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# Using multi-temporal satellite data to evaluate selective logging in Para, Brazil

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**Abstract.** Clear cutting in tropical forests is common. A newer phenomenon, selective logging, is evident in Amazonia when examined with high-resolution satellite data. We have quantified selective logging by digitizing satellite imagery and have found that it is much more difficult to detect than clear cutting. Selective logging is likely under-reported in satellite imagery-based estimates of change in Amazonia as the visible signal of selective logging may be evident for only a limited time. We have found that the areas affected by selective logging have increased over time and have become more widely distributed. Little land selectively logged, perhaps 10%, was converted to pasture. Selective logging altered 12% of the total forested area of one study region, yet was undetectable in satellite imagery three years later. It is unclear how long the visual clues of selective logging will remain apparent in satellite imagery in subsequent years.

## 1. Introduction

Recent estimates are that up to 10% of the tropical moist forests of Brazilian Amazonia have been cleared (Tucker *et al.* 1990, Fearnside 1992, INPE 1992, Stone and Schlesinger 1992, Skole and Tucker 1993). The majority of forest clearing that has been measured has been done by clear cutting and burning for pasture and for subsistence farming with little timber extraction. A relatively new trend in the forests of Amazonia, and one that is less obvious when viewed with satellite data, is selective logging of high-value timber (Uhl and Viera 1989, EMBRAPA-CPATU 1991, Uhl *et al.* 1991, Verissimo *et al.* 1992, Gullison and Hardner 1993, Verissimo *et al.* 1995).

There is little quantitative information on this new trend despite its potentially large impact in terms of carbon release, forest biomass, hydrology, sustainable development and biotic diversity. For instance, most carbon budgets for Brazil have not included selective logging in their estimates of carbon release (see e.g. Fearnside 1992, Schroeder and Winjum 1995). Therefore, some of these studies may be underestimating carbon loss to the atmosphere due to this new phenomenon. Although selective logging leaves most trees standing, the amount of biomass in the forest declines as loggers remove the larger trees that contain the majority of the biomass.

Many of the studies of deforestation in Amazonia have concentrated on simple, cleared forest versus uncleared forest statistics (Woodwell *et al.* 1987, Fearnside *et al.* 1990, Skole and Tucker 1993) because clear cutting followed by burning has been the dominant form of land conversion. In addition, synoptic measurements of forest change with satellite data, how most estimates are established, either ignore this subtler phenomenon or are unable to distinguish it. The most recent estimates of forest clearing of Amazonia have used visual interpretations of Landsat satellite data

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(Skole and Tucker 1993) or digital classification of 1·1 km resolution National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer (NOAA AVHRR) data (Stone and Schlesinger 1992, Stone *et al.* 1994). The former technique uses 1:250,000 black and white photoprints and manual digitization of forest and non-forest categories. Selective logging, though visible, was not examined (D. L. Skole, personal communication, 1992). In the latter case, the resolution of the imagery was too coarse to distinguish selective logging.

We sought, through examination of 1991, 1988, and 1986 Landsat satellite imagery, to determine the extent of this type of forest exploitation over areas west and north-east of the urban centre of Paragominas, Para. We also hoped to gain insights into how fast selective logging may be occurring, and to learn how long this type of clearing remains visible in Landsat Thematic Mapper (TM) data.

## 2. Regional setting: Eastern Pará, Brazilian Amazonia

The city of Paragominas is about 300 km south of Belém at 3° S latitude, 47° 40′ W longitude. The annual rainfall averages 1700 mm$^{-1}$ with a dry season from July to November. Annual temperatures are about 25° C. The region has both high forest and low forest regions (Uhl and Buschbacher 1985) whose above ground biomass is about 300 tons ha$^{-1}$ (Uhl and Buschbacher 1985, Nepstad *et al.* 1995).

Clearing of forest for pasture became less attractive by the late 1970s as government and bank support decreased (Uhl and Buschbacher 1985). At the same time, the effort needed to maintain increasingly impoverished pastures increased, and the subsidized road system improved to the point where timber extraction through selective logging became profitable. Subsequently, some timber was removed prior to burning and clearing for pasture. Timber extraction in this region began around 1975 (Uhl and Buschbacher 1985).

## 3. Methods and results

### 3.1. *Satellite imagery, calibration and geometric rectification*

Digital Landsat TM data were obtained from the Brazilian National Space Agency (INPE) (table). Imagery from 17 July 1986, 28 May 1991 and 16 August 1991 was obtained and examined for an area west of the city of Paragominas. Imagery from 1 September 1988 and 24 July 1991 of the region immediately north-east of the city was acquired and similarly examined. The 1986 imagery contained discrete cumulus clouds that covered about 2% of the common area of the three images examined. The common area covered by the May and August 1991 imagery was cloud-free. Cloud cover in the 1986 imagery limited the estimation of the rates of forest clearing for the larger area. The 1988 image also contained discrete cumulus clouds and shadows covering 18% of the landcover of the area examined. These two

Table 1. Landsat TM satellite data for the region of Paragominas, Para, Brazil, used in this study.

| Date of imagery | Path | Row | Comments |
|---|---|---|---|
| 17 July 1986 | 223 | 62 | West of city, clouds in north-east |
| 28 May 1991 | 223 | 62 | West of city |
| 16 August 1991 | 223 | 62 | West of city |
| 1 September 1988 | 222 | 62 | North-east of city, minor clouds |
| 24 July 1991 | 222 | 62 | North-east of city |

sets of satellite imagery were used to define the two regions, one region west of the city (the 'western region') and the other a region north-east of the city (the 'north-eastern region'), analysed in this study.

Bulk atmospheric corrections were applied to all the satellite data by subtracting from each band the lowest digital value found for that band in the image (Richards 1986).

There was inadequate mapping available for the western region and so those images were geometrically co-registered to the May 1991 Landsat TM image. For the north-eastern region, the Landsat TM digital images were geometrically rectified to a 1:100 000 scale Universal Transverse Mercator (UTM) projection map of the municipality of Paragominas (DSG 1986).

### 3.2. *The western region*

#### 3.2.1. *Thematic classification and analysis*

All images were classified using either a supervised (ERDAS Maxclas, a maximum likelihood algorithm) or unsupervised classification (ERDAS Clustr) algorithms (ERDAS 1991) into a few simple classes which included intact tropical moist forest, open water and rivers, fields and pastures, clouds, pasture shadows and forest shadows for the 1986 imagery. No attempt was made to classify the areas of selective logging automatically nor did we attempt to map separately forest regrowth (secondary forest) west of the city.

#### 3.2.2. *Digitization of areas of selective logging*

Because the selective logging process leaves behind a mixture of intact forest with treefall gaps, primary and secondary roads, patios or truck loading areas (patios dos estocagems) and damaged trees, it is doubtful that an automatic classification procedure could be developed to define the location and extent of logging. Instead, we relied upon visual interpretation to define the location and extent of the forest affected by selective logging for the 1986 and 1991 images. These areas were circumscribed digitally on a computer screen (figure 1) with polygons registered to the image's raster coordinates.

After all images had been classified into the simple categories of fields, forest, clouds, cloud shadows on forests, cloud shadows on fields, flood plain water and river water, the digitized polygons of regions of selective logging were used to define how much selective logging was found in the area classified as intact tropical moist forest. Categories of shadows on forest and shadows on field were combined into the forest and field categories respectively. The areas of selective logging that were classified as fields and pasture were small and were not included in the final selective logging statistics.

#### 3.2.3. *Results*

We found no spatial overlap when comparing the polygons of selective logging from 1986 and 1991 data in the western region. Those areas that were selectively logged in 1986 were not selectively logged in 1991. Also, there were no apparent visual clues in the 1991 imagery that allowed location of the areas that were selectively logged in 1986. Of the areas selectively logged in 1986, 91% were classified as forest in the 1991 imagery and only 9% were classified as fields, pasture and re-growth. Therefore, the majority of areas selectively logged five years earlier remained as forest and were not converted to pasture (table 2). Over the 1986 to 1991 period,

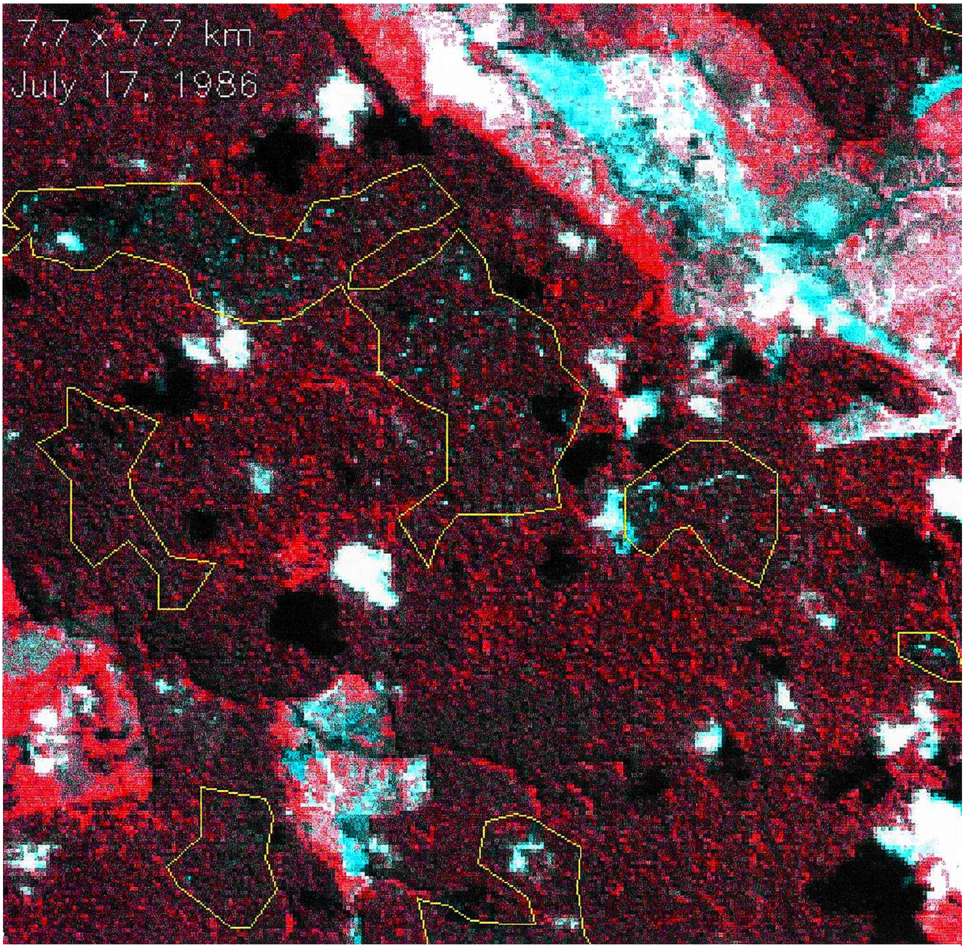


Figure 1. A 7 km by 7 km portion of Landsat TM data of the western region is shown in this figure with typical false colours. The yellow polygons enclose areas of selective logging defined by visual interpretation. Bright blue pixels within the polygons are 'patios' or locations where logs are stored and later loaded onto trucks. The large bright blue and light red clearings to the north-east and south-west are areas formerly clear cut and converted into pasture and agriculture.

selective logging did not seem to have been a precursor to clear cutting or conversion to pasture.

We found that the amount of undisturbed tropical moist forest in this area had declined by 1.2% since 1986, an average rate of 0.24% $y^{-1}$. The new selectively logged area totalled 78 $km^2$ while new pasture and fields totalled about 65 $km^2$ (i.e. 670 $km^2$–605 $km^2$). These estimates are for a small region and suffer from some cloud contamination in the 1986 imagery.

Although the amount of selective logging seems small, the time before the entire area will be selectively logged, if past trends continue, is short. If we assume the amount of selective logging found in 1991 was the result of two years of logging activity (77·8 $km^2$/2 y=38.9 $km^2$ $y^{-1}$) then it would take only about 42 years before all the remaining forest in the region has been selectively logged once. If we add to

Table 2. Classification results for the western region of 2459 $km^2$ based on 1986 and 1991 Landsat TM data. In this region there were 33 selective logging sites in the 1986 image with a mean size of 100 ha. The minimum size of the sites was 7 ha and the maximum size was 5236 ha. In the 1991 imagery, there were 77 selective logging sites with a mean size of 119 ha, a minimum size of 0·5 ha and a maximum size of 10 278 ha.

| | July 1986 | | August 1991 | |
|---|---|---|---|---|
| | (%) | ($km^2$) | (%) | ($km^2$) |
| Undisturbed forest | 69·5 | 1709 | 68·3 | 1679 |
| Field, pastures and secondary forest | 24·6 | 605 | 27·2 | 670 |
| Water | 1·8 | 44 | 1·3 | 33 |
| Region of selective logging | 1·4 | 34 | 3·2 | 78 |
| Clouds | 1·9 | 47 | 0 | 0 |
| Unclassified | 0·8 | 20 | 0 | 0 |
| Total | 100 | 2459 | 100 | 2459 |

this estimate clear cutting for pasture expansion, proposed clay mining in the region, and areas of earlier selective logging undetected in this work, then the time period remaining until all forest has been logged once is likely to be much shorter.

### 3.3. *The north-eastern region*

#### 3.3.1. *Thematic classification and analysis*

Both the 1988 and 1991 images were classified using a maximum likelihood supervised classification algorithm (Maxclas, ERDAS 1991) to obtain a few classes including forest, secondary forest, re-growing secondary vegetation and pasture. We were unsuccessful at defining a separate spectral class for selectively logged forest. Selectively logged sites are composed of a heterogeneous combination of intact canopy, damaged canopy, secondary growth forest, understorey vegetation, and bare soil, all of which are spectrally similar to other classes being analysed. Because logged forest was not distinguishable by spectral classification, other techniques to differentiate automatically logged forest were explored.

First, a texture image was created using TM band 4 (0·76–0·9 microns) for each of two images to investigate whether the forest canopy texture was significantly different in logged forest to that in undisturbed forest. Second, a normalized difference vegetation index (NDVI) image (Holben *et al.* 1980) was computed, where NDVI = (TM4-TM3)/(TM4 + TM3). Using this index produced typical values in the range of 0.00 to 0.60, where 0.00 is usually an unvegetated surface and 0.60 is vigorously growing vegetation.

#### 3.3.2. *Digitization of areas of selective logging*

Selectively logged areas were identified visually and digitized manually on each of the two images. Logged forests were identified by the patterns made by primary and secondary timber access roads and truck loading areas or patios. The digitized polygons were overlain on the classified image, the texture image, and the NDVI image from each date for analysis.

#### 3.3.3. *Results*

Eighty per cent of areas identified in the 1988 image as selectively logged forest were classified as forest in the 1991 image. Another 13% of the area identified in the 1988 image as logged forest was still identified as logged forest in 1991; this area occurred within the Del Rei community, a region known to have been logged continuously throughout our study interval (M. Mattos, personal communication, 1994). The remaining 7% of forest logged in the 1988 image was classified as secondary forest in the 1991 image. Virtually no visual clues of 1988 logging activity were evident in the 1991 imagery. No forest areas selectively logged in 1988 were later identified as cleared land. It appeared that all selectively logged areas were either left to recover or continued to be logged in 1991. For the north-eastern Paragominas region, like the western region, there was no evidence that selective logging was a precursor to clear cutting or to conversion to pasture. Clearing for pasture expansion did occur, however, with a total of 27 $km^2$ being cleared from what appeared previously to be undisturbed forest. The results of the two classifications are presented in table 3. Cross-tabulated area statistics of the two classifications are presented in table 4.

We found that the texture and the NDVI images were not helpful in defining

Table 3. Classification results for the 3183 $km^2$ north-eastern region based on 1988 and 1991 Landsat TM data. In this region there were 62 logging sites with a mean size of 340 ha, a minimum size of 10 ha and a maximum size of 2970 ha in 1988. In 1991, there were 55 selective logging sites with a mean size of 540 ha, a minimum size of 20 ha and a maximum size of 7960 ha.

| | September 1988 | | July 1991 | |
|---|---|---|---|---|
| | (%) | ($km^2$) | (%) | ($km^2$) |
| Undisturbed forest | 53·8 | 1712 | 63·0 | 2006 |
| Region of selective logging | 5·2 | 164 | 9·5 | 303 |
| Field, pastures and secondary forest | 22·7 | 723 | 27·5 | 874 |
| Unclassified | 18·3 | 583 | 0·0 | 0 |
| Total | 100 | 3183 | 100 | 3183 |

Table 4. Comparisons of 1988 and 1991 satellite classifications, for the north-eastern region. This table shows from which classes in the 1988 data, the 1991 classifications were derived. For instance, in 1988 some 52·8% of the region was defined as undisturbed forest. By 1991, the largest change to this forest was conversion to selectively logged forest (7·9%), and, secondly, to secondary forest (2·5%). Also, of the 5·2% of the area that was defined as selectively logged forest in 1988, almost all was indistinguishable from undisturbed forest by 1991. All values are in %.

| | 1991 Undisturbed forest | 1991 Selective logging | 1991 Secondary forest | 1991 Pasture, cleared | Sum 1988 |
|---|---|---|---|---|---|
| 1988 Undisturbed forest | 42·7 | 7·9 | 2·5 | 0·7 | 53·8 |
| 1988 Selective logging | 4·2 | 0·7 | 0·2 | 0·1 | 5·2 |
| 1988 Secondary forest | 1·2 | 0·1 | 1·4 | 0·2 | 2·9 |
| 1988 Pasture, cleared | 4·7 | 0·1 | 9·6 | 5·4 | 19·8 |
| 1988 Unclassified | 10·2 | 0·7 | 5·1 | 2·3 | 18·3 |
| Sum 1991 | 63·0 | 9·5 | 18·8 | 8·7 | 100 |

selectively logged forest. Mean values for texture and NDVI were compared between intact forest and logged forest for both images. The average values of NDVI for logged forest in 1988 were only slightly depressed compared to intact forest for the same year, and in 1991 the values were the same. Texture was slightly higher in 1988, and the same in 1991. In both cases where there were minor offsets in values for logged forests, the tendency was for selectively logged forests to resemble second-growth forest. Therefore, the usefulness of these indices for automated classification, where differentiation between primary and secondary forest is already problematic, is questionable.

If we examine the classification results for the north-eastern region we can see where some new land covers have their origins (table 4). Several conclusions are apparent. First, the majority of the 1988 undisturbed forest remained undisturbed. Second, the largest conversion of undisturbed forest was to selectively logged forest. Third, the majority of the area defined as selectively logged forest in 1988 was classified as undisturbed forest in 1991. Fourth, the area defined as secondary forest in 1988 was classified either as (first) secondary forest or (second) as undisturbed forest. Fifth, the areas defined as pasture in 1988 were defined as (first) secondary forest, or (second) as pasture and (third) as undisturbed forest.

#### 3.3.4. *Field verification*

One of us (P. Lefebvre) visited, in May and June 1994, the sites of selective logging identified on the satellite image to examine the sites several years after logging and to verify our classification of the other landcover types in the satellite image. As the intensity of logging activity varied greatly, the extent of damage to the forest was also highly variable. It was evident that soil compaction by heavy machinery impeded the establishment of new vegetation in roads and patios for several years following harvest. At one site, identified as logged in the 1988 image, former access roads still had no trees and little other vegetation rooting in the densely packed soil. However, the surface of the ground was covered with vines and other creeping growth that hid the soil from the satellite.

From the ground, dramatic changes in the forest canopy were still evident five years after logging; those trees not logged exhibited some canopy expansion, while fast-growing disturbance-following species (e.g. *Cecropia spp.*), together with vines and other understorey growth, combined to form a multi-layered and closed canopy. A view of this altered forest canopy from a satellite image would be composed of mixed pixels of partially shaded but vigorously growing vegetation, interspersed with the occasional large canopy of a remaining broadleaf tree. The spectral mixture of partially shaded vigorous growth with the texture provided by these emergent, residual trees, makes distinguishing this from an unlogged forest very difficult using satellite data. When viewed from the ground, there was no mistaking a logged forest from an unlogged forest. It was quite different from an intact forest, with a great increase in the variability of tree height and a generally reduced stature.

## 4. Discussion

Optical satellite data do not provide an ideal tool with which to study selective logging in Amazonia. They do, however, give a more synoptic view and the ability to assess the area affected on a yearly basis if cloud cover permits. Our results compared with ground-based work by Uhl *et al.* (1991) illustrate some of the differences of satellite images versus ground-based research. On average, Uhl and

Viera (1989) and Verissimo *et al.* (1992) found the sizes of selective logging sites to range from 15 ha to 166 ha. The satellite-based measurement found sites in the western region from 7 ha to 536 ha and 0.5 ha to 723 ha in size with a mean size of about 120 ha. This larger mean size is likely due to the more synoptic view provided by the satellite data. The small sample size of Uhl and Viera (1989) and Verissimo *et al.* (1992) was likely due to the difficulties of performing the field research and actually measuring the size of selectively logged sites on the ground. Also, it is likely that smaller sites were omitted from our analysis due to the resolution of the Landsat TM data (30 m).

Selective logging affected 385 $km^2$ of the north-eastern region forest during the period examined (1988–1991), or 12·1% (7.9%+4.2%) of the forested area within the study region. An increase in apparently undisturbed forest was noted from 1988 to 1991 (table 4), but this was offset by an uncertainty due to unclassified pixels in the 1988 scene. The area logged increased by 4.3% (9.5%−5.2%) in 1991, with only 0.7% uncertainty due to unclassified pixels. Secondary forest increased by 15.9% (18.8%−2.9%) and pasture decreased by 11.1% (19.8%−8.7%) during the period, with some of the lost pasture erroneously indicated as having changed to undisturbed forest. These differences are likely due to the 1991 image having been acquired more than one month earlier, in the dry season. Because of this, less herbaceous groundcover vegetation was senescent, and some areas of pasture were likely misclassified as re-growing vegetation.

Synoptic monitoring of selective logging is confounded by recent trends in the timber industry, where loggers return to previously harvested areas to extract new species of trees that were uneconomic during earlier harvests. As less and less intact forest remains in the region, this re-harvesting process can be expected to continue, and probably increase.

The statistics reported here on 'disturbed' versus 'undisturbed' forest are based solely on the information acquired from the satellite imagery; prior logging activity that did not show on the imagery may have been mis-classified as 'undisturbed' forest when it may have been, in fact, quite altered. Although the purpose of our field visits was ground verification of selective logging on sites which we had identified, many other untargeted areas showed definite signs of selective logging activity and were in some stage of recovery. That we could not recognize some logged areas on the imagery, even though this was our principal focus, indicated the oversights inherent in any large-scale inventory of eastern Amazonian forests conducted using satellite imagery. Special attention must be given to the visual interpretation of the subtle patterns of selective logging activity and the use of imagery of even higher resolution than Landsat TM data.

### 4.1. *Fire*

Fire affects the recovery of logged forests and their appearance on satellite imagery. An intact tropical moist forest is relatively resistant to fire, as the closed canopy prevents drying and keeps possible fuel at a high enough moisture content to prevent fire. However, once gaps have been opened in the forest through logging, available litter and other fuel may become dry enough to burn (Uhl and Buschbacher 1985, Uhl and Kauffman 1990, Nepstad, personal communication, 1994). Damage from logging can greatly increase the fuel availability in the forest, and catastrophic fires can result.

At the northern edge of the 1988 TM image used in this study, a fire scar larger than 1000 $km^2$ was identified. Upon closer examination of the image of the fire scar, it appeared that most of the forest that was burned had been logged prior to the fire. Secondary roads, patios and other typical indicators of logging activity were clearly discernible. There were also several areas of unburned forest in the path of the fire that showed no signs of logging activity in the imagery. The fire appeared to have burned along the edges of these areas and even infiltrated into the forest somewhat but was unable to penetrate completely, leaving islands of unburned and intact forest. A field visit to a ranch in the centre of the burn scar and interviews with the manager and ranch personnel who had fought the blaze confirmed our observation that much of the area had been logged, and that the fire had indeed burned in the logged forests. Most unlogged forests were only slightly damaged. The fire had occurred earlier in the same dry season and burned for a month.

## 5. Summary

In this part of Amazonia, selective logging affects an area about the same size as land newly cleared for pasture and fields. The amount of selective logging in the western region in 1991 (3·2%) was about double that seen in imagery of the same region five years earlier (1·4%). Selective logging in 1991 was more widely distributed geographically than it was in 1986, with more logging occurring farther away from the urban centre of Paragominas. In the western region, features of selective logging visible in the 1986 imagery were not apparent in the same locations in 1991 imagery. Little land selectively logged, perhaps 10%, was converted to pasture. In the western region, there was virtually no overlap between sites logged in 1986 and sites logged in 1991.

Selective logging altered 12% of the total forested area of the north-eastern study region during the period examined, but it was undetectable on satellite imagery three years after logging occurred. It is not clear how long the visual clues of selective logging remain apparent in satellite imagery from following years.

If selective logging continues at the rates that we have found, then it will be only three or four decades before all the forests in this region have been selectively logged once. The time until this occurs could be reduced as the remaining forest dwindles, as more tree species become economic and as the potential for forest fires increases.

We have shown that selectively logged forests are difficult to detect using traditional statistical classification techniques and digital satellite imagery. However, they can be quantified using visual interpretation techniques on imagery displayed at full resolution, provided that the imagery is acquired within a short period following logging. Selective logging does not appear to be a precursor to complete clearing of the land.

Satellite imagery of sufficient temporal frequency, when analysed visually in conjunction with common statistical classification techniques, can be useful for monitoring selective logging but it must be supplemented by field work. Satellite data cannot replace field work here, but its use does allow synoptic coverage when tied to field data. This could allow extrapolation to larger areas if appropriate cautions are used.

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