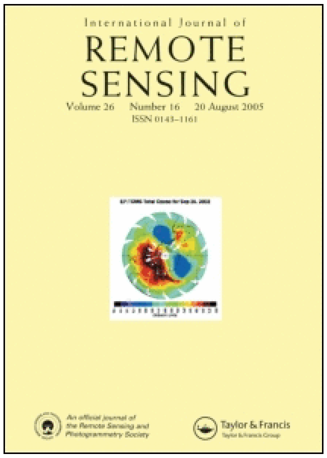

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Multi-temporal assessment of selective logging in the Brazilian Amazon using Landsat data

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Large-scale selective logging is a relatively new activity in the Amazon and its full consequences have yet to be evaluated. Impacts by selective logging alone have been estimated to increase approximately 4–7% of the annual carbon release from deforestation. In this research, visual interpretation and semi-automated remote sensing techniques were applied to identify and map areas of selective logging in tropical *terra firme* (upland) forests together with the correlated multi-annual measurement results for 1992, 1996, and 1999, for the Brazilian Amazon. The research results indicate that selective logging is rapidly increasing in both intensity (regional) and area (basin-wide). By 1992, at least 5980 km^2 of forest had been logged. During the 1992–1996 and 1996–1999 periods the area impacted expanded by an additional 10 064 km^2, and 26 085 km^2, respectively. Selective logging within protected areas increased more than twofold between 1992 and 1996, and more than fivefold between 1996 and 1999 in that region. We also estimated that at least 3689 km^2 had been actively logged in 1992, an additional 5107 km^2, and 11 638 km^2, had been logged in 1996 and 1999, and at least 10% of total logged forests detected in 1999 were previously logged in the period of analysis.

1. Introduction

Satellite-based remote sensing, focusing on forest and non-forest analyses, has been used for many years for land use and cover change assessment in different tropical forest regions in the world (Fearnside *et al.* 1990, Skole and Tucker 1993, Kuntz and Siegert 1999). Data from these studies, such as the rate of tropical deforestation, are often used to estimate human effects on the global carbon cycle (Fearnside 1997, Houghton 1997, Page *et al.* 2002). Nevertheless, these rates of annual deforestation

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might be underestimating more than 50% of the total forest impoverished each year and even more when weather anomalies occur in the region (Nepstad *et al.* 1999).

In addition to outright deforestation, tropical forests are increasingly being exposed to logging activities. Logging in these forests is often selective in that only the more economically valuable trees are removed. This type of logging can be based on as few as one or two high value species, as is the case for mahogany (Veríssimo *et al.* 1995), or it can encompass 100 or more species in more developed logging regions (Uhl *et al.* 1997). Using traditional felling techniques, the felling of a single tree can directly result in the death of 6 other nearby trees (Veríssimo *et al.* 1992). Furthermore, the sum total of damages from logging operations, with the creation of logging roads and skidder trails, often lead to as many as 11% of the remaining trees being killed or severely damaged (Uhl *et al.* 1991). The impacts of selective logging can be substantial, although they may vary with differences in the amount of currently marketable trees species, forest management techniques, forest characteristics, and particular economic situations (White 1994).

Selectively logged forests would be expected to accumulate carbon over time and recover to pre-harvest levels of biomass if left undisturbed. However, many forests are revisited several times when loggers return to harvest additional tree species as regional timber markets develop (Uhl *et al.* 1997, Veríssimo *et al.* 1998). These forests become highly degraded and may have 40–50% of the canopy cover destroyed within a radius of approximately 40 metres along logging roads during logging operations (Uhl and Vieira 1989, Veríssimo *et al.* 1992). The effects of selective logging include increased fire susceptibility (Holdsworth and Uhl 1997), damage to nearby trees and soils (Johns *et al.* 1996), increased risk of local species extirpation (Uhl and Vieira 1989, Martini *et al.* 1994), and emissions of carbon from selectively logged forests (Houghton 1996). Furthermore, forest exploitation by loggers catalyses deforestation by opening roads into unoccupied government lands and protected areas that are subsequently colonized by ranchers and farmers (Veríssimo *et al.* 1995).

Selective logging is becoming an increasingly important anthropogenic activity in the Amazon basin (8.85×10^6 km^2), which encompasses the largest concentration of tropical evergreen forest in the world (FAO 2000). According to IBGE (2005), more than 478 million m^3 of roundwood was harvested from the Brazilian Amazon, an average of 34.2 million m^3 yr^{-1} between 1990 and 2003, corresponding to about 80% of the total of Brazil's roundwood production. Based on saw mill surveys and roundwood production, selective logging may have severely damaged from 10 000 to 15 000 km^2 yr^{-1} of natural forests in 1996 and 1997 in that region (Nepstad *et al.* 1999) because it normally takes place without appropriate silvicultural procedures for tree harvesting (Veríssimo *et al.* 2002).

Although selective logging has been practised in Brazil's tropical forests for several years, forests impacted by selective logging have not yet been quantified basin-wide using remote sensing classification techniques because they are not easily detectable using unsupervised classification. For example, previous deforestation estimates for Brazil's Legal Amazon, reported by Michigan State University (MSU) and the Brazilian Space Agency (INPE) did not include most selectively logged areas.

In this research, visual interpretation and a textural algorithm were applied to identify and map selectively logged forests throughout the Brazilian Amazon. These data extend current Amazon-wide image classification techniques to include selectively logged forests in addition to the current seven thematic classes used in basin-wide land-cover assessments: forest, deforestation, re-growth, 'cerrado' (savannah), cloud, cloud shadow, and water bodies.

2. Methods

2.1 *Study area and data set*

The study area was Brazil's Legal Amazon. The Legal Amazon is considered an administrative area within the country of Brazil, first recognized on 6 January 1953 by the Brazilian Federal Law 1806. Currently, it is 5×10^6 km^2 and includes all of the states Acre, Amapá, Amazonas, Pará, Rondônia, Roraima, plus parts of Mato Grosso, Maranhão, and Tocantins. This analysis was based on more than 600 Landsat images of the Legal Amazon, obtained for deforestation monitoring at the Tropical Rain Forest Information Center (TRFIC), Michigan State University. Signs of logging were searched for throughout the basin. Evidence of selective logging was found in 30 Landsat TM images acquired in 1992 and 1996, and 38 Landsat ETM+ images in 1999 (figure 1). These images defined the subsequent effective areas of study used in this analysis.

For dates prior to 1999, Landsat 5 TM imagery was used for the analyses, and for 1999, Landsat 7 ETM+ imagery was used. Although we tabulated results for three different years (1992, 1996 and 1999) for measurement and analysis purposes, some of the imagery were acquired in different years depending on its availability and quality. A full listing of the individual scenes used is provided in table 1.

The deforestation dataset produced by the TRFIC for the whole Brazilian Amazon was also used. In the deforestation analysis, the imagery was classified using a technique involving unsupervised classification of bands 2, 3, 4, and 5, into seven thematic classes: forest, deforestation, regeneration, cerrado, clouds, shadows, and water. This dataset is available at the TRFIC in vector and grid format for 1992, 1996, and 1999.

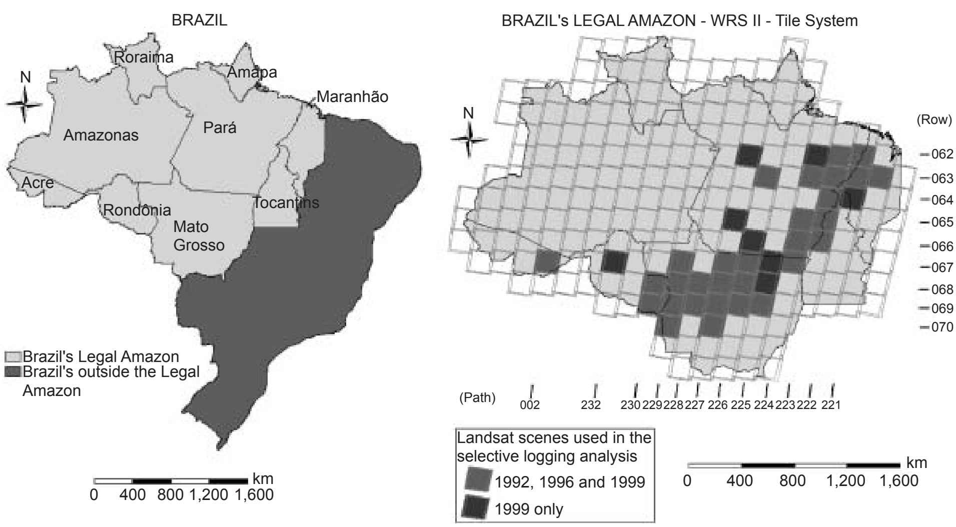

Figure 1. Study region location and Landsat imagery used in the multi-temporal assessment of selective logging in the Brazilian Amazon.

Table 1. Acquisition dates of the Landsat scenes for 1992, 1996, and 1999.

	Acquisition dates		
Path/row	1992	1996	1999
221/063	11 July 1992	30 May 1997	14 May 2000
222/062	24 July 1991	5 July 1996	14 July 1999
222/063	24 July 1991	3 June 1996	23 August 1999
222/064	*	*	23 August 1999
223/062	16 August 1991	12 July 1996	23 July 1999
223/063	28 May 1991	12 July 1996	13 July 1999
223/064	10 August 1992	10 June 1996	13 July 1999
223/065	2 June 1993	10 June 1996	23 July 1999
223/066	25 July 1992	9 May 1996	13 July 1999
224/062	*	*	24 October 1999
224/063	22 June 1992	19 July 1996	8 October 1999
224/065	16 July 1992	19 July 1996	8 October 1999
224/066	16 July 1992	3 July 1996	8 October 1999
224/067	16 July 1992	3 July 1996	8 October 1999
225/067	*	*	12 August 1999
225/068	*	*	12 August 1999
225/069	21 June 1992	1 July 1996	12 August 1999
226/063	20 July 1991	18 June 1997	3 August 1999
226/066	*	*	3 August 1999
226/067	19 May 1992	1 July 1996	19 August 1999
226/068	19 May 1992	1 July 1996	19 August 1999
226/069	19 May 1992	1 July 1996	19 August 1999
227/062	*	*	10 August 1999
227/065	*	*	10 August 1999
227/067	6 August 1992	27 July 1996	10 August 1999
227/068	6 August 1992	6 June 1996	10 August 1999
227/069	5 July 1992	6 June 1996	10 August 1999
227/070	5 July 1992	8 July 1996	10 August 1999
228/068	18 June 1992	13 June 1996	17 August 1999
228/069	18 June 1992	13 June 1996	17 August 1999
229/067	3 July 1992	22 July 1996	8 August 1999
229/068	11 July 1992	22 July 1996	11 October 1999
229/069	25 June 1992	6 July 1996	8 August 1999
229/070	11 July 1992	23 June 1996	8 August 1999
230/068	10 July 1992	17 October 1996	15 August 1999
230/069	15 May 1992	17 October 1996	3 July 1999
232/067	22 June 1992	25 June 1996	28 June 2000
002/067	30 August 1992	1 August 1996	2 August 1999

*Not mapped in 1992 and 1996.

2.2 *Field studies*

Field studies were conducted in the States of Rondonia, Para, and Mato Grosso during July 2002 and August 2003. We visited and observed both undisturbed and selectively logged forests previously detected on satellite imagery. We dated the time of logging activity of these areas through interviews with the local landowners. This information was double checked by examining evidence of selective logging on the available multi-temporal Landsat imagery and by observing forest regeneration stages of selectively logged sites. Forest damage and fire occurrence in selectively logged forests were also observed and those sites identified. A global positioning system (GPS) was used to locate geographically all visited sites and access roads.

These geographic locations were used to assess the geometric correction of the satellite images. Fieldwork information was also used to define the optimum buffer radius for two different regions and to image classification assessments. A detailed accuracy assessment of selective logging detection was conducted and further details are available in Matricardi *et al.* (2005).

2.3 *Calibration and geometric correction*

Landsat imagery from the Tropical Rain Forest Information Center (TRIFC) was used for this selective logging multi-temporal assessment. These images were geometrically system-corrected using a polynomial distortion model and nearest neighbour re-sampling technique and sensor geometry, calibration data, and altitude/positioning measurements. The root-mean-square (RMS) positional errors resulting from this imagery geometric correction varied between 0.20 and 0.45 pixels. Additionally, three Landsat scenes (path 232 row 067 acquired in 2000, path 226 row 068 acquired in 1999, and path 223 row 062 acquired in 1999) were tested for positional accuracy of the system-corrected imagery using ground control points at intersections of road segments acquired during the fieldwork in 2003. The measurement differences between these three Landsat scenes and the ground control locations averaged less than 33 metres $\pm$ 28.1 metres ($\pm$ standard deviation) and 35 metres $\pm$ 36.8 metres for X and Y directions, respectively.

2.4 *Selective logging detection*

As mentioned previously, visual interpretation and semi-automated techniques were applied to detect and quantify selective logging basin-wide in the Brazilian Amazon.

2.4.1 Semi-automated technique. Non-forest areas (deforestation, cloud, shadow, cerrado, water bodies, and regenerating vegetation) were masked out of band 5 of the Landsat images. Subsequently, the semi-automated technique was applied on each Landsat scene. The semi-automated technique involved applying a textural algorithm (variance), 5×5 moving window operator, on band 5 of Landsat TM and ETM+. The resultant texture images were used to detect patios, which are small clearings cut into the forest for the purpose of acting as temporary access and transportation, storage, and standing areas by loggers (figure 2).

Those texture images were binary (re)classified (1=logging patios and 0=forest) using Erdas modelling tools, selecting and capturing pixels values (mostly from 6 to 11) correlated to areas directly affected by selective logging, such as patios and roads. The non-forest mask was applied again to remove any regions where the suspected-logging areas overlapped with non-forested land cover classes. The binary classified texture images were converted to vector format and edited to remove any remaining extraneous features that were not associated with logging.

Finally, a buffer radius of 180 metres, as suggested by Souza and Barreto (2000) and tested by Matricardi *et al.* (2005), was applied around the detected patios (patios) in order to estimate the amount of forest actually affected by logging (figure 3). A buffer radius of 450 metres developed by Matricardi (2003) was used for the states of Rondônia and Acre because of the specific characteristics and spatial patterns of selective logging activities in these states. Those areas of selective logging estimated using different buffer radii here are described as ‘cryptic logging’.

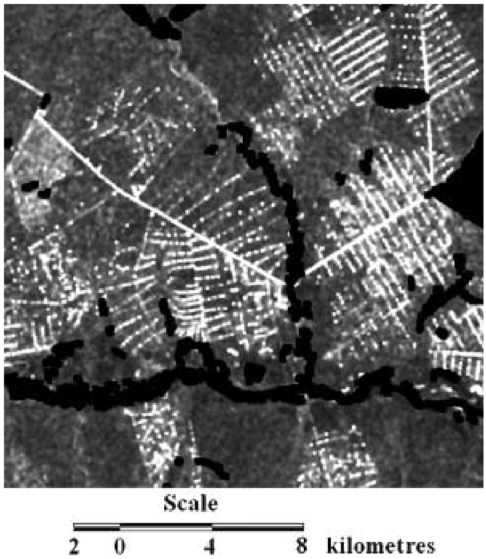

Figure 2. Enhanced log landings, detected using textural algorithm, band 5, 226/068, 2002.

2.4.2 Visual interpretation. Visual interpretation of logged forests was done using RBG 5/3/2 colour composite images, displayed at full resolution on a computer screen. The logged forests were digitized manually on each image at scales varying from 1 : 30 000 to 1 : 100 000, in the three different study periods (1992, 1996, and 1999).

The logged forests were identified by obvious canopy degradation, since logging activities leave patios and tree-fall gaps along with obvious forest canopy disturbance. This land use creates a characteristic pattern of white points on the Landsat images, which are patios or roads, embedded in the red hues of the forest canopy. The areas around the logging landings together with areas of obvious canopy degradation were digitized as polygons.

After areas affected by selective logging were identified, they were delimited and digitized into vector GIS layers. The digitizing process was done on the very edge (border) of canopy disturbance. Selectively logged forests were classified into two separate vector coverages: 'obvious' and 'subtle' logging. 'Obvious' logging includes spectrally bright patios, roads, and obvious canopy disturbance (figure 4). Subtle logging refers to logged areas that exhibit visible canopy disturbance and faded patios or no patios (figure 5). Forests that did not have visible canopy disturbance on satellite images were not digitized and, therefore, classified as non-logged forests for each period of analysis.

3. Accuracy assessments of the remote sensing techniques

Ecosystem damage from selective logging and its secondary impacts, such as desiccation, fire, and access-based colonization, are severe (Veríssimo *et al.* 1992, Nepstad *et al.* 1999). Canopy disturbance and soil exposure are commonly observed in selectively logged forests (Souza and Barreto 2000). These environmental changes are detectable using remote sensing and allow us to estimate the area impacted by selective logging in the Brazilian Amazon. Although these techniques are not applicable to all forests (e.g. areas of flooded lands), they are applicable in areas of

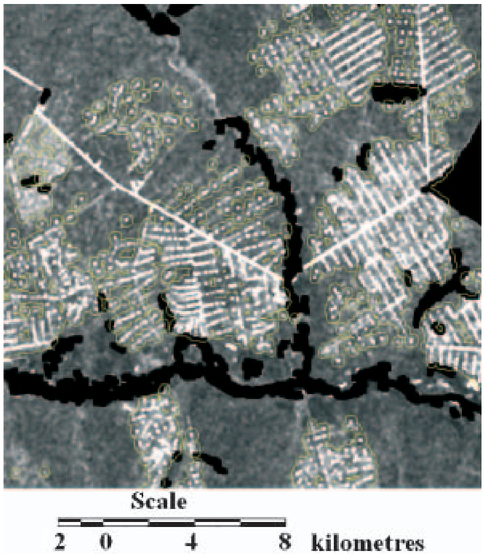

Figure 3. Buffer radius of 180 metres around of log landings detected using semi-automated technique on band 5, path/row 226/068, 2002. Areas within this buffer radius were considered cryptic logging.

terra firme (upland), which make up 80% of all forests and account for the vast majority of logging in the Amazon.

Matricardi *et al.* (2005) conducted a detailed accuracy assessment of applying semi-automated texture analysis and visual interpretation to detect selectively logged forests for a case study in the state of Mato Grosso, Brazil. Based on those research results, the user's accuracy of visual interpretation was 16.9% higher than that obtained by the semi-automated technique while the producer's accuracy of the

Figure 4. Obvious logging on Landsat image, 226/068, RGB 5/3/2, 2001.

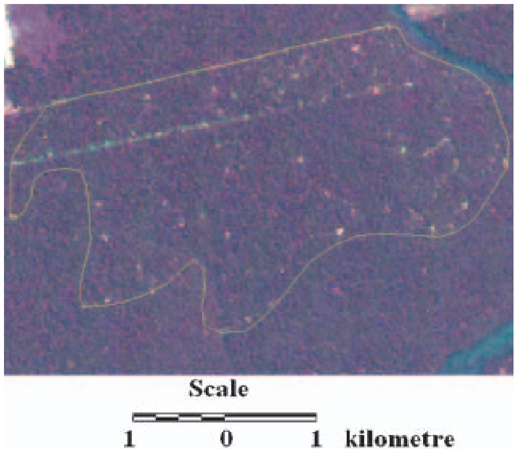

Figure 5. Subtle logging on Landsat image, 226/068, RGB 5/3/2, 2001.

semi-automated technique was 7.4% higher than visual interpretation. Visual interpretation and semi-automated showed, however, almost the same overall accuracy of 92.8% and 90.2%, respectively. The authors also estimated values of 82.9%, 91.2%, and 92.9% for user, producer, and overall accuracy, respectively, when combining visual and semi-automated techniques for that particular area. The overall Kappa coefficient was 0.82. Table 2 shows further details of accuracy assessment for visual interpretation and semi-automated techniques separately and their combination.

For the present basin-wide analysis, semi-automated detection technique (textural algorithm and buffer radii) incorporated roughly 64% of the total (semi-automated plus visual) logging areas detected in 1992, 1996, and 1999. Visual interpretation incorporated approximately 83% of the total in the given years. These areas were

Table 2. Accuracy assessment results of detecting selective logging using visual interpretation and semi-automated techniques for a study case in the State of Mato Grosso, Brazil.

Land use	Reference points	Classification points	Number correct	Producer's accuracy	User's accuracy
		Visual Interpretation			
Non-logging	20 537	22 338	20 441		
Logged forest	7185	5384	5288	73.6%	98.2%
Total	27 722	27 722	25 729		
Overall classification accuracy			92.8%		
		Semi-automated			
Non-logging	20 537	20 570	19 201		
Logged forest	7185	7152	5816		
Total	27 722	27 712	25 017	81.0%	81.3%
Overall classification accuracy			90.24%		
		Visual interpretation and semi-automated combined			
Non-logging	20 537	19 824	19 189		
Logged forest	7185	7898	6550	91.2%	82.9%
Total	27 722	27 722	25 739		
Overall classification accuracy			92.9%		

Source: Matricardi *et al.* (2005).

classified as either 'obvious' or 'subtle' depending on their characteristics. More specifically, areas of obvious logging had well-defined logging roads and patios and extensive canopy degradation. Areas of subtle logging had lesser degrees of canopy disruption or visible infrastructure, either due to being early in the logging process or because of substantial forest re-growth in previously logged forests. The division of the total detected logged forests by class, obvious (visual), subtle (visual), and cryptic (semi-automated) is presented in figure 6.

Visual interpretation only identified roughly 47%, 26%, and 36% of the detected logged forests, in 1992, 1996, and 1999, respectively, while semi-automated technique only added 17%, 21%, and 16% in the given years. The total overlap of detected logging using the two techniques was 36%, 53% and 49% for each of the three study years (table 3).

4. Results

By using semi-automated and visual interpretation techniques combined, we could detect a total of 5980 km^2 of selectively logged forests in 1992 in the entire Amazon basin. The detected selective logging areas were 10 064 km^2 in 1996 and 26 085 km^2 in 1999 (see table 4 for details by Landsat path/row). These areas were not previously reported in studies of deforestation (Skole *et al.* 2004), and represent an additional amount of degraded forests.

Our results show that visual interpretation detected an average of 83.4% (66.2% classified as 'obvious logging' and 17.2% as 'subtle logging'), while semi-automated method ('cryptic logging') detected an average of 63.7% of the total logged forests (table 5). Areas of selective logging detected in common between visual interpretation and the semi-automated method were 36%, 53%, and 49%, respectively, in 1992, 1996, and 1999. Visual interpretation only contributed in detecting an additional 47%, 26%, and 36%, respectively in 1992, 1996, and 1999 (figure 6 and table 3).

A state-by-state analysis of the results shows that the states of Mato Grosso and Pará contain the vast majority of the Legal Amazon's detectable selective logging (90.63% in 1992, 91.89% in 1996, and 89.92% in 1999). Mato Grosso and Pará also have the highest increment of selective logging areas in 1992, 1996, and 1999 (table 6).

These techniques did not, however, detect selective logging in the states of Amazonas, Amapá, and Roraima. Similarly, only a small amount of logged forest

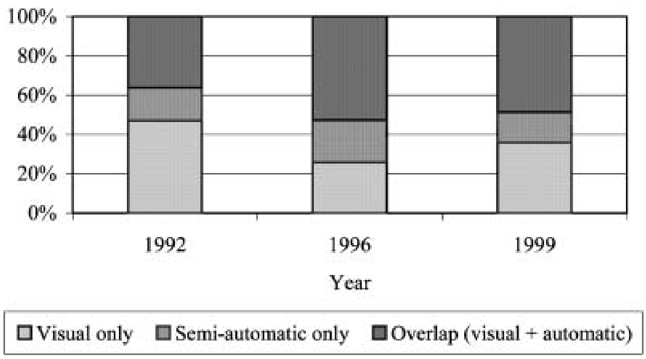

Figure 6. Areas of selective logging detected either using visual interpretation or semi-automated and areas detected using both techniques (overlap).

Table 3. Total area of selectively logged forests detected either using visual interpretation or semi-automatic technique and total selectively logged forests detected using both techniques (overlap).

Year	Visual only (V)		Semi-automated only (A)		Overlap (V/A)		Total area (km^2)
	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%	
1992	2817.17	47.11	1009.01	16.87	2153.63	36.02	5979.80
1996	2615.61	25.99	2155.10	21.41	5293.39	52.60	10 064.10
1999	9323.76	35.74	4060.90	15.57	12 700.74	48.69	26 085.40

was detected in states of Acre and Rondônia, even after applying a bigger regional buffer radius developed by Matricardi (2003) around patios for these last two states. Our field observations suggest that very selective and lower intensity logging can be easily observed in field in the Acre and Rondônia though it is not detectable using these remote sensing techniques. However, such low intensity logging does not constitute a major environmental impact, nor does it result in significant fluxes of carbon dioxide.

Multi-annual comparisons of detected logging in 1992–1996, 1992–1999, and 1996–1999 indicate areas in common of 267 km^2, 253 km^2, and 4,062 km^2 respectively among the given periods of time. These results also show that repetitive (revisited) logging in 1992, 1996, and 1999 is around 148 km^2. Multi-temporal comparisons between logging and deforestation data indicate that around 796 km^2 (13%) of logged forests in 1992 were deforested by 1996 and an additional 896 km^2 (15%) by 1999. Around 1074 km^2 (11%) of the logged forests in 1996 were deforested by 1999. Additionally, the buffer zones used in the semi-automated analysis expanded selective logging beyond the forest areas into deforested areas, which generated approximately 123 km^2, 204 km^2, and 820 km^2 of overlap between logged and deforested areas in 1992, 1996, and 1999, respectively. These overlaps due to the buffer zones were not included in the total area of logging.

Finally, we observed that around 1.8%, 2.3%, and 4.7% of the total selective logging detected in 1992, 1996, and 1999, respectively, were located within protected areas (indigenous lands and conservation units). Logging in indigenous lands constituted the majority of this 'illegal' selective logging (see table 7).

5. Discussion and conclusions

5.1 *Remote sensing techniques*

Although visual interpretation was more successful in detecting logged forests than semi-automated detection, it was also much more time-consuming. Stone and Lefebvre (1998) successfully quantified selectively logged forests in the state of Para using a similar approach and Landsat imagery acquired shortly after selective logging operations. In that study, evidence of selective logging was not visually distinguishable on Landsat imagery for older logging areas that had begun to recover. Furthermore, we note that visual interpretation is interpreter-dependent and results may be expected to vary among individuals. Hence, in this study, a single individual, the leading author, made all visual interpretations.

Semi-automated texture analysis provided a standardized technique for detecting selectively logged forests that was relatively half as time consuming and interpreter

Table 4. Total area of selectively logged forests detected in 1992, 1996, and 1999 per Landsat scene.

	Logging area detected (km^2)			
Path/row	1992	1996	1999	Annual logging estimated† (km^2)
221/063	46.22	14.29	39.88	7.74
222/062	515.76	893.71	1096.75	284.35
222/063	644.31	704.48	2728.60	490.44
222/064*	—	—	20.24	6.75
223/062	684.67	2018.67	3554.09	796.11
223/063	515.25	1553.23	2928.84	640.30
223/064	27.43	26.41	223.63	35.72
223/065	26.60	15.93	60.50	10.92
223/066	73.80	20.92	39.34	8.61
224/062*	—	—	691.87	230.62
224/063	7.64	20.17	40.47	8.66
224/065	47.17	60.47	111.03	24.50
224/066	295.93	193.09	743.27	133.77
224/067	23.58	74.33	322.70	56.72
225/067	—	—	15.53	5.18
225/068	—	—	93.68	31.23
225/069	1.69	17.75	62.94	11.53
226/063	5.02	55.19	8.17	9.05
226/066*	—	—	35.61	11.87
226/067	17.53	26.37	368.89	56.47
226/068	1245.05	1756.77	4502.92	894.24
226/069	873.82	1157.57	3318.36	639.42
227/062*	—	—	442.55	147.52
227/065*	—	—	111.26	37.09
227/067	4.41	13.08	161.06	24.88
227/068	303.67	325.41	1279.07	229.21
227/069	366.50	448.17	866.38	187.79
227/070	2.35	0.63	13.96	2.08
228/068	140.13	206.31	725.38	133.10
228/069	20.46	85.94	382.69	66.95
229/067	5.69	72.27	244.69	45.28
229/068	6.66	34.93	438.46	67.63
229/069	4.99	6.50	17.71	3.46
229/070	23.82	28.94	55.75	12.10
230/068	12.21	81.52	103.38	26.41
230/069	19.29	93.01	86.85	25.69
232/067	10.32	28.53	124.98	21.93
002/067	7.84	29.52	23.94	7.64
	5979.80	10 064.10	26 085.40	

*Not mapped in 1992 and 1996.
†Average of the total logging detected in 1996 and 1999 divided by 7 years (4 years in between 1996 and 1999 plus 3 years that logging may persist on satellite image).

dependent than visual interpretation. Although the technique identified less unique area (17–21%) of selective logging than did visual techniques (26–47%), the areas detected may be important since they are often small regions of newer logging that may expand in future years. Sousa and Barreto (2000) were able to estimate 97% of actual selectively logged area in the state of Para, Brazil. However, these authors cautioned that, due to the rapid vegetative re-growth, their technique detected only 60% of field-verified logging patios that were 1 year old and none that were 3 years

Table 5. Total area of selectively logged forests detected using visual interpretation and semi-automated techniques.

	Visual interpretation				Semi-automatic analysis		
	Obvious		Subtle		Cryptic		
Year	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%	Total*(km^2)
1992	3946.41	66.00	1269.36	21.23	3163.03	52.90	5979.80
1996	6553.37	65.12	1359.23	13.51	7451.55	74.04	10 064.10
1999	17 600.08	67.47	4428.84	16.98	16 767.06	64.28	26 085.40

*The overlap between obvious + subtle and cryptic logging areas was not double counted.

Table 6. Selectively logged forests detected by state in the Brazilian Amazon.

	1992		1996		1999	
State	Area (km^2)	%	Area (km^2)	%	Area (km^2)	%
Acre	7.84	0.13	29.52	0.29	23.94	0.09
Amapá	—	—	—	—	—	—
Amazonas	—	—	—	—	—	—
Maranhão	506.12	8.46	571.87	5.68	2276.91	8.73
Mato Grosso	3013.58	50.40	4196.50	41.70	12 662.47	48.54
Pará	2405.45	40.23	5051.16	50.19	10 793.87	41.38
Rondônia	41.81	0.70	203.05	2.02	315.20	1.21
Roraima	—	—	—	—	—	—
Tocantins	5.00	0.08	12.00	0.12	13.00	0.05
Total	5979.80	100.00	10 064.10	100.00	26 085.40	100.00

Table 7. Total area of selectively logged forests detected in 1992, 1996, and 1999 within protected areas.

	Selectively logged forests (km^2)				
Year	Indigenous land	%	Conservation unit	%	Total
1992	106.45	96.69	3.64	3.31	110.09
1996	216.56	95.12	11.11	4.88	227.67
1999	1189.78	96.38	44.66	3.62	1234.44
Total	1512.80	96.22	59.41	3.78	1572.20

old or more. It is important to point out that before applying semi-automated method, Landsat images, band 5, were masked for deforestation. Hence, some areas of selective logging visually observed on satellite images were not analysed by semi-automated analysis, partially contributing with this difference in detecting selective logging between the two techniques. In areas of overlap, the semi-automated procedure may also be more accurate since it is better able than the visual methods to deal with complex spatial mosaics of logging with edges and unlogged islands.

Semi-automated texture analysis and visual interpretation combine to form an efficient methodological approach for estimating the area affected by selective logging in the Amazon region. Moreover, the overlap areas that are common between the techniques are useful in providing confidence in the estimates since they were detected twice by using different methodologies.

Based on the findings of the field studies and remote sensing analyses conducted here for the entire Brazilian Amazon, we concluded that forests heavily impacted by selective logging activities were correctly detected and mapped by our techniques. Even areas of reduced impact logging could be estimated at a high level of accuracy. However, we believe that, in different circumstances, selectively logged forests could not be detected, as in the case of the states of Amazonas, Rondonia, and Acre. In these states, evidence of selective logging is not easily detectable using Landsat imagery because of lack of soil exposure by logging features on the ground and rapid forest regeneration. Additional experimental efforts to develop approaches to estimate these types of selective logging are needed.

5.2 *Analysis and evaluation of results and assumptions*

The process of logging can result in a heavily degraded forest environment. Selective logging activities leave a mixture of intact forest, tree fall gaps, roads, log-loading patios, and damaged trees (Stone and Lefebvre 1998, Nepstad *et al.* 1999, Souza and Barreto 2000). In spite of the damages and consequences of selective logging, few attempts have been made to estimate the area of impact for the entire basin. Depending on the methods used, the estimates have varied from between 10 000–15 000 $km^2 yr^{-1}$ in 1996 and 1997, using survey data (Nepstad *et al.* 1999) to as little as 1561 $km^2 yr^{-1}$ using visually interpreted Landsat prints (Krug 2000). The controversy over selective logging estimates in the Brazilian Amazon is directly related to the lack of accurate and comprehensive data on the spatial and temporal distribution of this land use.

In response to this controversy, we mapped distributions of logging activities in Amazonian forests for 1992, 1996 and 1999. However, due to the rapid disappearance of detectable selective logging from Landsat imagery, annual rates of logging are hard to determine. Without annual imagery, it is necessary to estimate logging rates based on specific knowledge of how the damage from logging activity and subsequent ecosystem recovery interact across the landscape. Previous research has shown that some logging activity can be detected in imagery more than a year after the timber extraction but that none of the logged forests detected should be more than 2 to 3 years old (Stone and Lefebvre 1998, Souza and Barreto 2000). Thus, in order to estimate annual rates of selective logging, the results of the inter-annual analysis conducted by Matricardi (2003) and Matricardi *et al.* (2005) for two case studies in the states of Rondônia and Mato Grosso, respectively, were extrapolated Amazon-wide.

The first assumption was that regions (Landsat scenes) showing an average of more than 100 $km^2 yr^{-1}$ of total logging (table 4) were more intensive in terms of forest impacts. Field studies showed that these types of logging operations were generally planned in advance, prioritized extraction of more lucrative export quality trees and required heavy machinery and systematic field operations. Therefore, the results from the Mato Grosso inter-annual study case were used to estimate annual logging rates from total detected logging that was evident in the scenes with this type of extraction activity.

Selective logging in the remaining Landsat scenes had less than 100 $km^2 yr^{-1}$ of logging activity, which appeared to be more opportunistic than systematic. Field research in these areas showed that loggers harvested fewer commercial trees and avoided extensive construction of roads to support their operations by making use of the relatively dense infrastructure of local colonization areas. Therefore, regions (Landsat scenes) showing an average of less than 100 $km^2 yr^{-1}$ of logging activity were assumed to be represented by the Rondônia case study results.

Two different methods were used to estimate annual selective logging rates from the total logging area that was evident in the satellite imagery. The first method simply used average relations between detected logging and annual logging from the case studies. Annual rates of new selective logging (increment) for 1992, 1996, and 1999, were estimated using the average annual increment percentages (calculated as total area of forest showing logging activity for the first time divided by the total area of forest wherein logging was detected) observed in the Mato Grosso and Rondônia study cases. The results for these states were 39.5% and 91.42% respectively.

The second method made use of observable trends in the changing relationship between detected logging and actual new logging activity. This approach accounted for the fact that, in the areas with intense logging activity, the average persistence time for previously logged forest evident in subsequent imagery-based logging detection increased over the period of the study (1992–1999). The reasons for this change are not certain but likely result from increased volumes of timber extraction over time as both smaller trees and new species became marketable (Uhl *et al.* 1997) and further, post-logging degradation of forests by fire (Cochrane *et al.* 1999). The change rates were calculated using separate equations for each case study region suggested by Matricardi (2003) and Matricardi *et al.* (2005). For the Mato Grosso case study, the increment of new logging areas was 60%, 48%, and 38% for 1992, 1996, and 1999, respectively. Slightly increasing rates were found for the Rondônia case study, 82%, 87%, and 91% for the years 1992, 1996, and 1999, respectively.

Differences between the total area detected and newly logged areas were quite large in the Mato Grosso region (60.5%) but much smaller for Rondônia (8.58%). These residual areas were considered to be mostly areas of previous logging that, due to severe forest damage, persisted as detectable logging on satellite imagery. However, it is noteworthy that a small portion of the former logging was actually secondary logging of previously logged sites (7% and 0.4% of the total detected for Mato Grosso and Rondônia, respectively).

Assuming that the equations presented by Matricardi (2003) and Matricardi *et al.* (2005) can be extrapolated basin-wide, the total increment of new selective logging areas in 1992 was at least 3689 km^2. By 1996 and 1999, the annual selective logging rate expanded to 5107 km^2 and 11 638 km^2, respectively. The remaining detected forests with logging that were not new to the actual year of the imagery grew from 2197 km^2 in 1992 to 5031 km^2 in 1996 and 14 962 km^2 in 1999. The total areas detected and annual rates of logging calculated by the two described methods are presented in table 8.

Although for 1999 the estimates of logging increment are almost the same, the estimated areas for 1992 and 1996 have a more significant difference. It seems that the equations can better represent the increment of selective logging basin-wide, since there is a natural reduction of raw material (timber), which forces loggers to increase intensity and revisit logged forests over time.

New logging areas increased 138% and 227% in the period between 1992 and 1996 and between 1996 and 1999, respectively. This supports the reports by Uhl *et al.* (1997) who observed that loggers are advancing more and more into undisturbed

Table 8. Total detected and estimated increase of new selectively logged forests in the Brazilian Amazon.

	Amazon-wide selectively logged forests (km^2)		
		Increase (new selective logging areas)	
Year	Total selective logging detected	Based on equations*	Based on annual averages†
1992	5979.80	3689	2547
1996	10 064.10	5107	4361
1999	26 085.40	11 638	11 889

*Equation (1): $y=6393.6-3.1794x$ ($R^2=0.58$, $P>0.000$) and equation (2): $y=-2619.7+1.3565x$ ($R^2=0.13$, $P>0.000$), where y=% of the total area of selective logging, which gives the estimate of new areas of selective logging and x=year of selective logging analysis (1992, 1996 and 1999). These equations were generated based on results of two multi-annual study cases conducted in the states of Mato Grosso and Rondonia by Matricardi *et al.* (2005) and Matricardi (2003), respectively. Equations (1) and (2) were used to estimate new areas of selective logging for all Landsat scenes showing total area of selective logging more and less than $100\,km^2\,yr^{-1}$ (see table 7), respectively.

†Average 1 (39.5%) and average 2 (91.4%) of selective logging increase were estimated for the Mato Grosso and Rondonia study cases, respectively. These averages were calculated as total area of forest showing selective logging activity for the first time divided by the total area of forest wherein selective logging was detected. Similarly to the previously mentioned equations, the averages 1 and 2 were used to estimate new areas of selective logging for all Landsat scenes.

forests in search of new raw materials, as well as re-logging some forests for second tier economic species.

Based on the results of the case study in the state of Mato Grosso presented by Matricardi *et al.* (2005), formerly logged areas are increasingly being re-logged. An average of 2.9%, 8.6%, and 10.3% of the total logged forest were revisited in the period of 1993–1996, 1996–1999, and 1999–2002, respectively. This shows that an increasing scarcity of raw materials is forcing the timber market and loggers to adjust to the natural resource availability, revisiting logged forests to search for previously non-commercially sized or species of trees.

Despite the methodological limitations discussed above, the logging estimates from this study (in 1996, 10 064 km^2 overall logging were detected and 5107 km^2 of new logging areas estimated) are well in the range of other published estimates for 1996, 1561 km^2 (Krug 2000) and 10 000–15 000 km^2 (Nepstad *et al.* 1999). In any case, the rate of growth in the area of detected logging, from approximately 5980 km^2 in 1992 to over 26 085 km^2 in 1999, is substantial. Even comparisons of only the most visible canopy degradation within the satellite images show 3936, 6524, and 17 600 km^2 respectively for 1992, 1996, and 1999. This indicates a 66% increase between 1992 and 1996 and a 347% increase between 1992 and 1999. In total, it was estimated that at least 37 465 km^2 (0.75% of the entire Brazilian Amazon) of forest were logged from 1992 to 1999 of which approximately 26 085 km^2 was still extant on the landscape in 1999.

5.3 *Multi-temporal assessment of selective logging Amazon-wide*

The final estimate of logged forest area was made using the union of the logged forest polygons detected by the semi-automated analysis ('cryptic' logging) and visual interpretation ('obvious' and 'subtle' logging). It also removed duplicated polygons in the overlap areas among paths and rows of Landsat images in order to avoid double counting.

Based on that, it was observed that the mapped logging areas are spatially concentrated in Pará and Mato Grosso (90%), with 75% of all logging concentrated in the vicinity of two major logging centres, Paragominas, state of Pará and Sinop, state of Mato Grosso (table 6). Figure 7 shows that selective logging activities are spreading throughout the Brazilian Amazon at an increasing intensity during the period of 1992 to 1999, revealing new timber centers in Northwestern Mato Grosso, and in Western and Southern Para. The balance of logged forests was found in the states of Rondônia, Tocantins, Maranhão, and Acre. No logging was detected in the states of Amazonas, Amapá, and Roraima.

Biophysical and socioeconomic factors, such as forest density, logging intensity, clear cutting, and differing logging practices could be some of the main reasons for not detecting some logged forest by using the present methods. Thus, the results of the applied methods are considered conservative, since, in different circumstances, logging areas cannot be detected, especially in *várzeas* (flooded lands) and in areas where logging was followed immediately by deforestation.

It was observed that 13% of logged forests in 1992 were deforested by 1996, plus 15% by 1999, that is, 28% of logged forests in 1992 were deforested by 1999. Additionally, 11% of forests logged in 1996 were deforested by 1999.

5.4 *Final considerations*

Based on these research results and on our field observations, we could speculate about three potential major factors that might explain the observed large increase in selective logging rates in the Brazilian Amazon during the 1996 to 1999 time period, compared with the 1992 to 1996 period. The factors may include the legislative changes, forest resource availability, and observed extreme droughts.

Legal changes regarding selective logging and deforestation activities that occurred during our periods of analysis could have increased the apparent logging rates as a result of the timber industry's response to a 1996 Executive Order by the Brazilian President. In 1996, Brazil's Forest Code was changed to stipulate that 80%, not the previously legislated 50%, of forests on individual properties must be protected. This action prohibited landowners from deforesting more than 20% of their landholdings. With less logs reaching sawmills from newly deforested areas, loggers may be expanding their presence in standing forests to acquire the timber necessary to maintain their production levels. This would help to explain the sudden increase in the amount of selectively logged forests.

A second factor is related to forest production and productivity. According to IBGE (2005), the roundwood production in the Brazilian Amazon did not increase during 1997 to 1999, approximately estimated at $20\times10^6\,m^3$, $16\times10^6\,m^3$, and $16\times10^6\,m^3$ per year, respectively in 1997, 1998, and 1999. If the roundwood production did not increase, it may be that forest productivity was drastically lowered after 1996. This would be a function of forest resource utilization where loggers utilize highly productive forests first and only use more marginal forest once high production areas decline. The fact that 80% of all of the increase in logging areas is concentrated in just nine of the 38 images indicating logging activity supports this argument.

A third factor is the effect of climatic events on tropical forests, such as the 1997–1998 El Nino, which caused extreme drought and increased wild fires in tropical

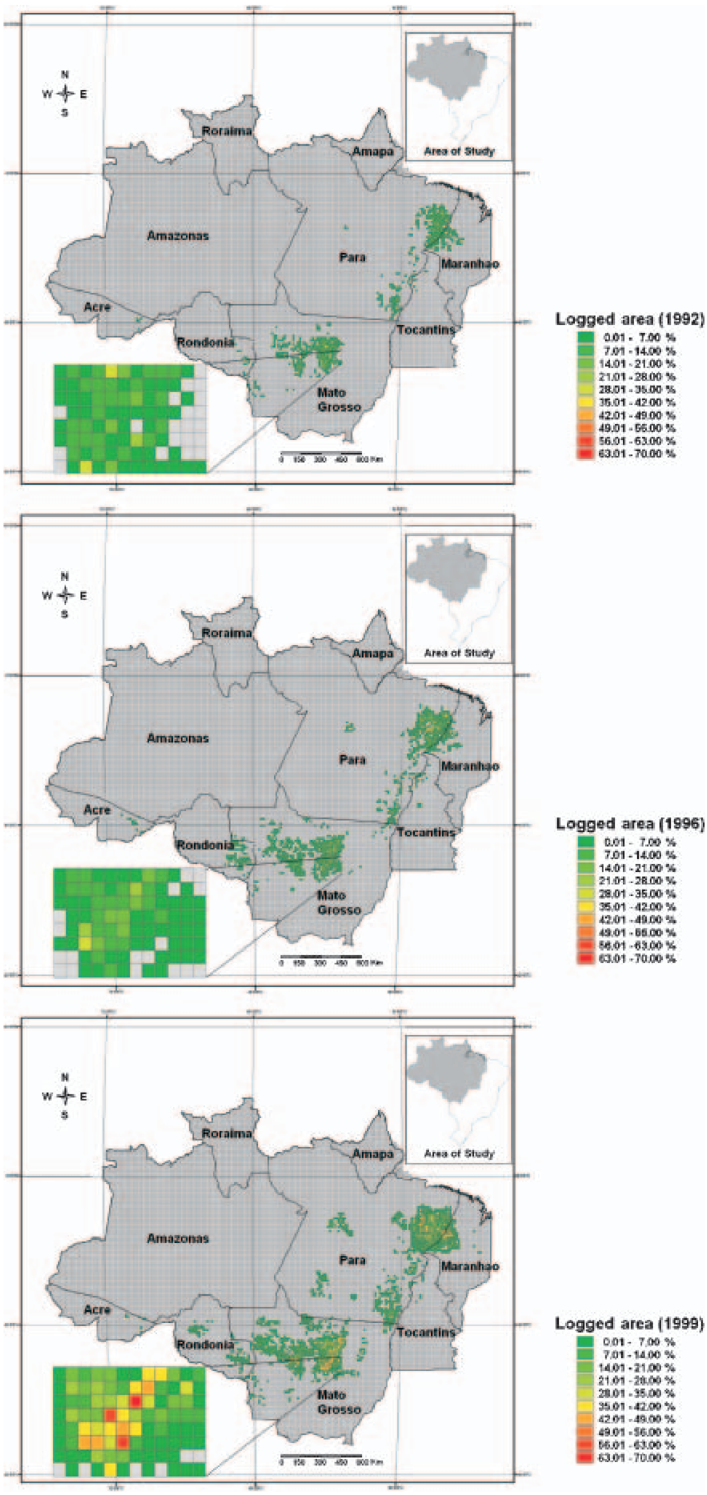

Figure 7. Spatial distribution and intensity (logged area/625 km^2 grid cell size) of selectively logged forests detected in 1992, 1996, and 1999.

regions (Kuntz and Siegert 1999, Siegert *et al.* 2001). Since selectively logged forests were more susceptible to fire (Holdsworth and Uhl 1997), this climate anomaly could have increased the degradation in logged forests through drought and fire, thereby enhancing the detection of selectively logged forests due to their more heavily degraded canopies.

These three factors seem to play an important role in the observed changes in detectable selective logging in the Brazilian Amazon. However, an actual growth in the logging industry across the study region should not be discounted either. In any case, the area impacted by selective logging is rapidly increasing making it a land use of growing importance and concern in Amazonian forests.

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