr after logging. The sites were localized, on the ground, using a global positioning system (GPS) and later used to perform geometric calibration of the satellite imagery. We also used the field observations to improve the IKONOS image visual interpretation, which made it more consistent with reality by identifying specific logging features in ground and satellite images.

4.3. Calibration and geometric rectification

The Landsat imagery was previously geometrically system-corrected at the CGCEO using the geometry of the sensor with sensor calibration data and attitude/positioning measurements. The 21 August 2002 Landsat scene positional accuracy was tested using ground control points of 10 road segments (total of 519.5 m), acquired in 2002 with GPS Trimble ProXR and Geo-Explorer II. These receivers yield positional accuracies of 1–4 and 2–5 m for open canopy and closed canopy forests, respectively (Karsky et al. 2000). The measurement differences between the Landsat scene (path 226 and row 068) and the ground control points averaged

<table>
<thead>
<tr>
<th>Date</th>
<th>Sensor</th>
<th>Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 May 1992</td>
<td>TM</td>
<td></td>
</tr>
<tr>
<td>26 Aug 1993</td>
<td>TM</td>
<td></td>
</tr>
<tr>
<td>12 Jul 1994</td>
<td>TM</td>
<td></td>
</tr>
<tr>
<td>29 Jun 1995</td>
<td>TM</td>
<td></td>
</tr>
<tr>
<td>1 Jul 1996</td>
<td>TM</td>
<td></td>
</tr>
<tr>
<td>5 Aug 1997</td>
<td>TM</td>
<td></td>
</tr>
<tr>
<td>5 Jun 1998</td>
<td>TM</td>
<td></td>
</tr>
<tr>
<td>19 Aug 1999</td>
<td>ETM+</td>
<td></td>
</tr>
<tr>
<td>18 Jun 2000</td>
<td>ETM+</td>
<td></td>
</tr>
<tr>
<td>8 Aug 2001</td>
<td>ETM+</td>
<td>Interannual</td>
</tr>
<tr>
<td>21 Apr 2002</td>
<td>ETM+</td>
<td></td>
</tr>
<tr>
<td>4 May 2001</td>
<td>ETM+</td>
<td>Intra-annual</td>
</tr>
<tr>
<td>8 Aug 2001</td>
<td>ETM+</td>
<td></td>
</tr>
<tr>
<td>27 Oct 2001</td>
<td>ETM+</td>
<td></td>
</tr>
<tr>
<td>21 Apr 2002</td>
<td>ETM+</td>
<td></td>
</tr>
</tbody>
</table>
30.6 ± 29.4 m (±standard deviation) and 33.5 ± 53.7 m for x and y directions, respectively. The 2002 Landsat image was subsequently used to georeference the other imagery in the multitemporal series by matching 10 coordinates of known and spatially well distributed physical features recorded by each of those images to geographic coordinates of the same features from the reference image. A polynomial distortion model and nearest-neighbor resampling method were used to rectify the images, resulting in root-mean-square (rms) positional errors varying between 0.21 and 0.46 pixels.

Geometric rectification of the IKONOS image was done using the bicubic resampling method provided by the IKONOS image distributor. We double-checked the geometrically corrected Landsat image using 10 well-defined feature centers on an IKONOS image of the same year. The measurement differences between the IKONOS scene (po_44060) and the Landsat image averaged 29.2 m (±14.3 m) and 24.3 m (±12.1 m) for x and y directions, respectively.

4.4. Accuracy assessment

Omission and commission errors of the semiautomated and visual techniques were estimated through comparison with both the IKONOS imagery and field-derived ground truth data. Specifically, the field data were used to verify that the visual detection of recent selective logging activity within the 1-m resolution, pansharpened IKONOS imagery provided accuracy equivalent to ground-based mapping. Visual interpretation of the red–blue–green (RBG) 3/4/2 color composite image, displayed at full resolution on a computer screen, was the only technique used to detect selectively logged forests for the IKONOS image. The result of this mapping effort was subsequently considered as “truthed” data and was used to assess the accuracy of semiautomated analysis and visual interpretation using the Landsat images.

For the regional Landsat subset, corresponding to the IKONOS image footprint, the accuracy, precision, and associated kappa statistics of the semiautomated and visual interpretation techniques for estimating selective logging areas were quantified. Comparison provided quantitative estimates of the relative classification accuracy and measures of both commission and omission errors for the two techniques (visual and semiautomated) for estimating areas affected by selective logging.

4.5. Detection of selectively logged forests

4.5.1. Semiautomated detection of selective logging

As previously discussed, patios are small clearings cut into the forest as temporary storage and staging areas for timber to be transported to regional sawmills by loggers (Stone and Lefebvre 1998; Souza and Barreto 2000).

As part of the deforestation analysis previously performed by the Center for Global Change and Earth Observations, images were classified using an unsupervised image classification model of bands 2, 3, 4, and 5 into seven thematic classes: forest, deforestation, regeneration, cerrado, clouds, shadows, and water. We used these deforestation maps to create masks of nonforested areas for each
image used in the multitemporal analysis. Nonforest areas (deforestation, cloud, shadow, cerrado, water body, and regenerating vegetation) were subsequently masked out of the Landsat imagery. Therefore, the semiautomated textural algorithm for detecting patios was applied solely to areas classified as being forested, both selectively logged and undisturbed (Figure 2).

We tested the use of the textural algorithm on variance information from bands 3, 4, and 5 derived using $3 \times 3$, $5 \times 5$, and $7 \times 7$ pixel moving windows. Band 5 using a $5 \times 5$ pixel window provided the best overall rate of patio detection and was used in the rest of the analyses. The textural algorithm segments an image and classifies the segments, giving the image sharper edges. It generally indicates the spatial variation in neighboring pixel values. The addition of texture to a satellite image enhances structural information that assists in the detection of cryptic landscape features (ERDAS 1997). A $3 \times 3$ median filter was then applied to the texture images to reduce “noise,” for example, small natural clearings caused by individual tree falls (Figure 3).

Textural images were assigned the binary classification of 1 for variance values of 6 to 16 and 0 for all other values. The $5 \times 5$ variance window generated erroneous pixel values, similar to patios, along forest to nonforest edges. Therefore, to correct this, an additional step was added to automatically remove the edge artifacts in the textural images. Specifically, the original nonforest mask was expanded by three pixels in all directions and applied to the texture image so that these erroneous edge pixels could be reclassified as nonpatio areas (value = 0).

The binary images were then converted to vector format and hand edited to

![Figure 2. Subset of the Landsat scene (path 226 and row 068; acquired on 8 Aug 2001), showing (left) a color composite (RGB 5/3/2) image and (right) band 5 with deforestation masked out.](image-url)
remove any remaining extraneous features that were not associated with logging patios. These included forest access roads and a few remaining forest edge artifacts such as those along rivers. It is important to note that, although access roads and forest edges may show pixel values within the same range of patios in the textural images, forest edges and logging roads were easily identified and separated from patios based on their spatial location, distribution, and characteristics. Patios are sparsely isolated within logged forests. Unlike patios, access roads show up as
4.5.2. Visual interpretation

A complementary visual interpretation by one of the authors (E. Matricardi) was used to determine the detection capability for delineating selectively logged forests using RBG 5/3/2 color composites of the Landsat images displayed at full resolution on a computer screen.

As criteria for the visual interpretation, logged forests were identified by obvious canopy degradation, since logging activities leave log landings and tree-fall gaps along with obvious canopy disturbance. This type of land use creates a characteristic pattern of white points on the Landsat images (bands 5, 3, and 2 color composites), which are patios or roads, embedded in the red hues of the forest canopy. Visible evidence of logged forest on satellite imagery included spectrally bright patios, roads, and obvious canopy disturbances as well as logged areas that exhibited faded log landings. The areas around the log landings, together with areas of obvious canopy degradation, were hand digitized as polygons into a vector GIS layer. They were then classified as logged forest. Hand digitizing was done along the periphery of visible canopy disturbance. Potentially logged forests, as evidenced by the existence of logging patios that did not have visible canopy disturbance on satellite images, were not digitized. Areas of visible logging were described as obvious logging. Logged forests were hand digitized on each image using GIS.

4.6. Multitemporal analyses

4.6.1. Interannual

Selectively logged forests were identified in the Landsat scene path 226 and row 068, on an annual basis, between the years 1992 and 2002. Pairs of data layers were created for each year, one using visual interpretation and the other using the semiautomated methods, yielding a total of 22 layers of selective logging coverage. For the interannual analysis, 11 additional layers were created to include the total selectively logged forests detected using a combination of both techniques, for each year of analysis.
The selective logging layers for each year of analysis were then overlaid. Cumulative logging was measured by adding all detected selective logging areas over the period of analysis. Overlapping areas of selective logging were not double counted. For incremental annual logging measurements, the year 1992 was the starting point. Logging areas detected in 1993, and not overlapping areas detected in the previous year, were considered to be new logging areas for the given year. Again, logging areas detected in 1994 and not overlapping areas detected in previous years were considered to be the new logging increment for that year. Logging areas that had previously been detected were not considered in the annual

![Image](image.png)

Figure 4. Textural image derived from Landsat image band 5, showing 180-m buffer radius around enhanced patios, which estimates areas impacted by selective logging activities (visibly or not) on satellite imagery.
increment. This procedure was carried out sequentially for all years of analysis. To prevent overestimation, no annual logging increment is given for 1992 because it was the first year of analysis and therefore has no previous year for comparison to control for existing logging.
We defined revisit logging as logging detected in areas of previous logging that had recovered sufficiently to become undetectable for one or more years prior to the return of the loggers. These areas were detected by sequentially examining the forest cover condition in previously logged forests and assigning each pixel a value corresponding to time since last detection as having been logged. Only those previously logged areas, which had gone for one or more years without any sign of logging activity, after having reestablished enough vegetation cover to become indistinguishable from unlogged forest, were classified as revisit logging once new logging activity was detected. Most previously logged forests were never revisited during the period of study and were therefore not classified as being subjected to revisit logging.

Finally, by overlapping the total selective logging areas with a sequential deforestation layer, the area of previously logged forest that was subsequently deforested each year was measured. The area of logged forest that was deforested in 2002 is not given because it is the last year of analysis, and hence, there is no following year of deforestation data with which to calculate values for deforested logging areas of that year.

4.6.2. Intra-annual

For the intra-annual analysis, we conducted analyses analogous to those in the interannual analyses but focused on four dates spanning a single year (Table 1). The more detailed temporal scale allowed us to better assess how the dynamic processes of selective logging and deforestation interacted. Specifically, the interrelation of logging and deforestation coverages from the various dates enabled us to quantify the amount of logging that occurred shortly before subsequent deforestation. This allowed us to assess how this activity could bias the annual logging estimates. In this progression, for example, a forest could be in a natural state in May 2001, have evidence of logging activity in August 2001, and be completely deforested in October 2001. These sorts of interactions and rapid changes were not quantifiable using the annual comparisons alone.

5. Results

5.1. IKONOS logging analysis

Analysis of the land-cover change in the IKONOS image subset (7 km x 7 km) of the study region showed that 14% had been deforested by 2000. Field data on the dates and locations of logging operations were compared to the visual detection of these operations in the 2000 image. Small features left behind in ongoing (1999–2000 logging events) selective logging areas, such as tree-fall gaps and skidder trails, were visually distinct on the pan-sharpened IKONOS image. In this case, the borders between logged and undisturbed forests for these areas were well defined and easily digitized. Logged forests prior to 1999 were also visually detectable on the IKONOS image, but the definition of the border between logged and undisturbed forest was partially obscured by ongoing forest regeneration. Logged forests from 1998 had a few visible areas of soil exposure in old patios and roads, but visual detection of logging damage in the surrounding forest was almost completely obscured by fast-growing secondary vegetation and crown closure. In these
relatively older logging areas, the heavy presence of secondary regrowth in the vicinity of log landings was used to delineate the borders of logged forests.

A total of 1266.5 ha (25.9%) of selectively logged forests were detected in the IKONOS image. The remaining 60% appeared to be undisturbed forest (Table 2). This area of detected logging in the IKONOS imagery was used as a ground truth proxy for subsequent evaluation of the accuracy and precision of the Landsat-based logging estimates.

5.1.1. Accuracy assessment of the remote sensing techniques

Both the visual interpretation and the semiautomated detection estimates of selective logging activity were evaluated against the known logging activity within the 4900-ha validation region. Visual interpretation of selective logging activity within the Landsat imagery detected an area equivalent to only 75% of the total logged forest that had been mapped using IKONOS and complementary field studies. The area delineated as having been logged was very precise, with a commission error of only 1.5%; however, the omission error of 26.5% was quite large.

The semiautomated analysis was tested for the same area using a buffer radius of 180 m. Using these parameters, the estimated area of logging was 99.8% of the known amount of logging. However, spatial comparison of the estimated and known areas of logging showed that, although the estimated area was nearly exact, the spatial positioning was not completely precise. The commission error was actually 18.9%, but this was very nearly canceled by an omission error of 19.1%. The complete detection results and errors of each technique are presented in Table 3.

Table 2. Land-use map based on visual interpretation of an IKONOS image, representing a subset of the entire study region. Source: Visual interpretation using RGB 3/4/2 and 4/3/2 color composites of the IKONOS image, displayed at full resolution on a computer screen.

<table>
<thead>
<tr>
<th>Land use</th>
<th>Area (ha)</th>
<th>Percent (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Logged forest</td>
<td>1266.5</td>
<td>25.9</td>
</tr>
<tr>
<td>Undisturbed forest</td>
<td>2939.8</td>
<td>60.1</td>
</tr>
<tr>
<td>Deforestation</td>
<td>686.7</td>
<td>14.0</td>
</tr>
<tr>
<td>Total</td>
<td>4892.9</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Table 3. Total selectively logged forest detected in 2000 in a subset* of a Landsat scene (path 226, row 068) using automated method, visual interpretation, and both techniques combined.

<table>
<thead>
<tr>
<th>Logged forest</th>
<th>Visual Area (ha)</th>
<th>Visual Percent (%)</th>
<th>Automatic Area (ha)</th>
<th>Automatic Percent (%)</th>
<th>Visual and automatic Area (ha)</th>
<th>Visual and automatic Percent (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correctly identified (overlap between IKONOS × Landsat)</td>
<td>930.3</td>
<td>73.5</td>
<td>1025.0</td>
<td>80.9</td>
<td>1156.7</td>
<td>91.3</td>
</tr>
<tr>
<td>Commission</td>
<td>19.1</td>
<td>1.5</td>
<td>238.7</td>
<td>18.9</td>
<td>244.8</td>
<td>19.3</td>
</tr>
<tr>
<td>Omission</td>
<td>336.1</td>
<td>26.5</td>
<td>241.5</td>
<td>19.2</td>
<td>109.8</td>
<td>8.7</td>
</tr>
<tr>
<td>Total detected**</td>
<td>949.4</td>
<td>75.0</td>
<td>1263.7</td>
<td>99.8</td>
<td>1401.6</td>
<td>110.7</td>
</tr>
</tbody>
</table>

* The subset encompasses an IKONOS scene (po_44060), a total of 4893 ha.
** The total logged forests detected using IKONOS were 1266.5 ha, which represents 100% of detected selectively logged forests in this subset.
Intercomparison of the polygons from the two techniques showed a 69% overlap in information. If combined, the resultant estimate equaled 110.7% of the actual logged area with an omission error of only 8.7%. The semiautomated and visual interpretation estimates provided unique contributions of 20% and 11%, respectively, to the composite estimate (Figure 6). Standard Producer’s and User’s accuracies and kappa statistics are presented in Table 4.

### 5.1.2. Buffer size sensitivity

Comparison of the buffer radii—150, 180, 210, 240, and 270 m—showed that omission errors decreased and commission errors increased with increasing buffer size. The maximum area of actual logging, 92.5%, was encompassed in the 270-m buffer size, but the overestimation (commission error) grew to greater than 51%. Conversely, at the 150-m buffer size, the commission error was only 14%, but the omission error was 26% (Figure 7).

**Table 4. Accuracy assessment results of detecting selective logging.**

<table>
<thead>
<tr>
<th>Techniques</th>
<th>User’s accuracy (%)</th>
<th>Producer’s accuracy (%)</th>
<th>Overall accuracy (%)</th>
<th>Kappa coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual interpretation</td>
<td>98.2</td>
<td>73.6</td>
<td>92.8</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.80*</td>
</tr>
<tr>
<td>Automated method</td>
<td>81.3</td>
<td>81.0</td>
<td>90.2</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.75*</td>
</tr>
<tr>
<td>Visual and automated</td>
<td>82.9</td>
<td>91.2</td>
<td>92.9</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.82*</td>
</tr>
</tbody>
</table>

* Overall kappa.
Analysis of the total error (commission plus omission) showed a minimum of 37.4% at the 210-m buffer size. However, this was only 0.6% better than that of the 180-m buffer error. Furthermore, the balance between commission and omission errors of the 180-m buffer was only 0.2%, as opposed to 9.8% for the 210-m buffer size. The 180-m buffer consequently provided the best estimate of the total logging area. For this reason, the 180-m buffer size was used for the remainder of the analyses.

5.2. Multiannual analyses of regional land-cover change

The regional land-cover change analyses using the entire spatial extent of the Landsat scene showed that less than 24% of the study region (path 226 and row 068) had been deforested by 2002. However, an additional 32% of the region’s forests had been selectively logged, one or more times, between 1992 and 2002 (Table 5).

The total annual amount of detected selectively logged forest increased substantially between 1992 and 2002, from approximately 1166 to 4397 km², respectively. The selectively logged area increment, which refers only to new areas of forest with logging activity, as opposed to older, still detectable logging areas or relogging of previously logged forests, was 1079 km² yr⁻¹ (±349 km²) from 1993 to 2001. A reduction of the annual logging area increment was observed during the 1994 to 1996 period, averaging roughly 730 km² yr⁻¹ with a minimum value of 676 km² in 1995. As seen in Table 6, 2002 has a very low increment (575 km²) of new logging areas, but this estimate covers only the 6-month period from October 2001 to April 2002. The greatest annual increment of new forests being logged, 1839 km², occurred in 1999.

In addition to forest areas impacted by selective logging, an annual increment of
Table 5. Cumulative deforestation and persistence of logged forest on satellite imagery. Path 226, row 068, which encompasses 30105 km². A mask of 972 km² of the cumulative clouds, shadows, and smoke was applied for all scenes. Approximately 36.3 km² of water bodies that were annually detected on all scenes were not included.

<table>
<thead>
<tr>
<th>Year</th>
<th>Undisturbeda</th>
<th>Logged undetectedb</th>
<th>Logged detectedc</th>
<th>Cumulative deforestationd</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(km²)</td>
<td>Percent (%)</td>
<td>(km²)</td>
<td>Percent (%)</td>
</tr>
<tr>
<td>1992</td>
<td>24 527.1</td>
<td>81.5</td>
<td>—</td>
<td>3403.6</td>
</tr>
<tr>
<td>1993</td>
<td>23 123.6</td>
<td>76.8</td>
<td>211.9</td>
<td>3900.3</td>
</tr>
<tr>
<td>1994</td>
<td>22 396.4</td>
<td>74.4</td>
<td>564.6</td>
<td>4246.4</td>
</tr>
<tr>
<td>1995</td>
<td>21 610.8</td>
<td>71.8</td>
<td>1345.2</td>
<td>4663.3</td>
</tr>
<tr>
<td>1996</td>
<td>20 641.5</td>
<td>68.6</td>
<td>1815.9</td>
<td>5036.8</td>
</tr>
<tr>
<td>1997</td>
<td>19 381.6</td>
<td>64.4</td>
<td>2202.5</td>
<td>5420.8</td>
</tr>
<tr>
<td>1998</td>
<td>18 094.9</td>
<td>60.1</td>
<td>2275.3</td>
<td>5733.4</td>
</tr>
<tr>
<td>1999</td>
<td>15 953.6</td>
<td>52.9</td>
<td>2692.6</td>
<td>6221.4</td>
</tr>
<tr>
<td>2000</td>
<td>14 793.2</td>
<td>49.1</td>
<td>3632.5</td>
<td>6357.7</td>
</tr>
<tr>
<td>2001</td>
<td>13 248.6</td>
<td>44.0</td>
<td>4665.8</td>
<td>6844.0</td>
</tr>
<tr>
<td>2002</td>
<td>12 430.1</td>
<td>41.3</td>
<td>5151.6</td>
<td>7117.5</td>
</tr>
</tbody>
</table>

a Total of cumulative undisturbed forest.
b Total of logged forest detected in previous years and undetected for that given year.
c Total of logged forest detected for that given year.
d Total of cumulative deforestation for that given year.

Table 6. Land-use and land-cover change in the study site area. A mask of 972 km² of the cumulative clouds, shadows, and smoke was applied for all scenes. Approximately 36.3 km² of water bodies that were annually detected on all scenes were not included.

<table>
<thead>
<tr>
<th>Year</th>
<th>Deforestation incrementa (km²)</th>
<th>Logging incrementb (km²)</th>
<th>Logging deforested by 2002c (km²)</th>
<th>Revisited logging (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>—</td>
<td>—</td>
<td>265.3</td>
<td>—</td>
</tr>
<tr>
<td>1993</td>
<td>496.7</td>
<td>1172.1</td>
<td>338.6</td>
<td>32.0</td>
</tr>
<tr>
<td>1994</td>
<td>346.0</td>
<td>720.0</td>
<td>308.0</td>
<td>51.4</td>
</tr>
<tr>
<td>1995</td>
<td>416.9</td>
<td>676.2</td>
<td>206.8</td>
<td>101.6</td>
</tr>
<tr>
<td>1996</td>
<td>373.5</td>
<td>802.4</td>
<td>158.1</td>
<td>148.9</td>
</tr>
<tr>
<td>1997</td>
<td>384.0</td>
<td>1033.9</td>
<td>138.9</td>
<td>319.3</td>
</tr>
<tr>
<td>1998</td>
<td>312.6</td>
<td>1113.0</td>
<td>185.6</td>
<td>431.7</td>
</tr>
<tr>
<td>1999</td>
<td>488.0</td>
<td>1838.9</td>
<td>145.6</td>
<td>491.6</td>
</tr>
<tr>
<td>2000</td>
<td>136.3</td>
<td>1169.9</td>
<td>122.7</td>
<td>394.5</td>
</tr>
<tr>
<td>2001</td>
<td>486.3</td>
<td>1181.0</td>
<td>36.15</td>
<td>455.3</td>
</tr>
<tr>
<td>2002</td>
<td>273.5</td>
<td>575.4</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>3713.9</td>
<td>10 282.7</td>
<td>1905.7</td>
<td>2426.3</td>
</tr>
</tbody>
</table>

Annual rate 371.0 ± 112d 1028.0 ± 366d

a Deforestation increase (new areas only).
b Selective logging increase (new areas only).
c Total selective logging from a given year deforested by 2002.
d Average for 1993–2001 period.
371 km\(^2\) yr\(^{-1}\) (±112 km\(^2\)) was deforested during the 1992 to 2002 interval. The most significant deforestation increases were observed in 1993, 1995, 1999, and 2001, at 497, 417, 488, and 486 km\(^2\), respectively. All annual cohorts of logged forests experienced deforestation (Table 6). The mean deforestation rate for logged forests was 3.8% yr\(^{-1}\). A total of 51.3% of all deforestation between 1992 and 2002 occurred in logged forests. During this interval, a total of 3714 km\(^2\) of forest was deforested while 11 449 km\(^2\) was selectively logged.

Undisturbed forest area in the study region decreased from 81.5% to 41.3% of the total land area between 1992 and 2002. Selective logging was mainly responsible for this reduction, being responsible for 31.7% of the drop while new deforestation occurred over 12.3% of the total study site area. There was overlap between logging and deforestation, with 16.6% of all detected logged forests having been deforested by 2002. Conversely, 53.9% of the relict logging areas had recovered sufficiently to be undetectable in the 2002 satellite imagery.

5.3. Intra-annual analysis

For the detailed intra-annual analysis of land-cover change in four images between May 2001 and April 2002, the total area of detectable logging was 4134 km\(^2\). The total increment of logging in previously unlogged forests was 1249 km\(^2\). Deforestation totaled 274 km\(^2\) for the study period. Of the deforested areas, 13% (36 km\(^2\)) occurred on land that had previously been logged (Table 6). Furthermore, roughly 3% of the selective logging that was detected during the 2001–02 interval was actually deforested by the time of the April 2002 satellite image (Table 7).

6. Discussion

6.1. Detection of logging

Our results show that the infrastructure (patios, roads) associated with most selective logging activities in the “terra firme” forests of this region of the Amazon are clearly detectable within Landsat imagery and that areas damaged by selective logging are visually distinguishable. Furthermore, we have shown, through comparisons with field-mapped logging areas and high-resolution IKONOS imagery-based analyses, that the semiautomated estimation of logged area, based on buffering of recent selective logging damage (e.g., patios and roads), can provide very

### Table 7. Intra-annual increment of selective logging.

<table>
<thead>
<tr>
<th>Period of time</th>
<th>Selective logging increment* Area (km(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 2001–Aug 2001</td>
<td>483.4</td>
</tr>
<tr>
<td>Oct 2001–Apr 2002</td>
<td>491.5</td>
</tr>
<tr>
<td>Total logging increment (2001–02)</td>
<td>1248.4</td>
</tr>
<tr>
<td>Total of 2001 logged forest deforested by 2002**</td>
<td>36.15</td>
</tr>
</tbody>
</table>

* Selective logging increase (new areas only) in a given period.

** Total cumulative deforestation from May 2001 to Apr 2002.
good estimates of the total area affected by logging. This is important because it shows that robust estimates of logging activity can be obtained using methods that are largely independent of the potential systematic biases of individual interpretation.

Visual interpretation was more precise in defining the limits of areas that were affected by logging. However, it also had substantially more omission of smaller, more recent, or low intensity logging events than the semiautomated method of detection and estimation. Despite the commission errors associated with the semiautomated technique, we believe it to be a more accurate tool for detection and estimation of the area impacted by recent logging operations. The semiautomated technique provided excellent detection of all logging areas, with very little false detections outside of them. The commission and omission errors are due to the regular shapes, resulting from the use of a constant buffer size, which cannot account for the irregularities of actual logging activities. Therefore, although loggers do, on average, tend to work within 180 m of logging patios and roads, they are sometimes constrained by physical boundaries (e.g., rivers, streams) or property lines. Likewise, they exploit areas outside of the average 180-m radius at times for convenience. The random nature of these variations in exploitation procedures helps explain why the commission and omission errors are roughly equivalent, effectively canceling one another out to provide a surprisingly accurate estimate of the total amount of logging activity. To confirm this, we divided the IKONOS-verified region of logging into a 500-m grid. Each grid cell had a calculated value of actual and detected logging. These grids were randomly ordered multiple times and the cumulative accuracy of the detected estimates was compared against the actual amount of logging. As can be seen in Figure 8, the accuracy of the estimates quickly converges toward 100% in all cases, with an expected error of less than 10% at sample sizes greater than 1000 ha. The key point is that the semiautomated technique precisely detects regions of logging activity and accurately estimates the amount of area in those regions that have been harvested, even though it may not indicate exactly which trees might have been damaged. The method is therefore robust, since the spatial errors are relatively insignificant, and the overall estimate of the logging activity will tend to increase in accuracy with larger sample sizes.

6.2. Land-cover dynamics

Selective logging of forests modifies subsequent land-use and land-cover dynamics in the region. Approximately 1900 km$^2$, or 16.6% of the logged forests detected during the period of 1992–2001, were deforested by 2002. Furthermore, the results of the intra-annual analysis that enabled us to investigate rapid land-cover changes showed that deforestation immediately followed logging activities in some cases. Despite having been logged, these areas with rapid clearing were classified as deforestation in annually classified imagery. These rapid land-use changes after logging may have reduced the total logging area detected by 2.9%. Since we only have 1 yr of intra-annual analysis, however, we do not know if this dynamic was characteristic of the entire study period. The rapid postlogging deforestation represented 13% of the total deforestation from May 2001 to April 2002.

Previous studies have shown that there is a synergism between forest fragmen-
In the study region, selectively logged forests exacerbate the landscape level fire dynamic. Overall, the probability of forest burning in 1999 increased by 49% in forests known to have been logged in either 1992, 1996, or 1999 (Cochrane et al. 2004). The effect was spatial, however, with logging enhancing the penetration distance of fire into forest interiors. Average penetration distances were 700 m in logged forests versus 240 m in unlogged forests. These findings were attributed to the greater fire susceptibility and fire spread rates (Cochrane et al. 2004) that are associated with the open canopies and rapid drying in degraded forests (Cochrane et al. 1999).

Logging activity itself seems to have changed within the region during the period of study. For example, comparison of the 1994–97 and 1998–2001 time periods shows that logged forests that persisted in a detectable state for multiple consecutive years have increased from 49% to 56% of the total annually detected logged forest. This may be indicative of increased harvest intensities and the growing number of species that are now being accepted by local sawmills. This progression of merchantable timber species has been documented in the mature timber markets of Paragominas, Pará (Uhl et al. 1997), and was confirmed for the study region by a local sawmill owner (A. Zanchete 2002, personal communica-

Figure 8. Cumulative accuracy of estimated logging for random selections of 500-m grid squares. The graph represents multiple random series and illustrates that the technique provides increasingly accurate estimates with larger sample sizes. The total sample size for validation was 4895 ha and for the larger study was $2.9 \times 10^6$ ha.
We have observed extraction intensities of between 70 and 80 m$^3$ ha$^{-1}$ of round wood within the study region, which corresponds to very high intensity logging (e.g., >69 m$^3$ ha$^{-1}$) in Paragominas, state of Pará, observed by Gerwing (Gerwing 2000).

The most pronounced change, however, was in the annual production area, defined as the newly detected logging increment plus the area of revisit logging for a given year’s timber harvest. Between 1992 and 1997, the production area averaged 892 km$^2$ yr$^{-1}$, varying between 728 and 1183 km$^2$ yr$^{-1}$. From 1998 to 2001, however, the average production area increased to 1735 km$^2$ yr$^{-1}$ with a range of 1432 to 2270 km$^2$ yr$^{-1}$. During this time period there was a large increase in revisit logging. We defined revisit logging as logging detected in areas of previous logging that had formerly recovered sufficiently to become undetectable for one or more years prior to the return of the loggers. The areas of revisit logging were 32, 319, and 455 km$^2$ in 1994, 1998, and 2002, respectively. In the 1991–97 time period, this activity accounted for only 9% of the total production area, but after 1998, it increased to 23.6% of the total area of production. This changing dynamic may be due to both the expansion of the number of marketable tree species and the decreasing availability of virgin forest resources over time.

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References


