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Remote Monitoring for Forest Management in the Brazilian Amazon

André Monteiro and Carlos Souza Jr.
Amazon Institute of People and The Environment-Imazon
Brazil

1. Introduction

Timber harvesting is an important economic activity in the Brazilian Amazon. In 2009, the timber industry produced 5.8 million cubic meters of logwood and generated US$ 2.5 billion in gross income along with 203,705 direct and indirect jobs (Pereira et al., 2010). Logging in the region is predominantly predatory, and is commonly known as Conventional. Only a small proportion occurs in a managed fashion (planned), known as Reduced Impact Logging (RIL) (Asner et al., 2002; Gerwing, 2002; Pereira Jr. et al., 2002; Veríssimo et al., 1992). In the conventional method activities are not planned (opening of roads and log decks[1], tree felling and log skidding), while with RIL planned management techniques are applied at all stages of harvesting (Amaral et al., 1998).

The two methods cause impacts ranging from low to severe on the structure and composition of the remaining forest (Gerwing, 2002; John et al., 1996; Pereira Jr. et al., 2002). However, the impacts of predatory logging are two times greater than those of managed logging (John et al., 1996). Among the main impacts are: greater reduction in living aboveground biomass (Gerwing, 2002; Monteiro et al., 2004), risk of extinction for high-value timber species (Martini et al., 1994), greater susceptibility to forest fires (Holdsworth & Uhl, 1997), increase of vines and pioneer vegetation (Gerwing, 2002; Monteiro et al., 2004) and substantial reduction in carbon stocks (Gerwing, 2002; Putz et al., 2008).

The impact of timber harvesting can be described by means of forest inventories carried out in the field, with which it is possible to evaluate the structure and composition of the remaining forest (Gerwing, 2002; John et al., 1996; Monteiro et al., 2004). Another method employed is remote sensing, which has advanced over the last decade. In the Amazon, there have been successful tests with satellite images to detect and quantify forest degradation brought about by logging activities in the region (Asner et al., 2005; Matricardi et al., 2007; Souza Jr. et al., 2005). Images with moderate spatial resolution, such as Landsat (30 m) and Spot (20 m), have been used to detect types of logging, damages to the canopy and roads and log decks for harvesting (Asner et al., 2002; Matricardi et al., 2007; Souza Jr. & Roberts, 2005). As for images with high spatial resolution, such as Ikonos (1 to 4 m), they are capable of detecting smaller features of logging, such as small clearings (Read et al., 2003), as well as making it possible to determine the size of log decks and width of roads (Monteiro et al.,

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[1] Clearings (500 m²) opened in the forest for storing timber.

2007). The use of remote sensing for monitoring forest management plans is of great importance for the Brazilian Amazon, given that logging activities are predominantly predatory and occur in extensive areas that are difficult to access.

Recent studies have shown how to integrate data extracted from satellite images with biomass data collected in the field, which makes it possible to estimate the loss of biomass in the forest submitted to different levels of forest degradation (Asner et al., 2002; Pereira Jr. et al., 2002; Souza Jr. et al., 2009). Our research has made advances in applying those techniques to assess the intensity and quality of logging (Monteiro et al., 2009).

In this chapter, we demonstrate how the impacts of timber harvesting can be characterized by means of forest inventories and combined with satellite images to monitor extensive areas. We also present the remote sensing techniques utilized for detecting, mapping and monitoring logging activities. Finally, we present the results of our system for monitoring forest management plans, applied in Pará and Mato Grosso, the two largest timber-producing States in the Amazon, which respectively account for 44% and 34% of the total produced in 2009 (Pereira et al., 2010).

2. Logging impact characterization based on field surveys

2.1 Change in structure and composition as a result of forest degradation

Characterization of the impacts of logging in the field is done by means of forest inventories. To do this, transects or plots are established in the forest to quantify the damages to its structure and composition in terms of soil cover, canopy cover and aboveground live biomass (Gerwing, 2002; John et al., 1996; Monteiro et al., 2004).

In the method developed by Gerwing (2002) 10 m x 500 m transects are opened, in which all individual trees with DBH (Diameter at Breast Height) ≥ 10 cm are sampled. In 10 m x 10 m sub-parcels, located at 50 m intervals along the central line of the transect, all individuals with DBH ≤ 10 cm are sampled. In those sub-parcels the soil cover is assessed, with the percentages of intact soil, soil with residues and disturbed soils being recorded; as well as the canopy cover, with four readings in a spherical densiometer, at 90° intervals, every 50 m along the central axis of the transect (Figure 1).

Additionally, the live biomass above the ground in each transect is estimated, adding together the weight of dry matter from different forest components using alometric equations available in the literature (Table 1). The estimate of biomass for trees < 10 cm is done by multiplying the number of stems in each diameter class by the biomass corresponding to the arithmetic average of the diameter for each class.

The forest inventory was carried out in 55 transects, including 11 in intact forest (reference) and 44 in forests in different classes of degradation due to different log harvesting methods. It was done in the Paragominas and Santarém regions, in the State of Pará, in Sinop, in Mato Grosso, and in Itacoatiara, in Amazonas (Figure 2). Below is a description of intact forest and forests in different classes of degradation according to Gerwing (2002):

i.   Intact forest: mature forest (> 40 years) without disturbance, dominated by shade-tolerant species.

ii.   Logged without mechanization (Traditional logging): forest logged without the use of skidder tractors, that is, without impact from construction of logging infrastructure: log decks, roads and skidder trails.

iii. Managed logging (Reduced Impact Logging-RIL): forest logged selectively following planning of harvesting activities: forest inventory, opening of decks and roads, felling and skidding of trees and transport of logs.

iv. Conventional logging: forest logged selectively and not following planning of the activities mentioned above. Log decks, roads and skidder trails are opened causing severe damage to the forest.

v. Logged and burned: forest logged selectively, without planning, followed by burning.

vi. Logged intensely and burned: forest logged selectively in a conventional manner more than once, and later burned.

vii. Burned: forest burned without having been logged.

To evaluate differences between the variables in the degradation classes we employed the analysis of variance (ANOVA with Type III Sum of Squares) followed by the Tukey's HSD post-hoc test with an individual error rate of 0.05% and with an overall significance of 0.08% using the R program (R *Development Core Team*, 2010).
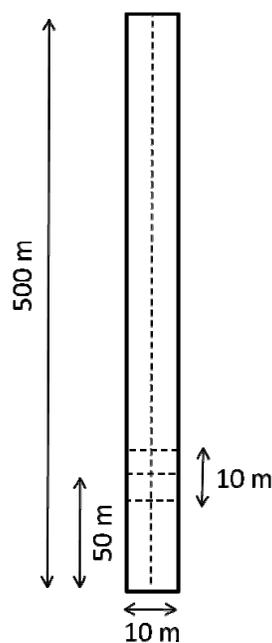

Fig. 1. Transect layout of the forest inventories.

Species group	Regression equation	Source
Forest tree species ≥ 10 cm DBH	DW= 0.465(DBH)$^{2.202}$ DW= 0.6*4.06(DBH)$^{1.76}$	Overman et al. (1994) Higuchi & Carvalho (1994)
< 10 cm DBH	log(DW)= 0.85+2.57 log(DBH)	J. Gerwing (data not published)
Pioneer tree species Cecropia sp. Other sp.	ln(DW)= -2.512+2.426 ln(DBH) ln(DW)= -1.997+2.413 ln(DBH)	Nelson et al. (1999) Nelson et al. (1999)

Table 1. Regression equations used to determine the dry weights (kg) of various forest components based on their diameters (cm).

In the subsections below, we present the results of characterizing forest degradation for the classes described above. That information is later combined with remote sensing data to evaluate the intensity and quality of logging. In the field we quantified forest degradation

related to soil disturbance (intact vegetation, residues and disturbed soil), canopy cover and aboveground biomass because those indicators present a direct relation with remote sensing data (Souza Jr. et al., 2009).
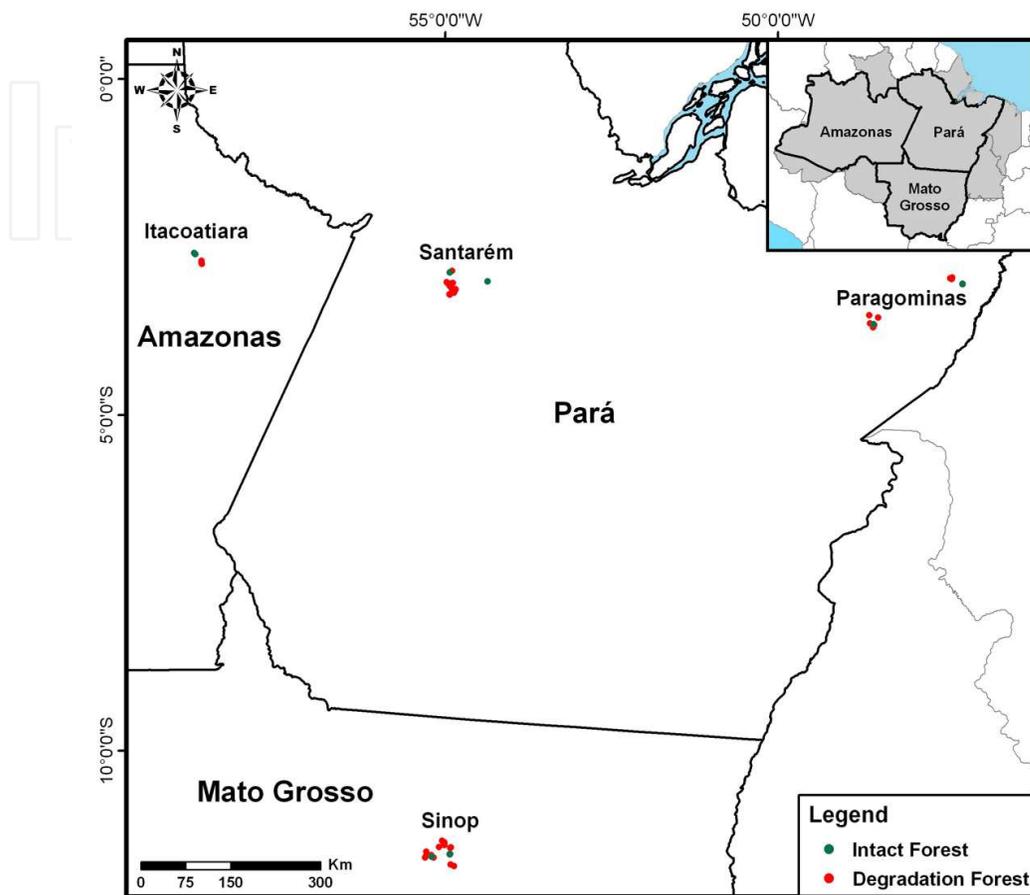

Fig. 2. Location of the forest transects sites.

2.1.1 Soil disturbance and canopy cover

The evaluation of soil disturbance (intact vegetation, residues and disturbed soil) and canopy cover in the field is crucially important, since those results directly influence the results of the satellite images. The greater the soil disturbance and the smaller the canopy cover of the degraded forest, the greater will be the signal for this damage in the image. Our results show that the area of intact vegetation was smaller in the classes with greater degradation. The smallest percentage of intact vegetation was observed in the intensely logged and burned class (4%), followed by burned forest (22%), with these presenting a significant difference in relation the intact forest and to the classes with less degradation. The quantity of residues in the soil was greater in the logged and burned forest (26%), followed by the burned forest (25%), however no significant differences were found between these classes and intact forest. The area of disturbed forest was greater in the intensely logged and burned forest (96%) and the burned forest (53%), presenting a significant difference in relation to the intact forest and the other degradation classes. The logged and burned class presented the lowest canopy cover (75%), with a significant difference in relation to the intact forest and to the classes with less degradation (Table 2).

2.1.2 Change in the live aboveground biomass

The live biomass aboveground was less in the forest degradation classes compared to the biomass in intact forest; however, no significant differences were found between them. Among individuals with DBH ≥ 10 cm, the logged and burned and intensely logged classes presented 36% lower biomass than the intact forest, followed by the burned class (18%) (Table 2). The lowest biomass for individuals with DBH < 10 cm was also observed in the logged and burned (44%) and intensely logged and burned (11%) classes (Table 2). The biomass in individuals with DBH ≥ 10 cm decreased with increasing degradation. The variation in biomass for individuals with DBH < 10 cm seems to be related to the incidence of pioneer species that tolerate moderate levels of degradation (Gerwing, 2002; Monteiro et al., 2004). The greatest loss of biomass is not related only to the greatest forest degradation. The distance from the first degradation may also influence a greater reduction in biomass (Gerwing, 2002; Monteiro et al., 2004). For example, data collection in the logged and burned forest (biomass for individuals ≥ 10 cm and < 10 cm = 232 t ha^{-1} and 5 t ha^{-1}, respectively) occurred approximately 2.5 years after the first degradation event, while in the intensely logged and burned forest (biomass for individuals ≥ 10 cm and < 10 cm = 234 t ha^{-1} and 8 t ha^{-1}, respectively), it occurred 16 years after the first degradation event.

	(a) Intact (n=11)	(b) Non-mechanized logging (n=9)	(c) Managed logging (n=14)	(d) Conventional logging (n=8)	(e) Logged and burned (n=4)	(f) Heavily logged e burned (n=5)	(g) Burned (n=4)
Ground cover (total area (%))							
Intact vegetation	95 (6) a	87 (22) b	96 (20) c	92 (15) ac	75 (7) d	4 (5) ef	22 (19) f
Woody debris	5 (6) a	23 (23) a	23 (12) a	13 (11) a	26 (10) a	0 a	25 (44) a
Disturbed soil	0 a	3 (4) a	10 (9) a	13 (11) a	7 (6) a	96 (5) b	53 (49) c
Canopy cover (%)	95 (3) a	87 (9) b	96 (2) a	92 (6) a	75 (8) c	86 (2) a	88 (1) d
Aboveground live biomass (t ha^{-1})							
Live trees ≥ 10 cm DBH	365 (50) a	347 (33) a	342 (52) a	321 (12) a	232 (11) a	234 (23) a	299 (14) a
Live trees < 10 cm DBH	9 (2) a	10 (2) a	9 (1) a	11 (1) a	5 a	8 a	9 a

[*] Means presented with standard deviation noted parenthetically. In the ground cover, canopy cover and biomass values, different forest class letters denote significant differences among stand classes at P<0.05 utilizing Tukey's HSD post-hoc test, with a global significance level of 0.8

Table 2. Comparison of ground cover, canopy cover and biomass among intact forest and degraded forest in the States of Pará, Mato Grosso and Amazonas in Brazil[*]

3. Remote sensing techniques to enhance and detect timber harvesting

Moderate satellite imagery such as Landsat Thematic Mapper (30-meters pixel size) and Spot Multispectral (20 meters) has been used to detect and map the impacts of selective

logging. However, the complex mixture of dead and live vegetation, shadowing and soils found throughout forest environments impose challenges to revealing these impacts, requiring advanced remote sensing techniques (Asner et al., 2005; Souza Jr. et al., 2005).

From the satellite vantage point, forest damage caused by logging seems to disappear within three years or less, making detection of previously logged forest (> 1 year) very challenging (Souza Jr. et al. 2009; Stone & Lefebvre, 1998). Remote sensing studies on logging in the Brazilian Amazon found that Landsat reflectance data have high spectral ambiguity for distinguishing logged forest from intact forest (Asner et al., 2002, Souza Jr. et al., 2005). Vegetation indices (Souza et al. 2005a; Stone & Lefebvre, 1998) and texture filters (Asner et al., 2002) also showed a limited capability for detecting logging. Improving the spatial resolution of reflectance data can help; 1-4 m resolution Ikonos satellite data can readily detect forest canopy structure and canopy damage caused by selective logging (Asner et al. 2002; Read et al., 2003; Souza Jr. & Roberts, 2005). However, the high cost of these images, and additional computational challenges in extracting information, requiring a combination of object-oriented classification with spectral information, severely limit the operational use of Ikonos and similar imagery.

Over the last two decades, the Brazilian Amazon has been a great laboratory for testing remote sensing techniques to detect and map forest impacts of selective logging (Asner et al., 2005; Matricardi et al., 2001; Read et al., 2003; Souza Jr. & Barreto, 2000; Souza Jr. et al., 2005; Stone & Lefebvre, 1998;). These techniques differ in terms of mapping objectives, image processing techniques, geographic extent, and overall accuracy. In terms of mapping objective, some image processing algorithms were proposed for the total logged area, including roads, log landings, forest canopy damaged and undisturbed forest islands, while others were focused only on the mapping of forest canopy damage. Techniques to map total logged area were based on visual interpretation (e.g., Matricardi et al., 2001; Stone & Lefebvre, 1998), combination of automated detections of log landings with buffer applications defined by logging extraction reach (Monteiro et al., 2003; Souza Jr. & Barreto, 2000), and textural filtering (Matricardi et al, 2007). More automated techniques are mostly based on SMA (spectral mixture analysis) approaches combined with spatial pattern recognition algorithms (Asner et al., 2005; Souza Jr. et al., 2005). Finally, image segmentation has been applied to very high spatial resolution imagery (Hurtt et al., 2003). Landsat images are the ones most used in the studies and in operational systems in the Brazilian Amazon.

Some research has shown that the detection of logging at moderate spatial resolution is best accomplished at the sub-pixel scale using SMA (Box 1). Images obtained with SMA that show detailed fractional cover of soils, non-photosynthetic vegetation (NPV) and green vegetation (GV) enhance our ability to detect logging infrastructure and canopy damage. For example, log landings and logging roads have higher levels of exposed bare soil with detection facilitated by Soil Fraction (Souza Jr. & Barreto, 2000). The brown vegetation component, including trunks and tree branches, increases with canopy damage, making NPV fraction useful for detecting this type of area (Souza Jr. et al., 2003; Cochrane & Souza Jr., 1998) and the green vegetation (GV) fraction is sensitive to canopy gaps (Asner et al., 2004).

A novel spectral index combining the information from these fractions, the Normalized Difference Fraction Index (NDFI) (Souza, Jr. et al., 2005), was developed to augment the detection of logging impacts. NDFI is computed as:

$$\text{NDFI} = \frac{\text{GV}_{\text{Shade}} - (\text{NPV} + \text{Soil})}{\text{GV}_{\text{Shade}} + \text{NPV} + \text{Soil}} \tag{1}$$

where GV$_{shade}$ is the shade-normalized GV fraction given by,

$$GV_{Shade} = \frac{GV}{100 - Shade} \qquad (2)$$

NDFI values range from -1 to 1. For intact forests, NDFI values are expected to be high (i.e., about 1) due to the combination of high GV shade (i.e., high GV and canopy Shade) and low NPV and Soil values. As forest becomes degraded, the NPV and Soil fractions are expected to increase, lowering NDFI values relative to intact forest (Souza Jr. et al., 2005). Canopy damage detection caused by forest degradation induced by factors such as logging and forest fires can be detected with Landsat images within a year of the degradation event with 90.4% overall accuracy (i.e., for three land cover classes, Non-Forest, Forest and Canopy Damage) (Souza Jr. et al., 2005).

The reflectance data obtained from Landsat data of each pixel can be decomposed into endmember fractions, which are purest component materials that are expected to be found within the image pixels. For the purpose of detecting forest degradation, we modeled the reflectance pixel in terms of GV (green vegetation), NPV (non-photosynthetic vegetation), Soil and Shade through Spectral Mixture Analysis – SMA (Adams et al., 1993). The SMA model assumes that the image spectra are formed by a linear combination of n pure spectra, such that:

$$R_b = \sum_{i=1}^{n} Fi\, R_{i,b} + \varepsilon_b \qquad (1)$$

for

$$\sum_{i=1}^{n} F_i = 1 \qquad (2)$$

where R_b is the reflectance in band b, $R_{i,b}$ is the reflectance for endmember i, in band b, F_i the fraction of endmember i, and ε_b is the residual error for each band. The SMA model error is estimated for each image pixel by computing the **RMS** error, given by:

$$RMS = [n^{-1} \sum_{b=1}^{n} \varepsilon_b]^{1/2} \qquad (3)$$

Identifying the correct endmembers is a crucial step in SMA model. To avoid subjectiveness in this process, we have built a generic endmember spectral library (Figure 3) as described in Souza Jr. et al. (2005).

The following steps are used to evaluate SMA results :
1. Fraction images are evaluated and interpreted in terms of field context and spatial distribution. For example, high Soil fraction values are expected in roads and log landings and high NPV in forest areas with canopy damage;
2. Fraction values should have physically meaningful results (i.e., fractions ranging from zero to 100%). Histogram analysis of fraction values can be performed to evaluate this requirement.

3. Fraction values must be consistent over time for invariant targets, i.e., that intact forest not subject to phenological changes must have similar values over time.
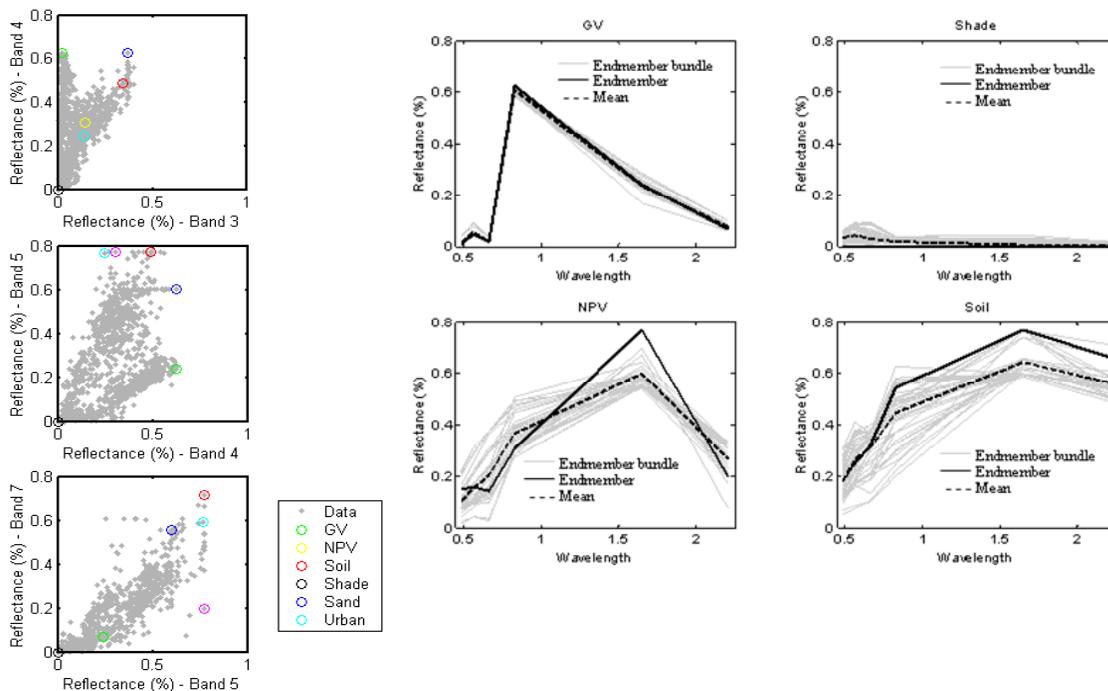

Fig. 3. Image scatter-plots of Landsat bands in reflectance space and the spectral curves of GV, Shade, NPV and Soil (source: Souza Jr. et al., 2005).

Box 1. Spectral Mixture Analysis (SMA)

4. Integrating field and remote sensing data

Assessment of the quality of timber harvesting has traditionally been done through measuring damages to the forest, e.g. quantification of the opening of log decks, logging roads and openings resulting from felling trees; and the density and biomass for remaining individuals (Gerwing, 2002; Pereira Jr. et al., 2002; Veríssimo et al., 1992). However, field surveys are expensive and lengthy, especially for extensive areas such as the Amazon. Recent studies have shown that it is possible to infer the quality of timber harvesting through satellite images that are calibrated with indicators of damages measured in the field, allowing greater speed, reduction of costs and monitoring of extensive areas. Using satellite images such as Landsat and Spot it is possible to evaluate the quality of logging activities based on mapping of roads, log decks and damages to the forest canopy (Monteiro & Souza Jr., 2006; Monteiro et al., 2009). We present below the items evaluated and the respective indicators for monitoring timber harvesting and the results of its application in order to qualify its impacts.

4.1 Roads and log decks
For the roads and log decks we evaluated the following indicators: the density of log decks and roads; the distance between secondary roads and between log decks; and spatial

distribution of log decks and roads. Those indicators were tested in 43 logging areas located in regions of Pará, Mato Grosso and Amazonas. The results were validated with measurements of the same indicators in the field, in areas of conventional (predatory) logging and managed logging in the Paragominas (PA) and Sinop (MT) regions (Monteiro & Souza Jr., 2006).

To do this we used Landsat 5 TM satellite images with 30 meters of spatial resolution. We first applied geometric and atmospheric correction to those images. Next, we obtained fraction images of vegetation, soils and NPV (non-photosynthetically active vegetation), based on the spectral mixture model followed by NDFI (Normalized Difference Fraction Image) to highlight the scars caused by logging (Souza Jr. et al., 2005). Finally, we digitalized the log decks and roads in the NDFI image and inferred the density of log decks and roads and the distances between log decks and between roads. Additionally, we classified the spatial distribution of log decks and roads as systematic and non-systematic. Systematic distribution is characterized by rectilinear and parallel roads and log decks regularly distributed along the roads, while non-systematic distribution is defined by sinuous roads with log decks interlinked by their segments.

The results of evaluating the indicators presented an average density of 16 meters/hectare for roads and 3/100 hectares for log decks. The average distance between roads was 623 meters, and between log decks it was 484 meters (Table 3). Conventional logging presented a higher density of log decks and roads compared to logging with forest management (Johns et al., 1996). As for the distance between secondary roads and between log decks, they are smaller in logging with forest management compared to the distances between secondary roads in conventional logging (Monteiro, 2005).

As for the spatial distribution of log decks and roads, the majority of areas evaluated that were logged using forest management presented a non-systematic distribution of log decks (60%) and roads (58%), which indicates low quality in planning that infrastructure (Monteiro & Souza Jr., 2006).

	Region	Logging type	Density*		Distance*	
			Road (m/ha)	Log deck (n/100 ha)	Secondary roads (m)	Log landing (m)
IMAGE	Pará, Mato Grosso and Amazonas	Managed	16 (5)	3 (2)	623 (232)	484 (148)
FIELD	Paragominas (PA)	Managed	23 (4)	8 (1)	469 (30)	260 (74)
		Conventional	36 (6)	15 (2)	513 (38)	301 (263)
	Sinop (MT)	Managed	32 (11)	7 (4)	455 (24)	347 (126)
		Conventional	19 (3)	1 (2)	508 (43)	512 (44)

*Mean density and distance with standard deviation within brackets.

Table 3. Comparison between the indicators (mean) measured in the images from Pará, Mato Grosso and Amazonas regions and those measures in the field in Paragominas and Sinop (Monteiro & Souza Jr., 2006).

4.2 Forest canopy

We evaluated the indicator of damages to the canopy caused by logging operations. To do that we utilized NDFI images to evaluate the area of forest affected. First, we delimited the logging area visible in the NDFI image by means of visual interpretation. Next, we selected around five samples from 100 in the NDFI image to represent logging and extracted the average values of those samples. The samples were composed of a mosaic of environments (forest, log decks, roads, skidder trails and clearings caused by felled trees).

The quality of logging is determined using thresholds obtained in the NDFI image and calibrated using field data (Monteiro et al., 2008), so that: NDFI≤ 0.84 represents low quality timber harvesting (predatory logging); NDFI= 0.85-0.89, intermediate quality harvesting (there was an attempt at adopting management, but the configuration of roads, log decks and clearings reveals serious problems with execution); and NDFI≥ 0,90, good quality harvesting (the configuration of roads, log decks and clearings is in conformity with the techniques recommended by forest management (Figure 4).

This method was tested in the States of Pará and Mato Grosso, the main timber producers, responsible respectively for 44% and 34% of the total produced in 2009 in the Brazilian Amazon (Pereira et al., 2010). We evaluated 156,731 and 177,625 hectares respectively of areas undergoing timber harvesting in the two States. In Pará, 21% of that total presented logging of good quality, 54% showed intermediate quality and 25% showed low quality (Figure 5). In Mato Grosso, only 9% of logging was of good quality, 55% showed intermediate quality and 36% showed low quality (Figure 5). In the images, the log decks appear as yellow points; and the roads as light green lines. In the areas with logging of good quality, we observed the low impact on the canopy as light green patches in the images. The medium impact on the canopy observed in areas with intermediate quality appears as intense light green patches. In low quality harvesting, the log decks and roads are mixed, with the high impact on the canopy and appearing as more intense patches, varying from light green to yellow) (Figure 4). The high percentage of areas harvested in Pará and Mato Grosso with intermediate and low quality indicates a low level of adoption of forest management. This may also point to technical deficiency among company forest management technicians.
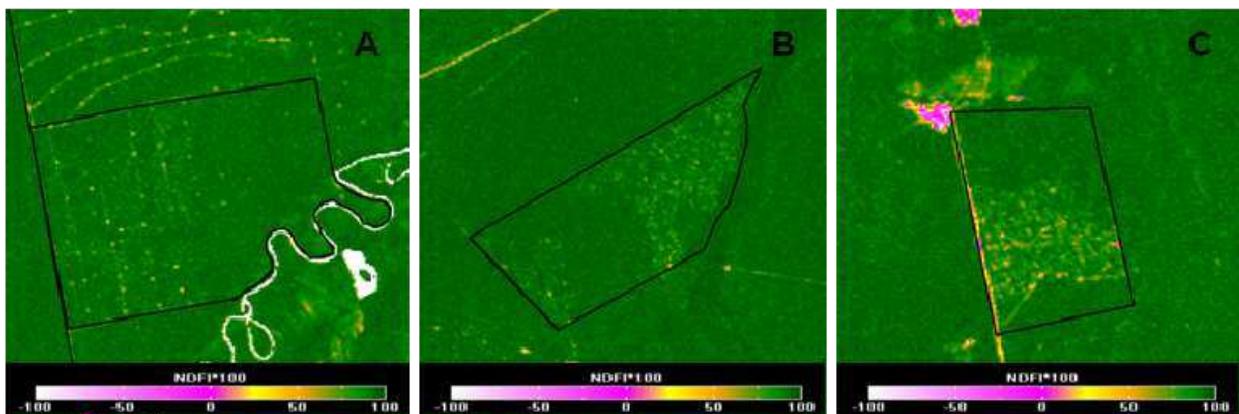

Fig. 4. Forest management of good (A), intermediate (B) and low (C) quality according to NDFI images.

To validate results of our assessment of the quality of timber harvesting as seen in satellite images, we went to the field to quantify it. To do this, we evaluated and scored impacts of

logging resulting from opening of log decks and roads, felling trees and damages to remaining trees. We verified that the greater the impact, the lower the quality of harvesting and vice-versa. We thus attributed a score (from 0 to 4) and a corresponding classification (low, intermediate and good), in which: score <2 = low quality; score 2-<3 = intermediate quality; and score 3–4 = good quality. In table 4 we present the results of that validation. However, in the samples validated in the field we did not have cases of low quality management, despite having detected this standard of quality in the images. The quality standards were correctly classified in 86% and 58% of cases, as intermediate and good quality respectively (Table 4). The cases in which results in the images were different from those in the field may be related to the fact that the area evaluated in the field was geographically not the same area evaluated in the image. In the image we sampled the forest management area that visually was the most disturbed; however, because of the difficulty in accessing that area in the field, we had to evaluate another area geographically closed to the real area. With this, we verified that the quality of forest management can vary within the same licensed area, confirming the importance of monitoring forest management by satellite as a planning tool in enforcement campaigns by environmental agencies.
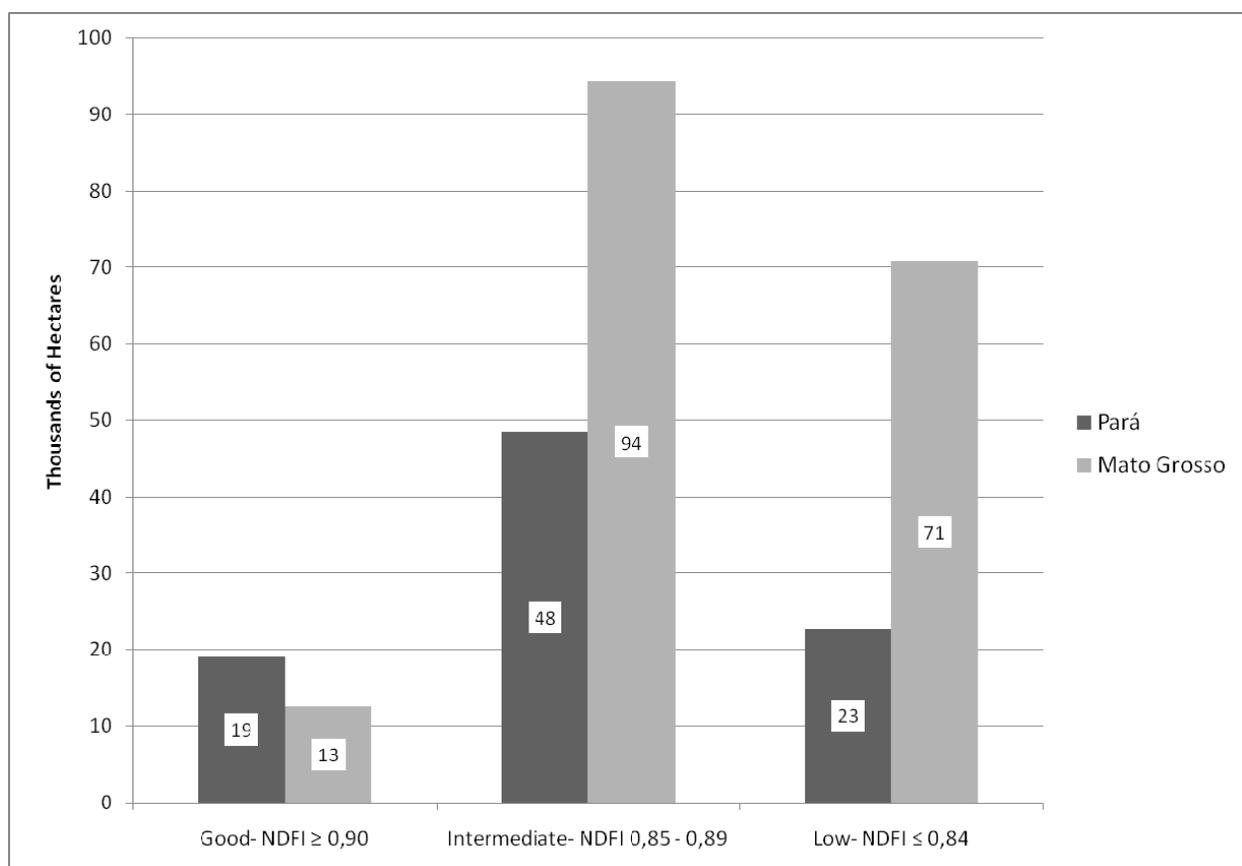

Fig. 5. Quality (in hectares) of timber harvesting in management plans in the State of Pará and Mato Grosso.

Forest Management Sample	Quality in the image		Quality in the field	
	Classification	NDFI	Classification	Scoring
1	**intermediate**	**0.86**	**intermediate**	**2.77**
2	**intermediate**	**0.89**	**intermediate**	**2.66**
3	intermediate	0.86	good	3.43
4	**good**	**0.90**	**good**	**3.18**
5	intermediate	0.85	intermediate	2.42
6	intermediate	0.88	intermediate	2.26
7	good	0.90	good	3.22
8	**good**	**0.90**	**good**	**3.00**
9	good	0.90	intermediate	2.54
10	**intermediate**	**0.88**	**intermediate**	**2.72**
11	good	0.91	intermediate	2.81
12	**good**	**0.90**	**good**	**3.09**
13	**good**	**0.91**	**good**	**3.09**
14	**good**	**0.90**	**good**	**3.36**
15	good	0.90	intermediate	2.81
16	**good**	**0.91**	**good**	**3.45**
17	good	0.90	intermediate	2.45
18	good	0.90	intermediate	2.45
19	**intermediate**	**0.89**	**intermediate**	**2.45**
20	good	0.91	intermediate	2.90
21	**good**	**0.91**	**good**	**3.27**
22	**good**	**0.91**	**good**	**3.18**
23	good	0.91	intermediate	2.45
24	good	0.90	intermediate	2.54
25	**good**	**0.91**	**good**	**3.09**
26	**good**	**0.90**	**good**	**3.27**

Table 4. Comparison of forest management quality obtained in the image and obtained in the field (Monteiro et al., 2011).

4.3 Forest biomass

We evaluated the loss of forest biomass indicator in the areas submitted to forest degradation. To do this, we first obtained an NDFI image to quantify forest degradation (Souza Jr. et al., 2005). Next, we integrated that information with the forest biomass data collected in the field (See section 2.1.2).

We observed that the NDFI value in the image diminishes with the increase in forest degradation. This means that the lower the biomass, the more degraded the forest; in

other words, there is a high negative correlation between the biomass values quantified in the field with the NDFI values of the forest degradation classes (Figure 6) (Souza Jr. et al., 2009). However, that negative correlation is only observed when the NDFI image is from the same year as the occurrence of the degradation event, since beginning in the following year, the degradation signal diminishes (Souza Jr. et al., 2009).
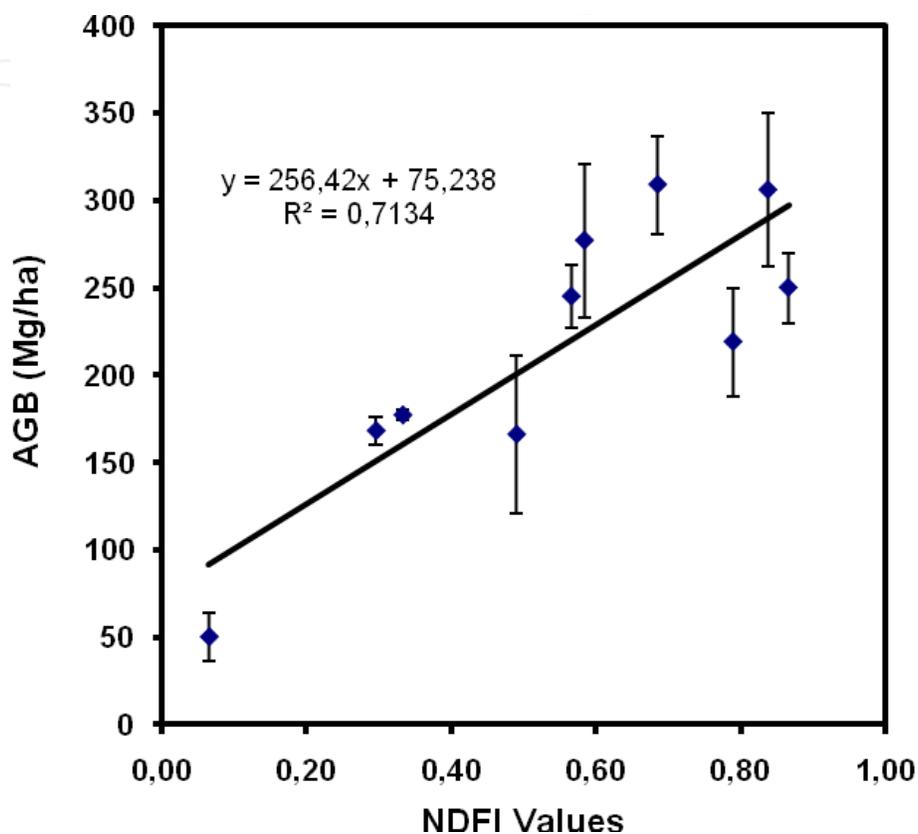

Fig. 6. Relationship between Aboveground Biomass- AGB and NDFI values for degraded forest of Paragominas and Sinop (Souza Jr. et al., 2009).

5. Applying remote sensing to monitor forest management in the Amazon

In the subsections below we present the results of remote monitoring in the timber harvesting areas of the States of Pará and Mato Grosso for the period of 2007 to 2009. We first mapped and classified timber harvesting as legal and illegal. Next, we identified the municipalities in those States where illegal forest activity is most critical. Later, we overlaid the map of illegal logging on the Protected Areas and land reform settlements so as to identify the areas under the greatest pressure from illegal timber harvesting. Finally, we integrated the information from satellite images with those of the forest control systems in those States.

5.1 Mapping of timber harvesting

We mapped logging using the NDFI images and overlaid that information on the map of forest management plans so as to identify non-authorized logging (illegal and predatory) and authorized logging (forest management). We quantified 543,504 hectares of logged

forests in Pará, of which 86% were not authorized and 14% had an authorization for forest management. In Mato Grosso, we mapped 460,134 hectares of logged forests, of which 39% lacked authorization and 61% were authorized (Figure 7).
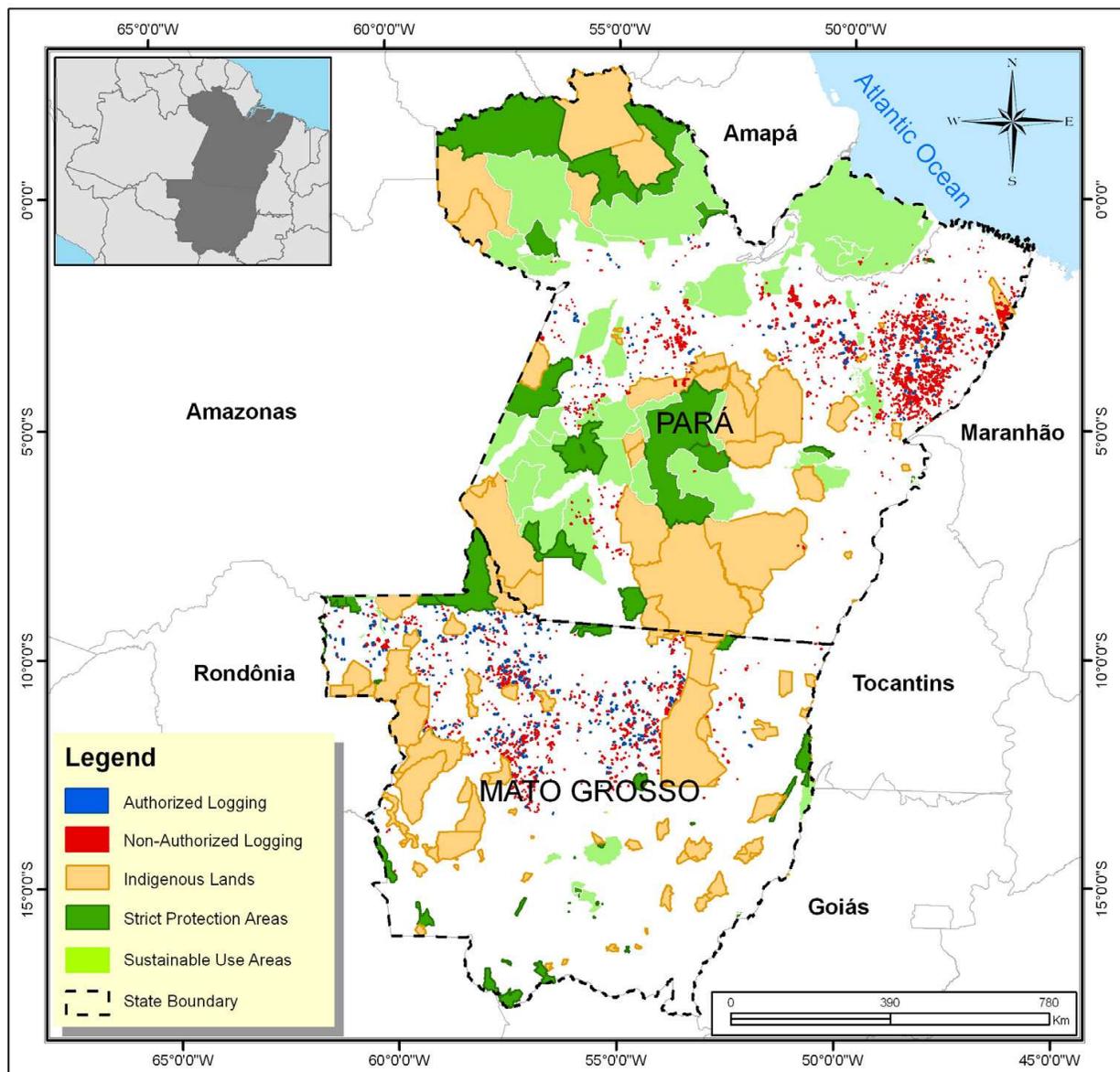

Fig. 7. Authorized and non-authorized logging from 2007 to 2009 in Pará and Mato Grosso states.

5.1.1 Non-authorized logging

Of the 466,979 hectares of forest logged without authorization in Pará between 2007 and 2009, the majority (77%) occurred in 10 municipalities. The remaining 23% were distributed more sparsely among 41 other municipalities. The municipality of Paragominas presented the largest area of non-authorized logging, followed by Rondon do Pará and Goianésia do Pará. In Mato Grosso, there were 179,155 hectares of forests logged without authorization, of which the majority (62%) occurred in 10 municipalities.

The remaining 38% were distributed more sparsely among 32 other municipalities. The municipality of Marcelândia presented the largest area of non-authorized logging, followed by Nova Maringá and Aripuanã.

From 2007 to 2009, illegal timber harvesting in Pará affected 54,874 hectares of forests in Protected Areas. Of that total, 83% was logged in Indigenous Lands (TI) and 17%, in Conservation Units (UC). TI Alto Rio Guamá was the most logged, followed by TI Sarauá and TI Cachoeira Seca. Among the Pará UCs, the National Forests (Flonas) of Jamanxim, Caxiuanã and Trairão are stand out as having the largest volume of timber harvesting. In Mato Grosso, illegal timber harvesting affected 10,524 hectares of forests in Protected Areas: 86% in TIs and 14% in UCs. TI Zoró had the highest amount of logging, followed by TI Aripuanã and TI Irantxe. Among the UCs, an Extractive Reserve (Resex Guariba/Roosevelt) and the Serra de Ricardo Franco State Park (PE) stand out with highest harvest volumes. Monitoring of Protected Areas is extremely important for guaranteeing their integrity and the sustainability of populations that depend on the forest for a living. Thus, environmental agencies can use this tool to restrain devastation of Protected Areas in the Amazon. Additionally, forest concessions in public forest areas such as Flonas need to guarantee income and employment for the population living inside and around those Protected Areas.

In the land reform settlements in Pará, timber harvesting without authorization between 2007 and 2009 affected 53,924 hectares of forests; the majority (75%) in 10 settlements. The most critical situation occurred in the Liberdade Sustainable Development Project (PDS) (50% of the total harvested), followed by the Ouro Branco I and II Collective Settlement Projects (PAC) (12% and 8%). In Mato Grosso, timber logging without authorization in the settlements affected 994 hectares of forests. The most critical situation was the Settlement Project (PA) of Pingos D'água (44% of the total harvested), followed by PA Santo Antonio do Fontoura I (33%). Rural settlement projects in the Amazon hold forest areas with great timber potential. However, in the majority of those projects logging is done in an illegal manner, meaning without a logging license. Programs that encourage forest practices through technical capacity-building for settlers can contribute towards reducing illegal timber harvesting in the settlements and generate income for those families.

5.1.2 Authorized harvesting

For the areas with authorized harvesting, in other words, with forest management, we evaluated the data contained in the Forest Harvesting Authorizations (*Autorizações de Exploração Florestal* - Autef) and in the timber credits issued from 2007 to 2009, in order to verify their conformity or consistency. That information is made available by the State Environmental Secretariats (Sema) in Pará and Mato Grosso, in their systems for forest control, Simlam (Integrated System for Environmental Monitoring and Licensing - *Sistema Integrado de Monitoramento and Licenciamento Ambiental*) and Sisflora (System for Sale and Transport of Forest Products - *Sistema de Comercialização e Transporte de Produtos Florestais*).

In Pará, 277,440 hectares of forests were licensed for management. Of that total, the majority (87%) did not present inconsistencies, while 13% revealed inconsistencies, such as: i) authorization for forest management in area totally or partially without forest cover (6% of

cases evaluated); ii) area authorized for management superior to the total area for forest management (4% of cases); and iii) authorization for forest management in area already harvested through logging activities (3% of cases).

In Mato Grosso, 498,783 hectares of forests were approved for forest management, of which the majority (81%) presented no problems and 19% revealed inconsistencies. Those include: i) timber credit commercialized does not correspond to credit authorized (16% of cases); ii) area authorized in deforested area (1% of cases); iii) area authorized greater than the area for forest management (1% of cases); iv) credit issued without authorization for forest harvesting (1% of cases).

Finally, we integrated information from the Autefs with our satellite image base to assess the consistency of forest management performance. In Pará, the largest percentage (45%) of the Autefs evaluated in the satellite image presented no problems, while in 31% it was not possible to make an evaluation because of cloud cover and 24% revealed problems, such as: i) lacking signs of scarring from logging in the images for the period in which the logging authorization was in effect (11% of cases); ii) area of forest management licensed overlaying a Protected Area (5% of cases); iii) logging carried out before issuance of the forest authorization (3% of cases); iv) area licensed for forest management deforested before receiving authorization for harvesting (3% of cases); and v) area logged above the authorized limit (2% of cases).

In Mato Grosso, the same analysis revealed that the majority (78%) presented no problems in the satellite image, whereas 22% revealed problems, which were: i) area was logged above the authorized limit (16% of cases); ii) area licensed for forest management deforested before receiving authorization for harvesting (3% of cases); iii) lacking signs of scarring from logging in the images for the period in which the logging authorization was in effect (1% of cases); iv) plan overlaying a Protected Area (1% of cases); v) logging carried out before issuance of the forest authorization (1% of cases).

The method proposed in this study is capable of monitoring the performance of forest management by timber cutters and forest management licensing by the environmental agencies. This makes it possible to reduce the errors and frauds in the forest control systems during the forest management licensing process and during commercialization of timber.

6. Conclusion

Characterizing the impacts of timber harvesting in the field is essential for determining changes in the structure and composition of the forest submitted to different levels of forest degradation. However, that activity is extremely expensive and lengthy. The advance in techniques for detecting and mapping timber harvesting and integration of that information with data from the field has made it possible to monitor logging (Monteiro et al., 2011) and quantify the loss of carbon from degraded forest in the Brazilian Amazon (Souza Jr et al., 2009).

On the other hand, there is the challenge of putting into operation a system for monitoring timber harvesting at the scale of the Amazon. Logging in the region is predominantly predatory, which has contributed towards an increase in forest degradation and a reduction of the stocks of individual tree species with timber potential. Currently, the Amazon has two systems for detecting deforestation (clearcutting) the

Program for Monitoring Deforestation in the Amazon (*Programa de Monitoramento do Desflorestamento da Amazônia* - Prodes), developed by the Brazilian Space Research Agency (Inpe), and the Deforestation Alert System (*Sistema de Alerta de Desmatamento* - SAD), developed by the Amazon Institute for People and the Environment (Imazon). The method for monitoring timber harvesting proposed in this study can contribute towards reducing illegal logging and improve the quality of harvesting through forest management in the region. With that, we can reduce emissions of CO_2 (Putz et al., 2008) and guarantee the sustainability of the forest-based economy in the Amazon. That method could also contribute towards improving forest management in the Amazon by making it more efficient and transparent.

7. Acknowledgments

8. References

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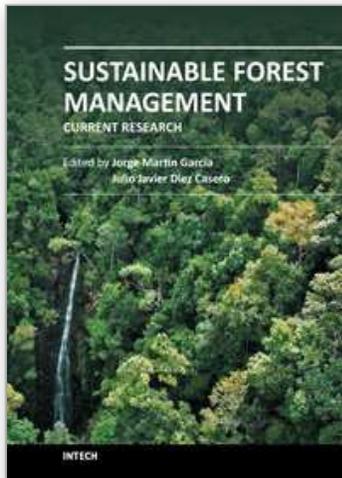
Sustainable forest management (SFM) is not a new concept. However, its popularity has increased in the last few decades because of public concern about the dramatic decrease in forest resources. The implementation of SFM is generally achieved using criteria and indicators (C&I) and several countries have established their own sets of C&I. This book summarises some of the recent research carried out to test the current indicators, to search for new indicators and to develop new decision-making tools. The book collects original research studies on carbon and forest resources, forest health, biodiversity and productive, protective and socioeconomic functions. These studies should shed light on the current research carried out to provide forest managers with useful tools for choosing between different management strategies or improving indicators of SFM.